European Commission

SCIENCE, RESEARCH AND INNOVATION PERFORMANCE OF THE EU 2022

Building a sustainable future in uncertain times

Research and Innovation

Science, research and innovation performance of the EU 2022 – Building a sustainable future in uncertain times
European Commission
Directorate-General for Research and Innovation
Directorate G – Common Policy Centre
Unit G1 – Common R&I Strategy & Foresight Service

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Manuscript July 2022

PDF	ISBN 978-92-76-53506-5	doi:10.2777/78826	KI-09-22-251-EN-N

Luxembourg: Publications Office of the European Union, 2022

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Co-creation of SRIP2022

The authors of this report gratefully acknowledge the policy steering by the Director-General for Research & Innovation (R&I), Jean-Eric Paquet, and the Director of the 'Common Policy Centre' in the Directorate-General for R&I, Julien Guerrier.

The 2022 edition of the SRIP Report is the result of a genuine co-creation process under the guidance of Alexandr Hobza, Chief Economist and Head of Unit 'Common R&I Strategy and Foresight Service' of DG Research and Innovation, and Erik Canton, Deputy Head of Unit. Julien Ravet was in charge of overall editing, coordination and steering, including the drafting of the Report, managing a number of working groups feeding into the process, and providing support to contributors (within the European Commission services and external experts and contractors).

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Ignacio Baleztena and Bianca Cavicchi led all communication aspects related to the production and dissemination of the Report. Grazia Angerame, Marta Albertini, Petros Malecos and Norbert Sokolowski provided support with communication activities and the SRIP website. ESN, notably Bettina Braun, supported the team with the graphic design of the communication deliverables.

The members of the SRIP 2022 Sounding Board were Vincent Aussilloux (France Stratégie), Dirk Pilat (OECD), Debora Revoltella (EIB), Susan Schneegans (UNESCO) and Reinhilde Veugelers (KUL, Bruegel), who played an essential role in assessing the analysis and key policy implications of the Report.

Particular thanks go to our colleagues Anneleen Vandeplas (co-author of section 4-3), Manon Prado (author of Box 1-1), Sven Schade (author of Box 2-2-1 and box 3-4), Sabine Prévost and Alexis Stevenson (authors of Box 3-1), Marta Albertini (author of Box 3-2), Alexis-Michel Mugabushaka and Zoltan Rakonczay (authors of Box 3-3), César Dro (author of Box 3-6), Eva Rueckert (author of Box 4-5), Nicolas Grassano, Hector Hernandez Guevara, Alexander Tuebke, James Gavigan, Fernando Hervas (authors of Box 5-2-1), Benjamin Turner (author of Box 6-1-2), Eleonora Bartoloni and Gregor Kyi (authors of Box 6-3-1), Gergely Tardos (author of Box 6-3-2), Kathrin Kapfinger (author of Box 7-1-4).

We are grateful for contributions of Andrea Ferrannini, Roberto Martino and Mario Biggeri (authors of Box 3-5), Silvia Appelt, Fernando Galindo-Rueda (authors of Box 5-2), Felix Roth (author of Box 4-3), , Paul Khayat, Simon Provençal, David Campbell (authors of Box 6.2-1), Matteo Gatti, Wouter Van Der Wielen, Sebastian Schich and Emily Sinnott (authors of Box 7-1-3).

Valuable analytical assessment and co-drafting was provided by Beñat Bilbao Osorio, Stefanie Kalff-Lena, Angelica Marino, Laurent Obresse and Lorna Schrefler.

Special thanks go as well to our colleagues for very useful comments and reviewing the text of the Report: Thomas Arnold, Michela Bello, Martjin Brons, Patrick Brenier, Nelly Bruno, Alexandru Ciungu, Giacomo Damioli, Stijn Delaure, Giorgio Di Pietro, Lewis Dijkstra, Krzysztof Kania, Enrique Fernandez Macias, Martin Huemer, Konstantinos Niakaros, Aliki Georgakaki, Anne-Catherine Gridelet, Helena Hernnas, Michel Horgan, Nikolaos Kastrinos, Anastasios Kentarchos, Maria Leek, Larisa Lorinczi, Malwina Mejer, Marin Mileusnic, Marija Mitic, Céline Peroni, Ramona Samson, Sven Schade, Paul Schlag, Pauline Sentis, Matteo Sostero, Philippe Tulkens, Stan Van Alphen, Frank Vandermeeren, Peter Voigt, Juergen Wengel, Angelo Wille.

The Report benefitted from valuable insights on data and reviews and we want to thank Roberto Martino, Sergio Inferrera, Felix Roth, Lukas Borunsky and Pierre-Alexandre Balland.

The design of the Report also relied on contributions from Román Arjona Garcia, Jessica Larsson, Lukas Borunsky, Ana Correia, Roberto Martino and Ruzica Rakic.

Furthermore, the Report benefited from comments and/or data from the Joint Research Centre, Eurostat and other services across the European Commission, the OECD STI department, the European Investment Bank, and the European Environment Agency.

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CHAPTER 0

Executive Summary

BUILDING A SUSTAINABLE FUTURE IN UNCERTAIN TIMES

Europe is going through testing times. The past two years have been dominated by the COVID-19 pandemic, which has shaken our private and professional lives. The damage done by the Russian invasion of Ukraine is immense and the war is expected to have significant implications for the years to come. Moreover, these events come on top of long-term challenges facing Europe, such as accelerating climate change, the severe loss of biodiversity, progressively ageing populations, diminishing productivity growth, sluggish digitalisation, growing inequalities, internal security threats, terrorist attacks, increased migration and pressure at the EU's borders. The ongoing crises interact with these trends, often making them more pronounced. The COVID-19 pandemic has not only claimed many lives but also has had huge economic and social implications, which are concentrated on specific groups, such as the young persons with disabilities or the older population. At the same time, it created windows of opportunity to address some long-standing challenges, for example through the boost to digitalisation. The invasion of Ukraine has also magnified important dimensions, such as dependencies and vulnerabilities in a globally interconnected world. As a result of these developments, it is likely that Europeans will continue to live in a more uncertain and fragmented world.

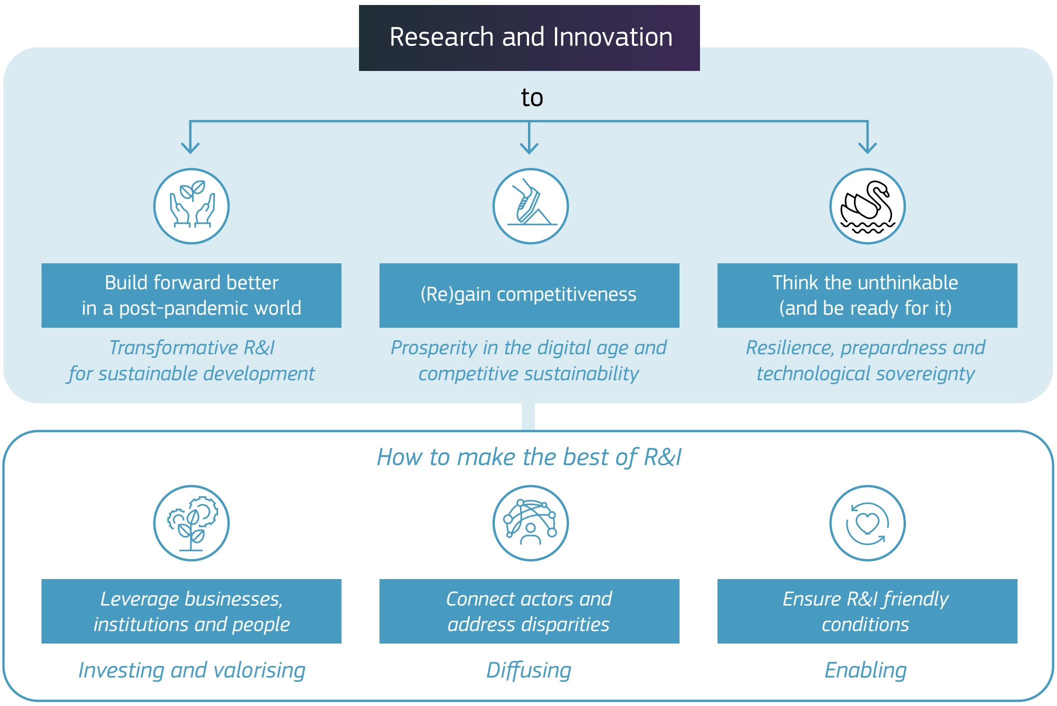
Research and innovation (R&I) are an integral part of the response to these challenges. Bold transformative policies are needed to ensure the success of Europe's digital and green agenda, to strengthen resilience and preparedness, and to support Europe's competitive edge in the global race for knowledge and tech sovereignty. R&I have the potential to produce novel solutions in areas like health, digital technologies, industrial transformation, resilient societies, natural resources, energy, mobility, environment, food, a low-carbon economy and security. For example, the success of the EU ambition to reach the net-zero emission objective by 2050 crucially hinges on development and widespread use of new technologies. Moreover, R&I activities generate benefits for the economy as R&I are at the core of the productivity and competitiveness of our economy and support the creation of new and better jobs and the development of knowledge-intensive sectors. R&I, in particular frontier research, can also strengthen the resilience of our economy and society by building a reservoir of knowledge over the long term.

Against this backdrop, the 2022 edition of the *Science, Research and Innovation Performance of the EU* report provides **insights into how R&I policies can help build an inclusive, sustainable, competitive and resilient Europe by leveraging the essential role of R&I as a source of prosperity and catalyst for social, economic and environmental sustainability.** It emphasises the need to transform Europe to make it fit to deliver on the fundamental objective of providing inclusive wellbeing to citizens while respecting planetary boundaries, as embedded in the European Green Deal and the UN's Sustainable Development Goals (SDGs). Recent experiences document the challenge of staying on a trajectory towards this overarching long-term objective, whilst addressing new crises that may detract policy attention, resources or generate outright trade-offs among the policy objectives. Policy frameworks thus must stay focused on implementing the green and digital transformations, which must be fair and inclusive, while building up capacity to react in a flexible and agile way to new crises and changing conditions. As the challenges we face are shared, we need joint actions and a coordinated approach.

The evidence presented in this report leads to six main policy guidelines for the EU's R&I policy, and beyond that are essential for delivering on our ambitions and objectives. These are:

- Build forward better in a post-pandemic world
- (Re)gain competitiveness
- Think the unthinkable (and be ready for it)
- Leverage businesses, institutions and people
- Connect actors and address disparities
- Ensure R&I friendly conditions.

Figure 0-1: Six main policy guidelines



1. Build forward better in a post-pandemic world

R&I has played a key role throughout the **COVID-19 pandemic**. R&I exerted a strong influence on the development of the pandemic and its economic and social consequences. The pandemic also demonstrated the importance of data and digital technologies as support for policy actions to address the health risks. Measures to contain the pandemic have generated an important change in the way firms operate, acting as a catalyst for the digital transition. At the same time, R&D investment in the EU declined during the crisis, with significant differences between sectors. R&I activities increased in health and ICT while the automotive sector, for example, recorded drops.

In the context of the recovery, R&I policy has also become more prominent in reforms taken at the national level in the EU. R&I are acknowledged as indispensable components of the **Recovery and Resilience Facility** (RRF). Plans developed by Member States include investments supporting the public science base, academia-business cooperation, business innovation and mobilising R&I capacities to accelerate the green and digital transitions and enhance resilience.

But more than ever, the pandemic has provided us with the opportunity to '**build forward better**' and aim for a more sustainable, more digital, more inclusive and, in particular, a more resilient Europe. Emerging technologies, and social and place-based innovations are essential parts of such a transformative change. In particular, the world will be exposed to an increasing frequency and intensity of extreme climatic events, which can lead to more and harsher disasters, as well as huge losses of biodiversity. In this context, the **European Green Deal** proposes deeply transformative policies, with an important role for R&I. And Europe has important strengths to build upon: the EU is the global leader in scientific publications on topics related to sustainability and in patenting activity related to climate action, the environment and secure, clean and efficient energy, although not all trends are positive.

EU R&I policies have a role to play in coordinating the main actors of the transition: industry, universities, national and regional authorities and civil society at large. Given the complexity of the challenges ahead, the structures governing R&I policy processes should be designed to mobilise and support deep transformations across societal and economic systems. Foresight, experimentation and co-creation participatory exercises can bring novel ideas to policymaking and challenge dominant visions. They can also help equip our authorities with the relevant technologies needed, for instance when responding to security incidents, emergencies or addressing new forms of crime. Citizen engagement is critical for reinforcing trust in science and facilitating the innovation process and its uptake. In this regard, the engagement of civil society in science has been a key focus of the EU's R&I policies. The uptake of new and green technologies should also be accompanied by a just transition, where the workers in downscaling, polluting areas are supported in their transition to related fields of work through reskilling and other support measures.

A transformative R&I policy requires some degree of directionality to national and EU investments, i.e., to facilitate and co-ordinate the alignment of R&I investments with EU priorities. A key new feature of Horizon Europe, the EU's R&I Framework Programme, are **missions** that aim to tackle major societal challenges, based on trust in our ability to create a greener, more resilient, more inclusive and better society for future generations. These missions embrace a collaborative approach to catalyse ambitious R&I efforts for the long term, aiming to bring about real change on the ground. The five missions cover areas related to climate change, cancer, ocean and waters, climate-neutral and smart cities, and healthy soils. They include clearly defined targets, time-lines and procedures for tracking and evaluating the results obtained. Horizon Europe also builds on close **partnerships** between different public and private stakeholders with the objective of steering public and private co-investment in a more focused, ambitious and efficient way to ensure they deliver on the Commission's political objectives. Under Horizon Europe, European Partnerships are set up to contribute to EU-wide transitions towards sustainability and push the digital transformation.

What are the implications of COVID-19 for R&I?	More in Chapter 1
What is the role of R&I for sustainability?	More in Chapter 3
What are R&I missions?	More in Chapter 5
What is EU's R&I output in green-related areas?	More in Chapter 6
How do crises affect intangible assets?	More in Chapter 9
What policies can help foster a transition towards green technologies?	More in Chapter 10
How can artificial intelligence help to address the SDGs?	More in Chapter 11

2. (Re)gain competitiveness

In the current era of geopolitical tensions and regional economic rivalries, the quest to maintain or even boost competitiveness gets additional importance. It determines the nature of Europe's participation in global value chains as well as its ability to benefit from this participation and actively shape it. In this respect, our R&I performance is a main driving factor. In the global landscape, the EU remains an R&I **powerhouse**: as it produces about 20 % of the world's scientific and technological output, while having just 7 % of the world's population. However, this position has been eroding as the EU's major trading partners have been improving their innovation performance at a faster pace over the recent years. China is thus the global leader in terms of volume of scientific publications today and the USA has retained its lead in terms of quality and impact. This trend continued during the pandemic, which further skewed the global tech race in favour of the US and China, in particular in relation to digital technologies.

At the same time, **business dynamism has been declining in the EU**, fuelling concerns about the implications for innovation and economic growth. Despite some improvements, the EU keeps lagging behind its main international competitors in terms of number of start-up and scale-up firms. The number of EU unicorns is also increasing, but still is much below those located in the EU's main competitors. As young, fast-growing firms producing disruptive innovations are typically a key driver of the digital and green transition, efforts are still needed to improve the overall framework conditions for innovative companies to thrive.

Improving EU's business environment and innovation capacity requires addressing longstanding issues with a renewed vigour, such as shortcomings in access to finance, innovation-averse regulatory frameworks, the persistent divide between strongly performing firms and laggards, and difficulty in attracting and retaining talent. For the EU to ensure scientific excellence and remain a key scientific player on the global stage, there is a need to increase the effectiveness and performance of EU public research systems through stronger R&I investments and policy reforms. At the same time, it is crucial to continue reinforcing less developed national and regional research systems, aiming at narrowing the current knowledge gap within and between EU countries.

More generally, **R&I are key engines to foster Europe's productivity growth, competitiveness and socio-economic outcomes**. Human capital combined with R&D investments drives companies' ability to create, absorb and diffuse innovation. Enhanced productivity is also a means to achieve inclusive growth and desirable outcomes for society. At the same time, addressing the defining challenges of our time, in particular the climate and environmental crisis, is an opportunity to relaunch our economies in a sustainable manner, promoting **competitive sustainability**.

But despite the huge potential of the digital revolution, Europe has experienced **a secular decline in productivity growth**. This significant slowdown, affecting most advanced economies for over past decades, points to difficulties in generating, exploiting and diffusing new technologies and innovations that would allow for a more efficient use of resources. Moreover, the digital divide between more productive and less productive firms has likely increased with the COVID-19 crisis. Efforts directed at easing the access to and adoption of productivity-enhancing technologies are important to increase competitiveness while reducing inequalities.

How does R&I link to productivity, business dynamism and competitiveness?	More in Chapter 4
How does EU R&I compare to global partners?	More in Chapters 2 and 6
How does COVID-19 affect productivity growth and what are mitigation measures?	More in Chapter 12

3. Think the unthinkable (and be prepared for it)

The experience with the COVID-19 pandemic and the military aggression of Russia against Ukraine show that Europe needs to reinforce its **preparedness** to effectively address new challenges. The rising environmental, geopolitical, economic and social instability in the world increases the likelihood of extreme events with disruptive effects. These events can come as a surprise (in the literature they are often called **black swans**, i.e., very rare and unpredictable events with very high impact), but they can also occur after a series of warning signs accompanied with visible evidence (these are likened to charging **grey rhinos** which can be seen from afar but difficult to stop once in motion). In the case of black swan events, there is a need for the R&I ecosystem to be agile and sufficiently flexible to quickly react to the new, unexpected challenges. Most crises can, however, be identified with some lead time if sufficient attention is paid to early warning signs – these are the grey rhinos. This emphasises the importance of foresight to identify and assess different crisis scenarios and start preparing for them. In this sense, experts had been pointing to a high likelihood of a global pandemic. However, these warnings had not generally been translated into an appropriate level of preparedness. On the positive side, previous investments in the development of new mRNA technologies then allowed a very quick production of efficient COVID-19 vaccines. Systematic foresight exercises, which help us reduce the space of unthinkable events, followed by appropriate adjustments in policies, can effectively increase preparedness and make EU R&I policy more agile to effectively respond to a crisis. Intensive foresight exercises have accompanied the strategic planning of Horizon Europe to ensure that strategic orientations are suitably informed by ongoing trends and take into account possible future contingencies (such as health or energy crises).

The Russian invasion of Ukraine has further emphasised the EU's dependencies. The globalisation of value chains had been a source of productivity gains in the past, but has also created vulnerabilities, including in the R&I domain. This experience calls for reinforcing resilience and strengthening the **EU's technological sovereignty**. As a case in point, the Russian invasion has clearly exposed the vulnerabilities of the EU energy sector. The new emphasis on the need to reduce EU dependency on Russian gas implies that R&I investments and efforts must be strengthened to accelerate the development and deployment of energy efficient and clean energy technologies. This will not only help reduce the dependency on Russia but also significantly contribute to the implementation of the European Green Deal. In this context, R&I policy can play a major role in shaping the direction of innovations and choices concerning the portfolio of energy technologies. The EU is well-positioned here and leads the international scene in terms of clean energy innovation. In addition, while the EU shows strengths in technological areas related to advanced manufacturing and advanced materials, its technological sovereignty is at risk in other fields, including in artificial intelligence (AI), big data, cloud computing, cybersecurity, robotics and micro-electronics. Finally, the Russian invasion of Ukraine has shown how important it is for the EU to invest in its own internal security, making sure its police, border guards and first responders can benefit from the latest technologies.

Hence, future R&I policies will have to be developed in a **complex triangle of transformation policies, competitiveness policies and technology sovereignty considerations**[1]. Reducing strategic dependencies in key technological areas and value chains is necessary to strengthen EU resilience.

In doing so, the EU should not sacrifice the welfare gains stemming from an open and fair international division of labour by reverting to short-sighted protectionist policies driven by domestic interest groups under the pretext of technology sovereignty. In addition, a reinvigorated multilateral approach could help the EU reinforce its open strategic autonomy, strengthening its role as a leading actor in fostering international cooperation.

What is the position of EU R&I in the global stage?	More in Chapters 2, 5, 6
How does the global geopolitical context affect R&I?	More in Chapter 2

1 Jakob Edler, J., Blind, K., Kroll, H. and Schubert, T. (2021), *Technology Sovereignty as an Emerging Frame for Innovation Policy – Defining Rationales, Ends and Means*, Fraunhofer ISI Discussion Papers Innovation Systems and Policy Analysis No. 70.

4. Leverage businesses, institutions and people

Europe needs to invest in R&I and make the most out of this investment. R&D intensity stood at 2.3 % of GDP in the EU in 2020, which is still far from the agreed 3 % target[2]. R&D intensity has actually increased since 2000 in most Member States, but significant heterogeneity persists across the EU. The EU accounts for almost 20 % of global R&D expenditure, though its share has been on a declining trend. It is particularly important to boost private investments in R&D, which have been lower than for most competitors (1.5 % of GDP in the EU compared to 1.7 % in China and 2.3 % in the US). During the COVID-19 pandemic, R&D business investments in the EU decreased from EUR 208 billion in 2019 to EUR 205 billion in 2020.

R&I performance heavily relies also on other assets such as ICT and human capital. The COVID-19 pandemic has accelerated the digitalisation process in the EU, but has also exacerbated the digital divide between EU firms, households, regions and countries. The boost to digitalisation after the pandemic has not been sufficient enough to reduce the gap between the EU and its international competitors. Against this backdrop, the EU will pursue a human-centric, sustainable vision for digital society throughout the Digital Decade to empower citizens and businesses. COVID-19 has also negatively impacted the formation of human capital. More than ever, inclusive human capital policies are crucial to increase Europe's innovation capacity.

Educational and training policies in combination with measures targeted at students from disadvantaged socio-economic backgrounds, as well as students with a disability or those with an ethnic minority background, will be fundamental in the post-pandemic era. Without a strong role for higher education institutions, we cannot achieve the necessary transformations in our society, and the **European Education Area** and **digital education** are key in this context.

More efforts are also needed to bridge the gap between research outputs and marketable innovations. The comparably low performance of the EU in patent applications and in the share of high-tech exports, stands in contrast with its large, qualified workforce and significant scientific production. This situation calls for addressing deficiencies by promoting a culture of knowledge valorisation in the EU's R&I system, ensuring that knowledge-based institutions know how to manage their intellectual capital, and by improving the links between academia, industry, citizens and policymakers.

2 COM/2020/628. A new ERA for Research and Innovation.

A major tool to foster R&I at the EU level is the **Framework Programme for R&I.** The budget of the Framework Programme for 2021-2027, Horizon Europe, is EUR 95.5 billion, accounting for almost 10% of public funding for research in Europe and representing the largest European research programme so far. **Cohesion Policy** will also invest in the 2021-2027 programming period more than EUR 56 billion in R&I by financing innovation in firms, bringing research results onto the market, supporting close business science cooperation with a particular emphasis on the less developed regions. The revitalised **European Research Area** (ERA) agenda also includes a set of ambitious political objectives and R&D investment targets, which aim to spread excellence, enhance international collaboration, including the mobility of researchers, and better connect universities and companies. The objective is to encourage and support national authorities in implementing needed structural reforms of their R&I systems and to appropriately prioritise and align R&I investments and activities to maximise their impacts across Europe in line with our common political priorities. This also calls for enhanced national strategies tailored to the national context and specific needs, ensuring a timely delivery on those key objectives.

How much does the EU invest in R&I?	More in Chapter 5
How large is EU's scientific and technological output, and why do we need to valorise knowledge?	More in Chapter 6
What are the tools to leverage R&I?	More in Chapter 8
To what extent do scientific research findings reach the market?	More in Chapter 15

5. Connect actors and address disparities

Europe faces high levels of disparities in terms of income distribution, opportunities and regional development, which raise concerns about fairness as well as efficiency. Within its borders, Europe faces the divisions stirred by a sequence of crises, from the great financial crisis to the surge in migration, the COVID-19 pandemic and Russia's invasion of Ukraine.

R&I performance also exposes a deep geographic divide. R&D expenditures, scientific publications and patent applications are **concentrated in more developed regions**. The least innovative regions recorded a low and even declining growth of patent applications over the past decade. As a result, convergence across EU regions in terms of technological production has stalled. Productivity catching up, which has been experienced by many less-developed regions in Central and Eastern Europe, has been driving the rapid expansion of global supply chains and foreign direct investment, with only a limited role for innovation-driven productivity growth. Moreover, R&I ecosystems are very regionalised, which limits the scope for the geographical diffusion of innovation. For example, about 75 % of collaborations on patents have been intra-regional in the EU and only 3-5 % have been **inter-regional across national borders.**

To close the innovation divide, it is important to **connect different actors in R&I ecosystems**. This would facilitate innovation diffusion and transfer to less-performing regions and help trigger economic dynamism, which would benefit the competitiveness of the EU as a whole. Cross-border collaboration on research and innovation activities could optimise R&I efforts and generate scale economies in knowledge creation. Complementarities in R&I activities between EU regions in terms of industrial specialisation and knowledge transfer could be also strengthened to ensure a smooth integration of the latest research findings and inventions across regions and countries. There is also a need to strengthen the capacity of the business sector to engage in R&I collaborations with academia and research centres, in particular, in high-tech sectors and in countries with less performing research systems. Continuing divergence between EU Member States on researchers' mobility patterns also calls for a better understanding of the drivers and barriers to international and intersectoral mobility as well as the implementation of policies to foster brain circulation.

At the same time **technological changes, including automation, machine learning and artificial intelligence, will pose challenges for workers and carry a risk of further contributing to increasing disparities**. The new technologies are progressively changing the skills requirements needed in labour markets. As a result, we have seen the shares of highly skilled jobs rising, middle-skilled jobs diminishing, while low-skilled jobs have remained relatively steady. In the digital era, job market requirements are shifting towards non-routine, abstract, analytical and social skills. In the EU, there is a strong heterogeneity of skills levels across countries, urban-rural areas and age groups. Hence, **reskilling policies for low- and middle-skilled workers** will be crucial for sustainable and inclusive economic growth. Lifelong learning and training have become increasingly important to keep workers' skills aligned with evolving job market demands and support longer working lives. Education and training policies should increase the emphasis on developing non-cognitive skills that complement digital skills, such as social intelligence, collaboration, creativity, and adaptability. Current trends in this respect are encouraging: adult participation in learning, R&D personnel and researchers, the share of tertiary graduates among youth, and ICT graduates are rising across the EU, while NEETs (those not in employment, education or training) are decreasing.

Disparities also remain in terms of gender representation in R&I-related activities. Women are significantly underrepresented in the EU's entrepreneurial landscape. Women represent the majority of tertiary graduates, yet they are underrepresented in ICT and engineering studies, as well as in the researchers' population. With the COVID-19 pandemic, women researchers, particularly those with young children, experienced the highest decline in time devoted to research, with possibly adverse effects on their careers in the long term. These significant gender gaps are still to be tackled. The empowerment of women entrepreneurs and researchers remains a key policy objective so as to unleash the EU's untapped growth potential. Providing financial support to women in innovation and entrepreneurship is also essential to creating fair, inclusive and prosperous European R&I ecosystems.

How large are regional disparities in Europe?	More in Chapter 2
How does technological change affect the labour market?	More in Chapter 4
What is the gender representation share for entrepreneurs and researchers?	More in Chapters 4 and 5
Do firms in the EU's cohesion regions invest differently in digitalisation and in green measures compared to firms in non-cohesion regions?	More in Chapter 13
Are key technologies spatially concentrated in the EU's regional ecosystems and what are the implications?	More in Chapter 14

6. Ensure R&I friendly conditions

One of the main structural barriers faced by deep-tech and innovative companies is **limited access to finance**. The EU financial system continues to be strongly dependent on banks and equity investments still play a relatively minor role. While venture capital (VC) investments have only marginally been hit by the COVID-19 crisis, the EU still struggles to attract riskier and more patient investments, especially at the scale-up stage. Against this backdrop, promoting a transition to a green and digital economy requires a significant amount of financing resources. New financing tools need to be targeted towards more innovative EU businesses, while ensuring coherence with the already existing financial instruments available to EU firms. Integrating sustainability criteria into firms' financing is also essential to pursuing the objective of decarbonising the economy. The increasing financing opportunities coming from online finance can be expanded through policy actions aiming to reduce the fragmentation of the Digital Single Market and facilitate digital innovation, while ensuring consumers' protection.

In order to ensure well-functioning markets that incentivise competition and innovation, thereby maximising the impact of EU R&I investments, Europe needs a fit-for-purpose, forward-looking and overall **innovation-friendly institutional and regulatory framework**. Good institutions are characterised by political stability, transparency and accountability, and show high degrees of rule of law with a low risk of expropriation and corruption. Regulation can be a powerful instrument to foster innovation in the EU. A stable and predictable regulatory environment encourages planning and investment, and enables firms to operate on safe legal grounds. Regulation can also create a strong stimulus for innovation through standard setting or regulatory stringency.

The emergence of new practices, technologies and business models, and the acceleration of innovation **call for more flexible and experimental approaches to regulation**, such as regulatory sandboxes. Access to efficient digital infrastructures and data is also essential to foster the EU's digital transition, but the ability of firms to invest in digitalisation varies significantly across the EU's regions.

Are framework conditions favourable for innovation in Europe?	More in Chapter 7

PART I

CHAPTER 1

COVID-19, RECOVERY AND RESILIENCE

COVID-19, RECOVERY AND RESILIENCE

KEY FIGURES

-3.1 %
EU business R&D between 2019 and 2020

+16 %
EU scientific publications in health over 2019 to 2020

86 %
of EU citizens think that the influence of science and technology is positive

KEY QUESTIONS WE ARE ADDRESSING

- How did COVID-19 impact R&I activities, science and scientists in Europe?
- What role did R&I play in the COVID-19 crisis?
- What is the way forward for R&I policy?

KEY MESSAGES

What do we learn?

- Overall R&D investment in the EU declined during the COVID-19 crisis, with significant differences between sectors. R&D investments increased in health and ICT while sectors like automotive recorded drops.
- The COVID-19 pandemic led to a surge in R&I output in the health sector as measured by scientific publications. It has also demonstrated the importance of data and digital technologies to support policy action to address the health risks.
- Measures to contain the pandemic have generated an important change in the way firms operate, acting as a catalyst for the digital transition.
- The pandemic demonstrated the key role of science, yet female and young researchers have been negatively affected by the pandemic.

What does it mean for policy?

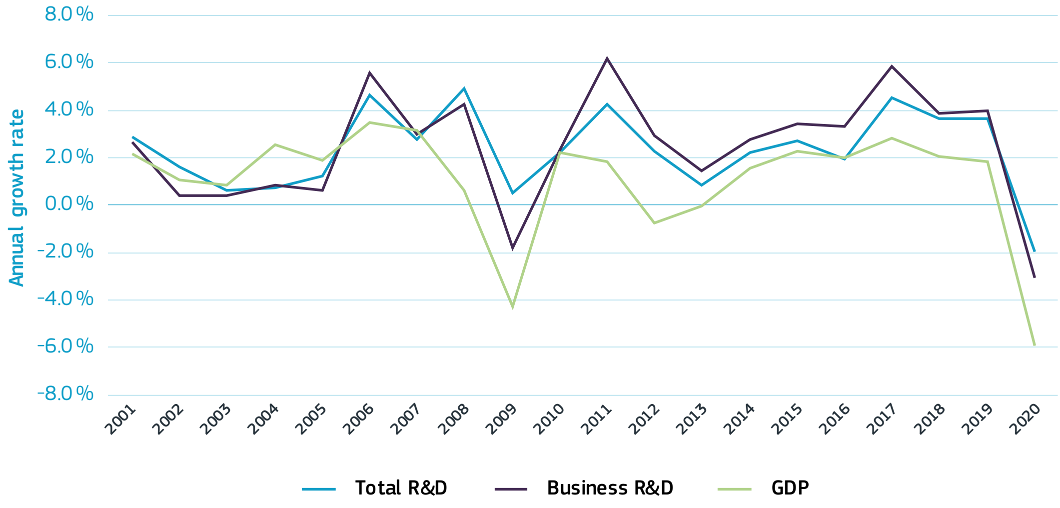
- The pandemic has provided us with the opportunity to 'build forward better' and aim for a more sustainable, more digital and in particular a more resilient Europe.
- In a post-pandemic world, well-directed research and innovation have the potential to ease the social and territorial divides, and achieve a cohesive and inclusive innovation-driven growth of countries, regions and companies.
- R&I is dependent on a experimentation-driven and socially-connected educational and research system.

The COVID-19 crisis is unprecedented. It has disrupted our lives, economy and society and the world has been struggling to contain the pandemic. While research and innovation (R&I) have been at the core of the response to the pandemic itself in the areas of virology, vaccines development, treatments and diagnostics, it is also crucial in the economic recovery from the crisis. R&I is not only essential to spur economic activity, but also to accelerate the transitions that our planet and society need – a new economy for health, wellbeing and equality in a broad sense. R&I also helps in building system-wide resilience. Technologies already help alleviate, at least partially, the severity of the economic shock, with digital technologies being at the core of business continuity in several sectors. Overall, R&I has played a role of paramount importance in fighting the pandemic, and it will also be vital in the longer term and in the aftermath of the crisis as a key driver of the recovery.

1. How COVID-19 has impacted R&D efforts in Europe

Research and development activities tend to be pro-cyclical (Barlevy, G. 2007, Fatas, A. 2000, Rafferty, M. C. 2003, Comin, D., & Gertler, M. 2006). This means that R&D moves in tandem with economic growth: R&D declines during recessions and increases during economic booms. During recessions, different factors may cause R&D investors to face reduced incentives to invest in innovation creation and adoption. For instance, in sectors with a faster obsolescence rate of knowledge or with more difficulties in protecting intellectual property (e.g. higher positive externalities), expected declines in demand may lead to the postponement of innovative activities (Fabrizio and Tsolmon, 2014). Similarly, R&D spillovers and the quasi-public nature of knowledge may lead investors to weigh more short-term profits than long term profits (Barlevy, 2007; Sedgley et al., 2019). The aggregate pattern may also be explained by micro dynamics, most notably when firms face credit constraints that have severe implications for investment decisions, especially in risky innovative projects (Aghion et al., 2012) or for start-ups that rely heavily on external sources of capital (Howell et al., 2020). Empirical evidence supports the cyclicality between R&D and output, and further develops on the link between the slow-down of R&D spending and its implications for innovation diffusion, its adoption and long-run growth (Anzoategui et al., 2019).

Figure 1-1: Annual growth rate of EU GDP, Total R&D expenditure and business R&D expenditure (in constant prices), 2001-2020



Science, research and innovation performance of the EU 2022

Source: Source: Eurostat (online data code: rd_e_gerdtot and nama_10_gdp)

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-1-1.xlsx

EU R&D investment declined during the COVID-19 crisis (see Figure 1-1), with a decrease of 1.9% in constant prices[1]. This decrease is largely driven by the decline of private R&D (3.1% in constant prices[2]). The COVID-19 pandemic has impacted quite significantly business dynamism. Employment and firm entry have dropped from 2019 to 2020 (see Figure 1-2) and not yet fully recovered to the 2019 levels by mid-2021[3]. The ECB also reported an initial surge in demand for credit from enterprises in 2020 in the euro area, reflecting emergency liquidity needs (ECB, 2020). But overall, the number of business bankruptcies has decreased after the outbreak of the COVID-19 pandemic, most likely as the result of the massive policy support issued by national governments and through the EU programmes. It appears that small R&D investing firms in the EU have suffered on average more than big R&D investing firms during the pandemic (Grassano et al., 2021).

The impact of the crisis on R&D was significantly different among sectors. When considering the top 2500 R&D investing companies worldwide, some sectors positively affected by the crisis have increased their R&D investments, namely Health (9.5%), ICT Services (9.9%) and ICT Producers (6.1%). However, most other sectors experienced R&D investment reductions, in particular Aerospace & Defence (-19.8%) and Automobiles (-6.1%). The latter are however still the strongest R&D investors in the EU, thus

1 Growth rate in current prices is -0.4%.

2 Growth rate in current prices is -1.5%.

3 Eurostat.

Figure 1-2 a): COVID-19 impact on employment and business registrations

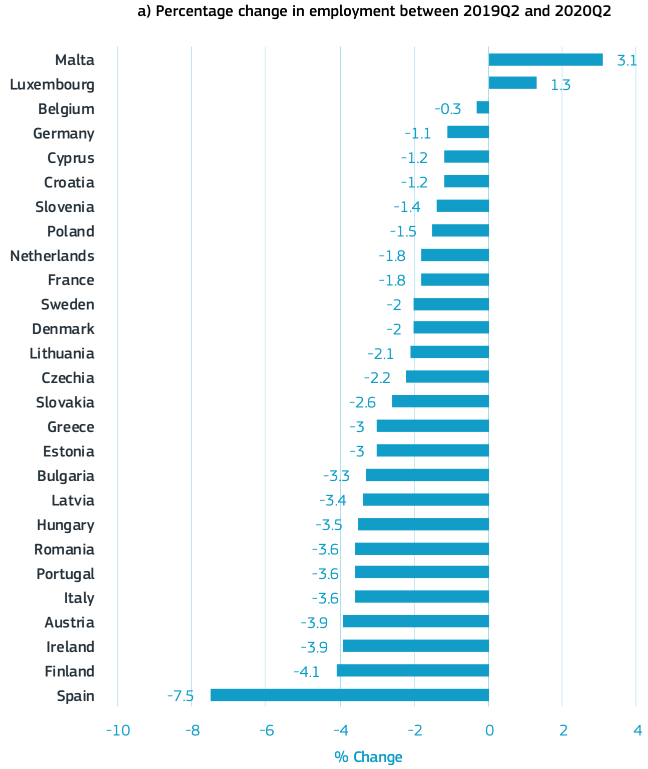
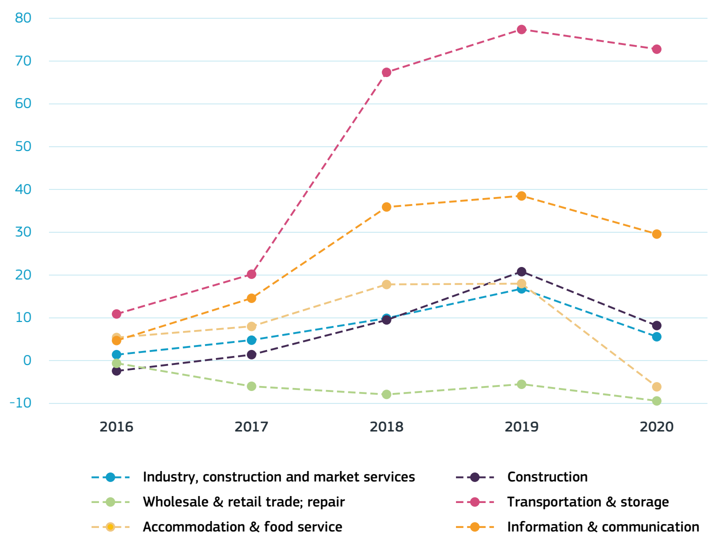


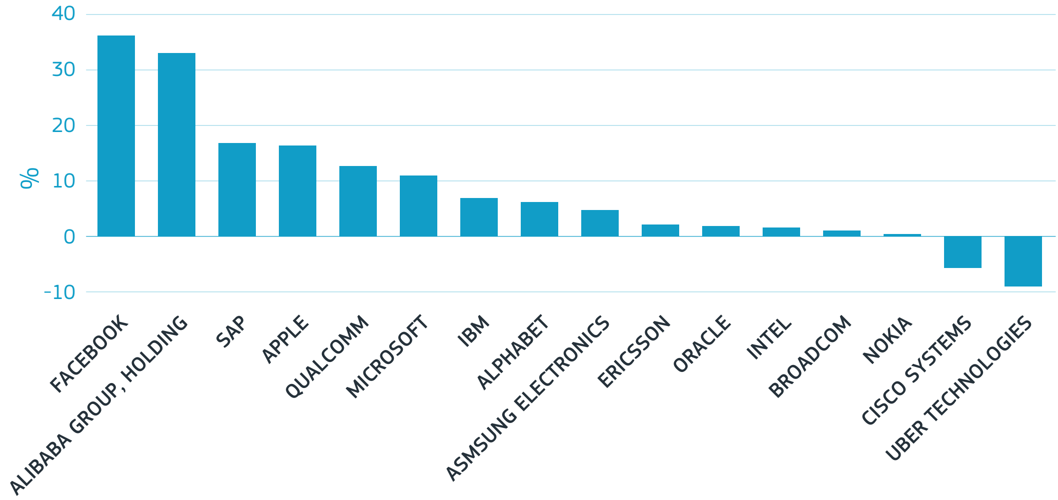
Figure 1-2 b): Business registrations in EU per industry sectors (percentage change - index 2015=100)



Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Eurostat (online data code: sts_rb_a and namq_10_a10_e)

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-1-2.xlsx

Figure 1-3: Growth in R&D spending for the software, computer services and electronic equipment sector (% change from 2019 to 2020)

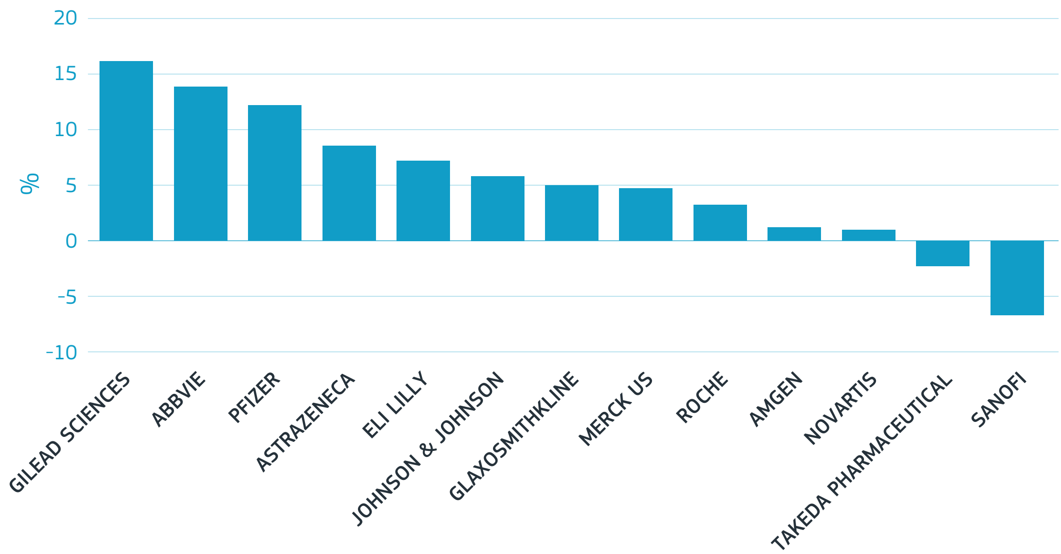


Science, research and innovation performance of the EU 2022

Source: OECD Main Science and Technology Indicators Highlights on R&D expenditure, March 2021 release (Link).

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-1-3.xlsx

Figure 1-4: Growth in R&D spending for the pharmaceuticals and biotechnology sector (% change from 2019 to 2020)

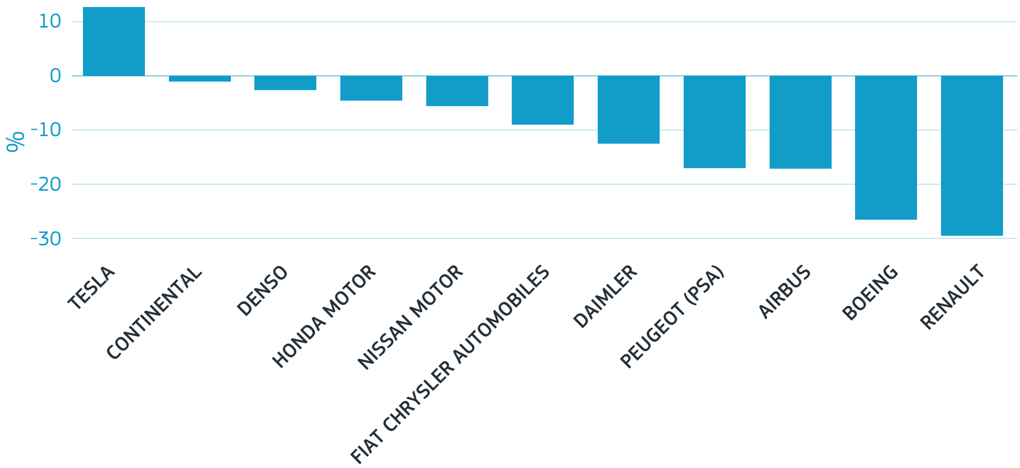


Science, research and innovation performance of the EU 2022

Source: OECD Main Science and Technology Indicators Highlights on R&D expenditure, March 2021 release. (Link).

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-1-4.xlsxx

Figure 1-5: Growth in R&D spending for the automotive, aerospace and defence sector (% change from 2019 to 2020)

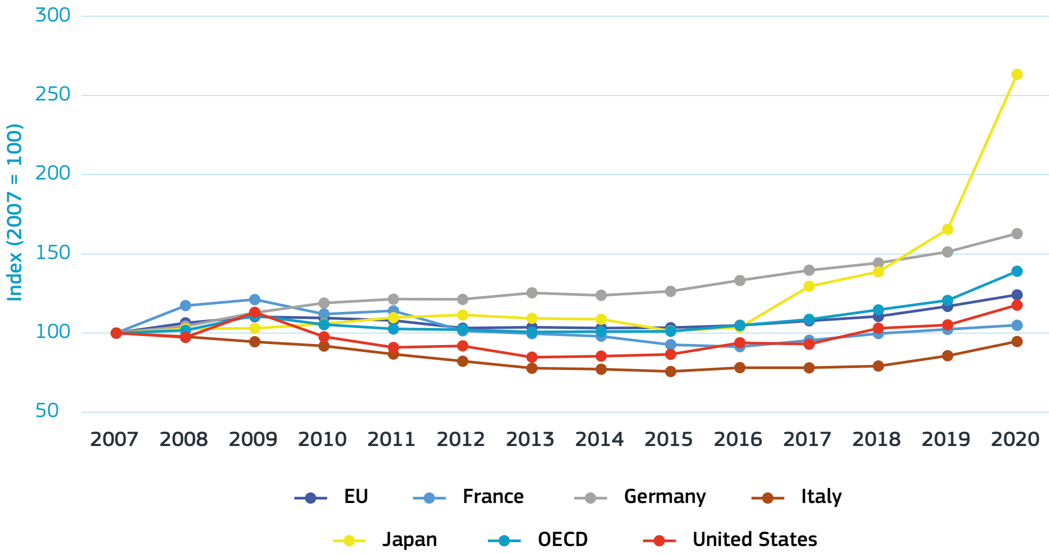


Science, research and innovation performance of the EU 2022

Source: OECD Main Science and Technology Indicators Highlights on R&D expenditure, March 2021 release. (Link).

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-1-5.xlsx

Figure 1-6: Total Government Budget Allocation to R&D at constant prices and PPP $, 2007-2020



Science, research and innovation performance of the EU 2022

Source: OECD Main Science and Technology Indicators (MSTI) database. (Link).

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-1-6.xlsx

causing an overall R&D decline, while also in the EU ICT and Health companies increased, albeit having a lower share in the total (JRC, 2021).)

Public R&D spending increased in 2020 by 6.2 % in real terms in the EU (15.2 % across OECD countries, Figure 1-6). This figure represents a relevant increase compared to 2019, when public R&D budgets went up by around 3 %. This may be the result of a combination of planned boost to R&D funding plans before the pandemic and additional emergency support for health-related R&D to develop vaccines and treatments in response to the COVID-19 pandemic.

The comparative resilience of industrial R&D investments – also in sectors witnessing a reduction in 2020 – shows their strategic importance (JRC, 2021). This underlines the need for policies effectively mobilising and accelerating the growth of private R&D spending. To support a strong and resilient recovery, policy interventions should boost technology diffusion, provide the right conditions and incentives for start-ups, and ensure business-friendly framework conditions to enable experimentation and promote an efficient allocation of resources (OECD, 2021a).

During the crisis, the European Innovation Council (EIC) introduced a combination of support in the form of grants, investments and business acceleration services, particularly to the benefit of start-ups and SMEs. Besides, the EIC has introduced greater flexibility in its operations to accommodate the needs of their beneficiaries and changing market conditions. Specific services were also proposed to foster resilience, for example tailor-made advice on reducing greenhouse gas emissions and a women leadership programme. The **Marie Skłodowska-Curie Actions (MSCA)** programme used a similar approach. MSCA introduced measures to support researchers and organisations in implementing their projects and allowed modifications to research activities, including more flexible approaches regarding budget and working conditions.

The European Institute of Innovation and Technology (EIT) also mobilised its multi-disciplinary innovation communities and launched specific targeted initiatives to support innovators powering high impact solutions to tackle the COVID-19 pandemic in the fields of health, climate change, digitisation, food, energy, urban mobility, manufacturing and raw materials. The EIT investment supported new innovation projects as well as highly innovative start-ups, scale-ups and SMEs crucial to the European's economy's fast recovery.

2. A surge in health R&I

The COVID-19 pandemic has demonstrated the crucial importance of R&I and policy cooperation to rapidly deliver solutions. (OECD, 2021a; Borunsky, Correia, Martino et al., 2020; Paunov, C. and Planes-Satorra, 2021). As the crisis hit so suddenly and so severely, coordination at EU level has been challenging. However, R&I actions have been an essential part of the coordinated EU response to the public health threat (European Commission, 2021a). These actions focused on funding and financing R&I in virology, vaccine development, treatments, translating research findings into public health policy, and citizen outreach and communication. Horizon 2020 has played a central role in mobilising funds on COVID-19-related R&I projects. It has shown that the EU can be agile in mobilising its tools. The ERAvsCorona Action Plan also set out key measures at an early stage that the Commission services and the Member States have been activating to coordinate, share and

Box 1-1 Manifesto for EU COVID-19 Research

The Manifesto for EU COVID-19 Research is a policy statement providing guiding principles for beneficiaries of EU funded research grants to ensure that their results are made available in a timely and affordable manner to guarantee the highest potential impact in the fight against COVID-19. It is an integral part of the EU Research and Innovation contribution to the common European response to the coronavirus outbreak.

The set of guiding principles anchored in the Manifesto are:

- Make the generated results, whether tangible or intangible, **public and accessible** without delay, for instance on the Horizon Results Platform, on an existing IP sharing platform, or through an existing patent pool.
- Make scientific papers and research data available in **open access** without delay and following the FAIR principles via preprint servers or public repositories, with rights for others to build upon the publications and data and with access to the tools needed for their validation. In particular, make COVID-19 research data available through the European COVID-19 Data Platform.
- Where possible, grant for a limited time, **non-exclusive royalty free licences** on the intellectual property resulting from EU-funded research. These non-exclusive royalty free licenses shall be given in exchange for the licensees' commitment to rapidly and broadly distribute the resulting products and services under fair and reasonable conditions to prevent, diagnose, treat and contain COVID-19.

So far, more than 650 organisations (including universities, research institutes and private companies) and more than 1 875 individuals endorsed the Manifesto from all over Europe and beyond. The Manifesto also generated a high level of engagement from SMEs (more than 180 SMEs endorsements). International organisations such as the World Health Organization and the Medicines Patent Pool have endorsed it as well. This shows a clear commitment and strong engagement towards a better valorisation of research results, leaving no one behind.

The Commission has extended the Manifesto by one year, until 1 January 2023, aiming to allow Manifesto endorsers to maintain their initiatives under the current Manifesto principles and to offer the possibility for others to still endorse it and engage in concrete actions to facilitate the sharing and access to IP in response to the COVID-19 pandemic.

jointly increase support for R&I. At the EU level, the European COVID-19 research data platform has aimed at speeding up and improving the sharing, storage, processing of and access to research data and metadata on COVID-19. The European Commission also launched in September 2021 the European Health Emergency preparedness and Response Authority (HERA) to prevent, detect, and rapidly respond to health emergencies. The Manifesto for EU COVID-19 Research was also launched in 2020 to maximise the accessibility of research results in the fight against COVID-19 (Box 1-1).

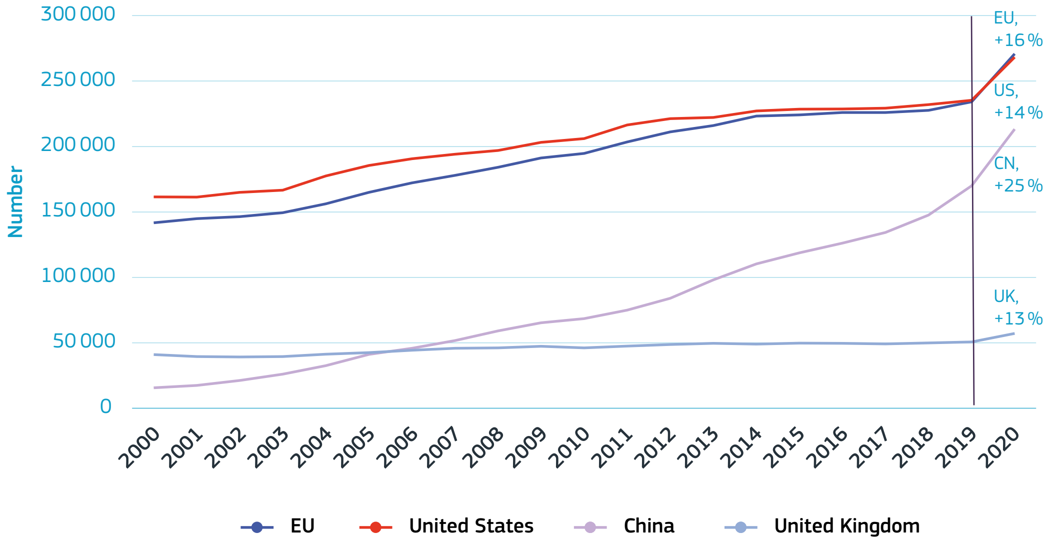
The European Commission has a long tradition of supporting research into infectious diseases and epidemics. Between 2007 and 2019, EUR 4.1 billion[4] was invested in research into infectious diseases through the 7th Framework Programme and Horizon 2020. For example, investments in vaccine research and innovation that preceded the current pandemic enabled the development of the mRNA vaccine technology, recognised as a major breakthrough in the COVID-19 pandemic.

Mugabushaka (2021) identifies almost 3 000 publications related to COVID-19 and relevant previous coronavirus research[5] funded by the EU's R&I Framework Programme, including 1 277 in 2020 (Figure 1-7). Marie Skłodowska-Curie Actions (MSCA), the European Research Council (ERC) and the Health Programme account for about 80 % of them. These cover a diverse range of research fields and over half are internationally co-authored. One-third of the publications entirely rely on EU funding. The key outcomes of this EU-funded research include among others: the development of the first diagnostic tool, published almost immediately after the release of the Sars-cov2 virus genome; discoveries of SARS-CoV-2 neutralising antibodies; the first results of clinical trials testing the efficacy of drugs used to treat rheumatoid arthritis in COVID-19 patients; and the findings of epidemiological studies which have been used, among others, in WHO clinical guidelines and other guidance documents.

4 Source: https://ec.europa.eu/info/research-and-innovation/research-area/health-research-and-innovation/coronavirus-research-and-innovation_en

5 Based on the COVID-19 database.

Figure 1-7: Evolution of scientific publications in health[1], 2000-2020



Science, research and innovation performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Science-Metrix using Scopus database.

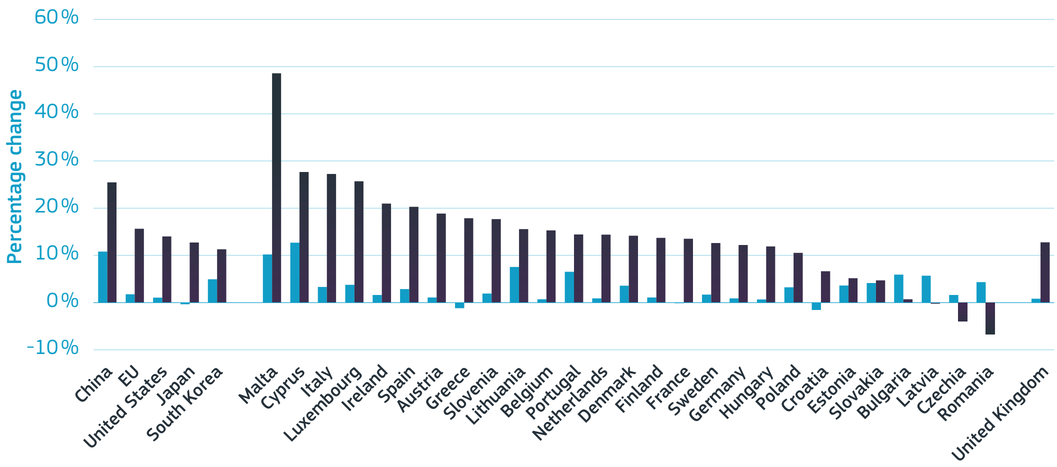
Note: [1]Fractional count of publications in the area of health, demographic change and wellbeing

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-1-7.xlsx

Beyond the EU R&I Framework Programme, the COVID-19 pandemic was, as expected, responsible for a surge in scientific output in health in the EU landscape in 2020 (Figures 1-7 and 1-8). The EU and US, already in the lead before the crisis, experienced an increase of respectively 16 % and 14 % in publications in health between 2019 and 2020, which is drastically higher than their pre-COVID growth rates (2 % for the EU and 1 % for the US over 2011-2019). China's scientific output in health presents a rapid evolution over the last decade (11 % annual increase over 2011-2019), but also an impressive increase of 25 % between 2019 and 2020 due to the pandemic. Publications in the UK, also an important scientific producer on the global stage (4 % of publications worldwide), increased by 14 % in 2020 (compared to a 0.8 % average annual change over 2011-2019). Within Member States, most countries experienced a major increase in their publications in health, with the exception of Latvia, Czechia and Romania.

These increases at the onset of the pandemic were driven by publications in basic medicine, clinical medicine and health sciences (see Table 1-1). While the number of publications in basic medicine and health sciences was multiplied by 3 in the EU, US and China, the most significant increases can be found in publications in clinical medicine, which increased by more than 400 % in the EU and US, and by more than 600 % in China. At the same time, other areas in medical science showed a decrease in scientific output in 2020. This holds in particular for medical biotechnology – which accounts for more than 70 % of publications worldwide in medical and health science (75 % in the EU).

Figure 1-8: Impact of Covid-19 on scientific publications in health[1]



Science, research and innovation performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Science-Metrix using Scopus database.

Note: [1]Fractional count of publications in the area of health, demographic change and wellbeing

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-1-8.xlsx

Figure 1-9: Scientific publication in health-related topics[1]

		2011-2019 (average annual % change)	2019-2020 (% change)
Basic medicine	EU	2%	203%
	United States	0%	168%
	China	9%	208%
Clinical medicine	EU	2%	437%
	United States	1%	448%
	China	14%	620%
Health sciences	EU	5%	181%
	United States	2%	178%
	China	11%	233%
Medical biotechnology	EU	1%	-7%
	United States	1%	-6%
	China	9%	-2%
Other medical sciences	EU	2%	-22%
	United States	0%	-1%
	China	7%	-13%

Science, research and innovation performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Science-Metrix using Scopus database.

Note: [1]Fractional count of publications by Frascati fields

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-1-9.xlsx

Innovation by the corporate sector also rapidly increased in response to the pandemic. Hundreds of clinical trials targeting COVID-19 drugs and vaccines were launched by the biopharmaceutical industry to address the health emergency. **Emerging technologies**, in particular, engineering biology and robotics, have shown potential in keeping health systems afloat, thereby contributing to enhance social and economic resilience. For example, biofoundries can improve the reliability and reproducibility of bio-manufacturing, with mRNA vaccines being amenable to this approach (OECD, 2020c). Also, because of the lack of time and resources available, especially at the beginning of the crisis, there was a surge of frugal innovations. Harris et al. (2020) identify three frugal innovation approaches in responding to the COVID-19 threat: repurposing, reuse and rapid deployment. This includes for example the repurposing and reuse of existing materials for the rapid production of ventilator machines by Mercedes and Tesla.

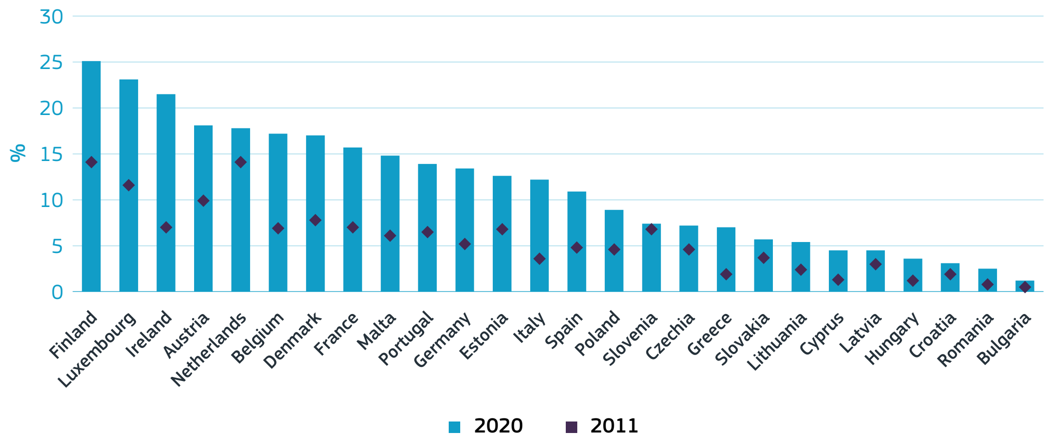
The COVID-19 pandemic demonstrated the importance of data and digital technologies to support the health sector. The resilience of the health service delivery system has relied on epidemiological surveillance, using data and artificial intelligence, openly accessible, machine-readable, interoperable data, together with telemedicine and mobile health applications (Negreiro Achiaga, 2021; Borunsky et al, 2020). **AI-related applications** have been effectively applied to detect visual signs of COVID-19 on images from lung CT scans, monitor changes in body temperature in real time, provide an open-source data platform to track and monitor the spread of the disease through population screening, and help identify potential treatments and cures. **Additive manufacturing** (commonly known as 3D printing) has been mobilised to address the shortages of personal protection equipment and ventilators (Borunsky et al., 2020). The logistical challenges and consequent supply chain disruptions due to restricted movements and the rise of infections called for the mobilisation of versatile technologies that could be rapidly deployed in response to emergencies (Longhitano et al., 2021).

3. COVID-19 as a catalyst for the digital transition

The COVID-19 pandemic triggered a massive change in the way firms operate. While teleworking[6] was already a widespread practice in several sectors before the onset of the COVID-19 pandemic (He et al, 2020), it has significantly accelerated with the outbreak. The lockdown measures to combat the spread of the virus have led to a change in work practices, with employees' homes becoming a forced extension of the traditional workplace (Contreras et al, 2020). Nevertheless, the measures adopted to contain the spread of the virus determined an acceleration in the digitalisation of the economy and the society as a whole (Peleaz et al. 2020).

The percentage of employed persons usually working from home increased from 5.4% in 2019 to 12% in 2020[7]. Similarly, the share of self-employed workers usually working from home also experienced an increase over the same period, from 19.4% in 2019 to 21.9% in 2020. There are however pronounced differences across Member States. Finland (25.1%), Luxembourg (23.1%) and Ireland (21.5%) report the highest share of people working from home in 2020, while in Romania and Bulgaria this share is less than 1% (Figure 1-9). According to a survey conducted between April and May 2020, when most of EU Member States were facing the first lockdown, about 36% of EU

Figure 1-10: Share of employed persons usually working from home 2019 vs 2020, per EU Member State[(1)]



Source: Eurostat (online data code: lfsa_ehom)
Note: [(1)]2020 data not available for Sweden
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-1-10.xlsx

6 According to the Eurofound definition, 'teleworking refers to a form of organising and/or performing work, using information technology, in the context of an employment contract/relationship, where work, which could also be performed at the employer's premises, is carried out away from those premises, on a regular basis, as defined in the European framework agreement on telework. The characteristic feature of telework is the use of computers and telecommunications to change the usual location of work'.

7 Eurostat.

employees started to work remotely as a direct result of the pandemic (Eurofound, 2020a). Nevertheless, the COVID-19 overall led to a deterioration of the labour market conditions in EU. Employment declined in all Member States as a result of the pandemic. At sectoral level, an opposite trend was observed only in sectors such as insurance, computer programming and telecommunications, characterised by jobs easily carried out from home and requiring low social interactions (European Commission, 2021b).

According to the 2020 Digital Economy and Society Index (DESI), EU enterprises are becoming more digitalised. The share of enterprises using big data[8] has risen in comparison to the results of DESI 2018 (from 10 % to 12 %)[9]. Big data usage has been particularly useful after the outbreak of the virus as a key tool to manage servers, as well as to store and process large amounts of user- and machine-generated information. E-commerce has also played a relevant role in allowing business to continue during the lockdowns. In 2020, the share of enterprises having received orders online was 18 %, and e-commerce turnover increased from 18 % to 20 % between 2019 and 2020[10].

However, the digitalisation process comes with its own challenges. Innovation and digitalisation proved to be firms' best weapons against the challenges posed by the pandemic, allowing companies to ensure business continuity during the period of lockdowns.

Furthermore, teleworkers appear to be satisfied with remote working when they are provided with the necessary IT equipment to carry out their job activities, do not have to do significantly overtime, and when remote working does not interfere with their family time (European Commission, 2021b). Nevertheless, the structural changes since the beginning of the COVID-19 crisis determined a radical transformation of inter-personal relationships, with significant social consequences (Pelaez et al., 2021). As noted by Contreras et al. (2020), COVID-19 has significantly affected the organisation of work. The massive shift to exclusively remote working and/or hybrid formats as a result of the lockdown measures have come along with social and professional exclusion, tension and anxiety (Contreras et al., 2020; Eurofound, 2020a). An online survey carried out by Eurofound[11] reports a reduction in life satisfaction and happiness during the first period of lockdowns. In April 2020, the average life satisfaction score was 6.3 on a scale of 1 to 10, showing a decrease compared to the score given in 2016 (7.0)[12]. Similarly, average happiness also experienced a reduction, decreasing from 7.4 in 2016 to 6.4 in April 2020. Mandatory teleworking is reported as one of the key determinants of this trend. The massive increase of exclusive home working has blurred work-life boundaries, negatively impacting several job quality indicators as a result of the increased sense of isolation, and emotional and physical draining (Eurofound, 2020b).

8 Big data refers to the large, diverse sets of information that grow at ever-increasing rates, and are too complex to be dealt with traditional data processing methods. Big data may be analysed computationally to reveal patterns, trends, and associations, especially relating to human behaviour and interactions.

9 DESI 2020, European Commission

10 Digital economy and society (Eurostat).

11 Eurofund (2020b).

12 European Quality of Life Survey (EQLS), 2016.

Although the phasing out from COVID-19 measures has brought people back to traditional work premises, **teleworking keeps remaining an important part of work life**. This is particularly the case of big cities, where the share of remote job posting has significantly increased since the onset of the pandemic (Kleine-Rueschkamp and Adrjan, 2021). This trend suggests that hybrid work is likely to become the consolidated practice in the post-pandemic phase, especially in those sectors better predisposed to teleworking activities.

4. Impact of COVID-19 on the scientific community

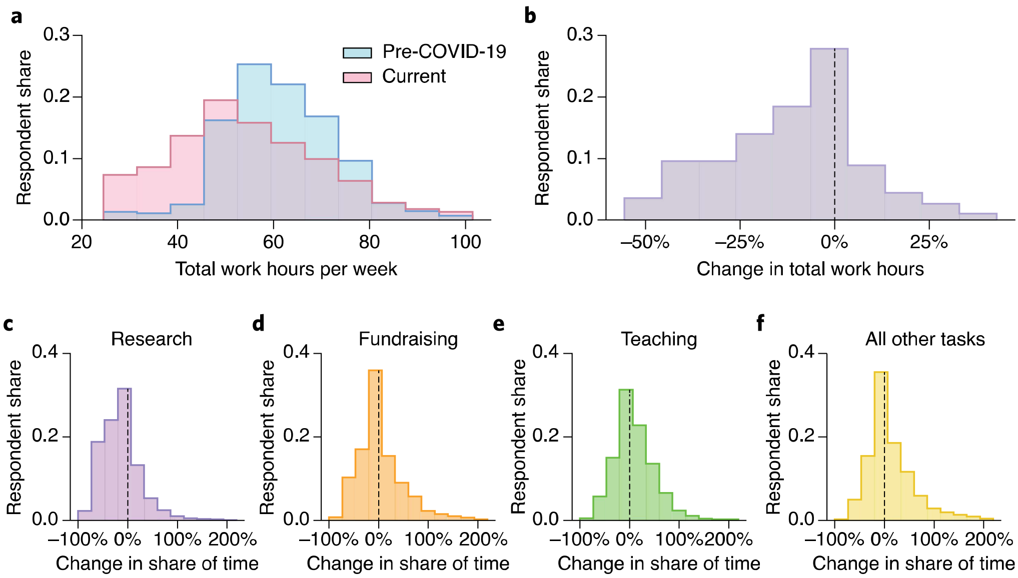
4.1 How researchers coped with the pandemic

The scientific community populating our universities and research centres has also been affected by the pandemic (Sachini et al. 2021). Indeed, while COVID-19 related research was running at unprecedented speed, most of non-COVID-19 related health research (including cancer research) was scaled down. The limitations to international travel, together with lockdowns, closures and social distancing implied that most of research experiments and fieldwork had to be stopped, postponed or cancelled (Ledford, 2020, Servick et al. 2020). Labs closed and job openings were cancelled (Woolston, 2020a and 2020b).

COVID-19 significantly increased the mental strain of researchers. The pandemic broadly impacted on researchers' mental strain, research time, paper submission rate and way of doing research. Yet such impacts interacted with our societal and academic structures, resulting in widening pre-existing inequalities and inflating associated costs. In this context, female researchers and young scholars paid a heavier price (Woolston, 2020c; Viglione, 2020; Gibson et al. 2020; Gewin, 2020; Deryugina et al., 2021; Vincent-Lamarre, 2020; Squazzoni et al 2021). According to a survey among researchers in Greece, 53.3% of the respondents reported that they were experiencing a high to very high level of personal psychological strain due to the lockdown and social distancing measures. Additionally, 53.7% of the researchers said the lockdown had taken a toll on their family environment, adding a further burden. Below 8% of researchers stated that they experienced no personal or family mental strain (Sachini et al., 2021). The study also found that female researchers experienced a substantially higher level of personal as well as family mental strain than male researchers did.

The COVID-19 pandemic negatively impacted researchers' productivity and working hours. Fields of research with physical labs and women researchers with children were the most affected. Myers et al. (2020) surveyed 4535 faculties from American and European universities to uncover the impact of the COVID-19 pandemic on researchers' productivity. The study finds an overall decline in total working hours, with the average dropping from 61 hours per week pre-pandemic to 54 hours in the first months of the pandemic (Figure 1-10). Furthermore, the impact was distributed unevenly across research fields, with the areas of research that rely on physical laboratories and time-sensitive experiments (biochemistry, biological sciences, chemistry, and chemical engineering) facing the largest declines in research time. Fields that are less equipment-intensive (mathematics, statistics, computer science and economics) showed the lowest declines in research time. Finally, women researchers, particularly those with young children, experienced the highest decline in time devoted to research, with possibly adverse effects on their careers in the long-term. Figure 1-8 shows how the impact of COVID-19 on research time has been drastically different across research fields, reaching a negative percentage change of around 40% for biochemistry, biology, engendering and other lab-based sciences, while more

Figure 1-11: Changes in levels and allocations of work time



Science, research and innovation performance of the EU 2022

Source: Myers, K. R., et al. (2020)

Notes: a, Distribution of total hours spent on work pre-pandemic and at the time of the survey. b, Distribution of changes in total work hours from pre-pandemic to time of survey. c–f, Distribution of percent changes in the share of work time allocated to research (c), fundraising (d), teaching (e) and all other tasks (f).

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-1-11.xlsx

limited impacts of around 10% are found in mathematics, computer science, economics, and other non-lab-based subjects of research. Deryugina, T. et al. (2021) employed a global survey to a broad range of academics across various disciplines (19905 respondents) together with a difference-in-differences approach to estimate the effects of COVID-19 disruptions on the gender gap in academia. The findings show that female academics, particularly those who have children, report a disproportionate reduction in time dedicated to research relative to what comparable men and women without children experienced, clearly identifying how housework and childcare still burden on women (Figure 1-12).

Figure 1-12: Field and group-level changes in research time

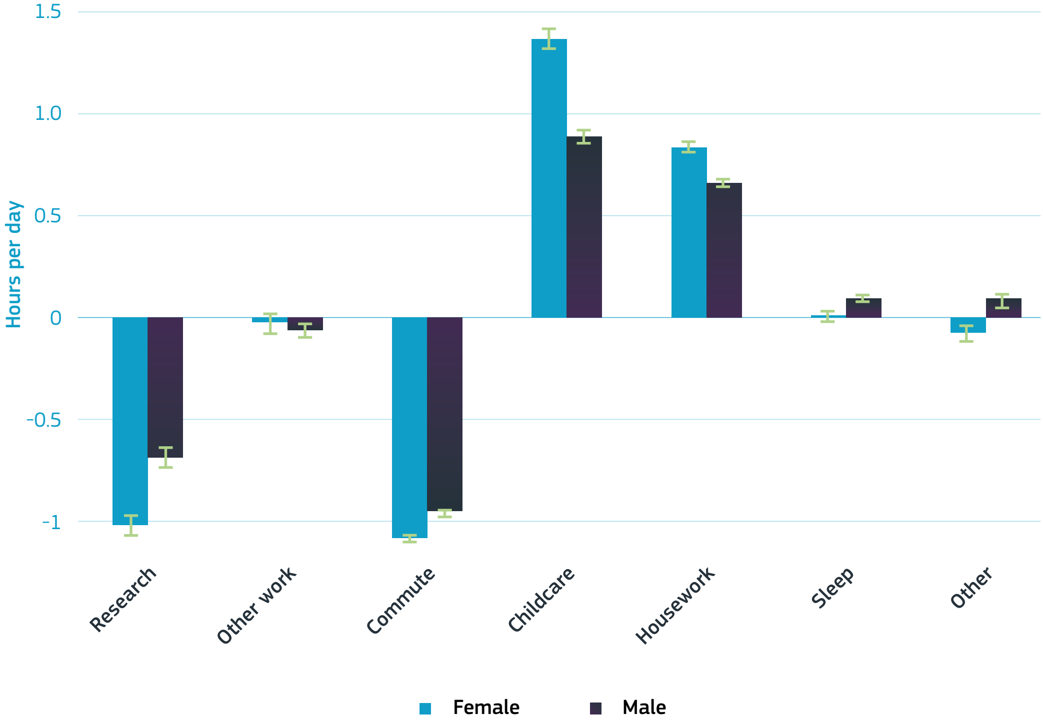
Science, research and innovation performance of the EU 2022

Source: Myers, K. R., et al. (2020)

Notes: a, Field-level average changes in research time. b, Group-level average changes in research time. c, Changes in research time associated with important features of scientists or their fields, after controlling for other factors. To untangle different factors, the authors use a Lasso regression approach to select features that are most predictive of declines in research time. Error bars indicate 95% confidence intervals.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-1-12.xlsx

Figure 1-13: Changes due to COVID-19 disruptions in the number of hours spent on each activity by gender



Source: Deryugina, T. et al. (2021)

Notes: Error bars represent 95% confidence intervals using robust standard errors.

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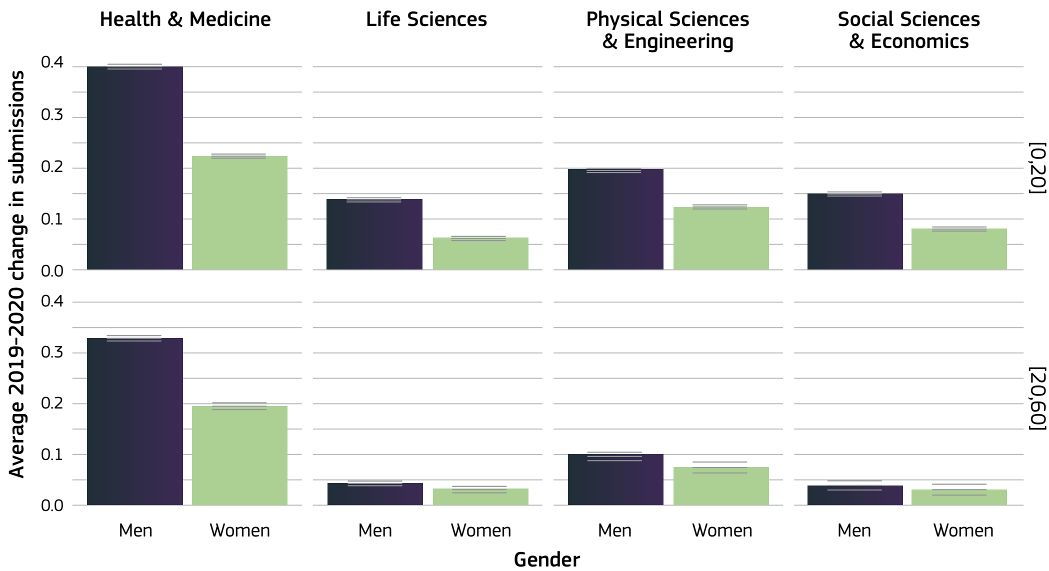
Despite the reduction in research time during the pandemic, the submission rate of research papers increased. During the first months of the pandemic there has been an unusual high submission rate of academic articles, likely due to the sense of urgency and novelty of topics (Kambhampati et al. 2020, Else, 2020). However, the heterogeneous effect of the pandemic on research time and mental strain across gender spilled over to paper submissions and publications (cf. Squazzoni et al., 2021). Similarly, women researchers contributed less to COVID-19-related research and made less pre-print articles during the pandemic, compared to their male peers (Vincent-Lamarre, 2020). Figure 1-13 shows how the increase in research paper submissions during the pandemic has been sharply unequal among gender and research subjects.

Figure 1-14: Changes in submissions



Source: Squazzoni, F et al. (2021).
Note: The graph depicts the average change in submissions by research area and age, the latter variable including authors in the first cohort (less than 20 years from their first publication) in the first group with older authors in the second. Bars represent standard errors.
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-1-14.xlsx

Young scholars have been disproportionally affected by the pandemic. Compared to senior staff, PhDs and Postdoc researchers could to a lesser extent rely on past co-authors and research groups to continue their research activities during the pandemic. Fry et al. (2020) showed how during the pandemic senior researchers preferred to cooperate with known colleagues, reducing collaborations with colleagues outside their network. Nature's worldwide survey, interviewing 7670 postdocs working in academia, depicts a gloomy picture (Woolston, 2020b). About 61% of the respondents report that the pandemic has negatively affected their career prospect, 13% were sure to have lost a job offer due to the pandemic, 80% had troubles performing experiments and 60% had troubles discussing research ideas with their peers.

Many universities have frozen hiring, pushing many young researchers to wait one year or look for alternatives outside academia. This was more pronounced in the US and UK, as higher education systems in the EU have more stable income streams from public funding (Woolston, 2020a).

Scientific production increased during the COVID-19 pandemic, carrying a risk of compromising quality. As noted earlier, a sense of urgency fostered the scientific community to work, and fast, on COVID-19 related topics. Academic journals speeded up their peer-review process and researchers more quickly put working paper versions of their work online. Some evidence also suggests an increase in dubious and retracted research, and an occasional lowering of normal scientific standards as a price that is paid for rushed research (Pai, M. 2020, Else, H. 2020). These elements are to be crucially considered when talking about science communication, as compromised scientific quality can easily erode public faith in research.

4.2 Do Europeans still trust in science?

An intellectual tour de force by scientists led to the development, with an unprecedented swiftness, of safe and effective COVID-19 vaccines. Gupta et al. (2021) estimated that within the first five months after the beginning of the vaccination programme, 140 thousand lives were saved in the US thanks to the vaccines. Worldwide numbers are several orders of magnitude more massive, and rising day by day.

Yet, objective success does not imply perceived success. There is a wide and broad literature on the relationship between science accomplishments and science perception of the broader public. As an example, it is found that scientific disputes are found to diminish general public trust in science due to misunderstanding by the public of how science operates (Dieckmann et al., 2019).

In the EU, there is a high level of trust in science, yet a slightly lower level of trust on the reliability of scientists. Research shows that it easier to erode trust in scientists and leaders than in science itself. Indeed, science is perceived more as a great tool which may fail in biased hands (Aksoy et al. 2020, Eichengreen et al. 2021). The 2021 release of a Eurobarometer survey shows that 9 in 10 EU citizens (86 %) think that the overall influence of science and technology is positive. However, in line with the empirical literature, scientists are perceived as more intelligent than reliable, with 89 % of EU citizens defining them as intelligent and only 68 % considering them as reliable.

During periods of emergency, misunderstood lively academic debates and societal/political pressures can damage popular trust in science. Scientific debates are common and crucial for the development of new ideas. However, in the public sphere such debates may erroneously be interpreted as fundamental disagreements among scientists. Furthermore, in periods of crisis with inflated pressure on the scientific community to quickly produce and disseminate scientific findings, discord among different experts (or the perception thereof) can feed distrust. Sceptics may find it symptomatic for scientists' bias or dishonesty (Eichengreen et al., 2021). At the same time, political and electoral interests can incentivise political leaders to dismiss or undermine scientific expertise (Friedman et al., 2020).

In times of pandemics, popular trust in scientists and political institutions tends to erode, unless political institutions act in a timely manner. Aassve et al. (2021) find that the global pandemic caused by a lethal influenza virus in 1918-19 (commonly called Spanish Flu) had long-lasting negative consequences for individuals' social trust, also carrying over into later generations. Using epidemics data for 142 countries from 1970, Aksoy et al. (2020) also find a negative impact of past exposure to epidemics on individuals' confidence in political institutions and leaders. Eichengreen et al. (2021), employing data for 138 countries on global epidemics since 1970, find that past epidemic exposure has no impact on views of science as an endeavour, yet it significantly reduces trust in scientists and in the benefits of their work. On the other hand, Fluckiger et al. (2019) find that exposure to the Ebola epidemic in West Africa enhanced trust in government, particularly when governments managed to respond with timely measures.

Trust in science can face fatigue due to contradictory statements from authorities and experts. Battiston et al. (2021) found that in Italy responsiveness to COVID-19 information from experts weakened over time, likely due to attention fatigue and contradictory statements from health authorities and experts.

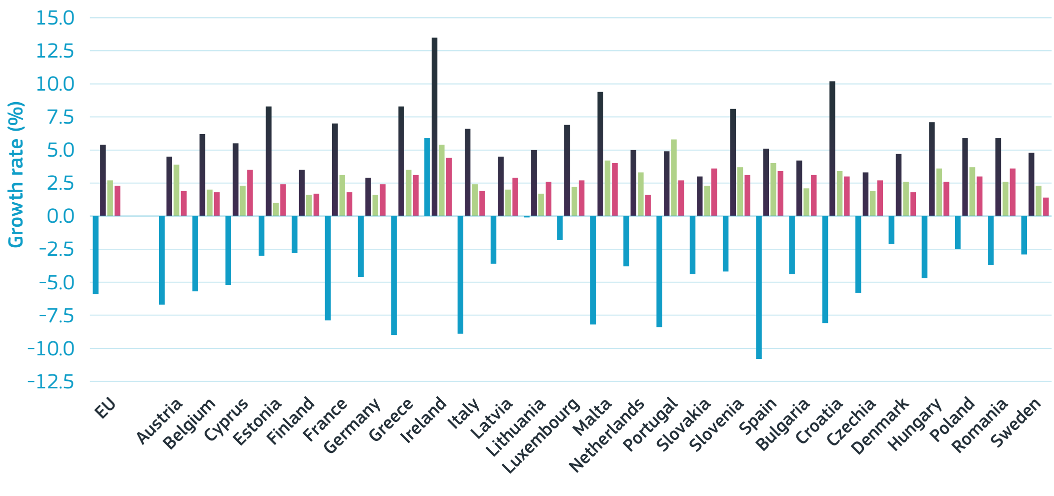
To sum up, the impact of pandemics on trust in science is not exclusively related to its successes to develop effective vaccines, but also depends on the endorsement of scientific insights by the government, and on an ability to develop an inclusive communication strategy. Hence, as the voluntary participation in vaccination programmes is heavily related to individuals' trust in science and health authorities (Sturgis 2021), the cultivation of scientific social trust through well-informed communication and nudging activities acquires an elevated degree of priority and importance.

5. The way forward

5.1 Recovery and resilience

Due to the pandemic and associated policy responses to contain the virus, the EU recorded a historic drop in economic activity in 2020, corresponding to a decrease of 5.9% of GDP compared to 2019[13]. This was mitigated to a certain extent by the adaptation of firms and households to cope with the new situation and continued strong policy support. **The EU economy initially seemed to recover from the recession faster than expected** (Figure 1-14). Growth perspectives in the short run are supported by a continuously improving labour market, favourable financing conditions and the deployment of the Recovery and Resilience Plans (RRP) developed under the Recovery and Resilience Facility (RRF) (European Commission, 2022a). However, **the war in Ukraine**, as well as the disturbances in global trade caused by the drastic COVID-19 containment measures still applied in parts of **China**, are **likely to dampen the expected post-pandemic economic recovery**. According to the Spring 2022 forecast of the European Commission (European Commission, 2022b), as a consequence of these developments real

Figure 1-15: Economic Forecast (GDP growth, volume)



Source: Spring 2022 Economic Forecast (DG ECFIN) and Eurostat.
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-1-15.xlsx

13 Source : Eurostat. Real GDP growth rate.

GDP growth in the EU is expected at 2.7 % in 2022 and 2.3 % in 2023, which is down from the 4.0 % and 2.8 % predictions of the winter 2022 interim forecast.

The Recovery and Resilience Facility, with a budget of EUR 672.5 billion, is at the core of the NextGenerationEU programme, the post-COVID recovery programme agreed by EU leaders mid-2020. It will support large-scale reforms and investments, through plans submitted by the Member States. **R&I is an indispensable component to deliver on Europe's recovery and increase resilience**, i.e. withstanding and coping with challenges and undergoing transitions, and making Europe's green and digital transformation a reality. Through the RRF, the Commission encourages Member States to strongly invest in R&I, with seven flagship areas at its core that range from clean technologies and renewables to buildings efficiency, and to strengthen national and regional R&I systems. Under the RRF, countries have to dedicate at least 20 % of the funds to the digital transition and at least 37 % to the green transition.

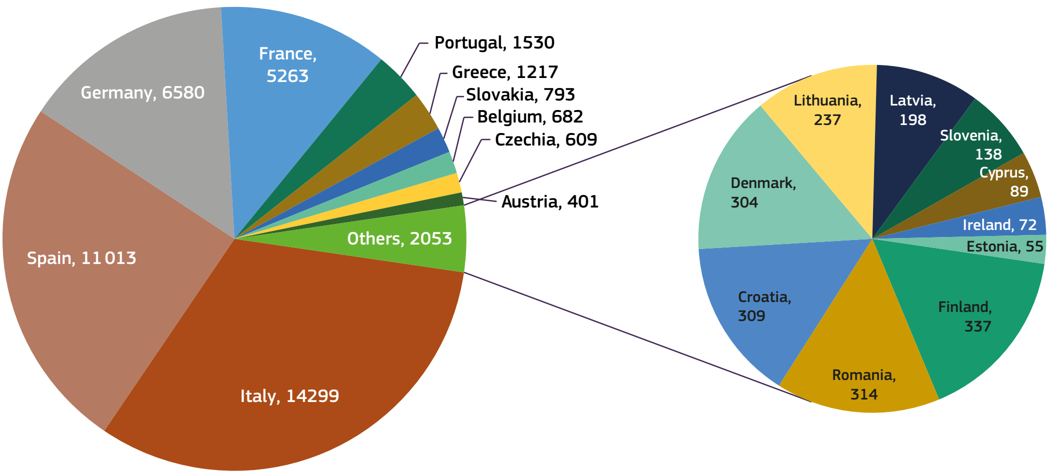
The overall expenditure for R&I in the Recovery and Resilience Plans is significant. All approved RRPs[14] include a total of 224 measures related to R&I (55 reforms and 169 investments) for a budget of around EUR **44.4 billion**[15]. The amount of R&I investments in the RRPs represents typically between 4 % and 13 % of the RRF grants allocation of a country, with a few outliers below or above this range and an average of about 10 % (Figures 9 and 10).

For several Member States, the Recovery and Resilience Facility can be instrumental in the development of their R&I system, shaping it in the years to come, and with a real transformative impact should the efforts be maintained over time. For example, in several Eastern and Southern Member States, which are characterised by high RRF grants allocation and low R&D intensity, the investments included in the RRPs amount to over one year of (pre-COVID) public investments in R&I. Moreover, in some of those countries, these investments are linked to important R&I policy reforms (see Box 1-2).

14 The recovery and resilience plans of the following 22 Member States have been approved so far: Austria, Belgium, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, France, Ireland, Italy, Germany, Greece, Latvia, Lithuania, Luxemburg, Malta, Portugal, Romania, Slovakia, Slovenia, and Spain.

15 This amount corresponds to the total estimated costs of all measures addressing research, development and innovation priorities, including those directly related to the green or digital transitions.

Figure 1-16: Absolute expenditure allocation to R&I projects in Recovery and Resilience Plans per Member State in million EUR

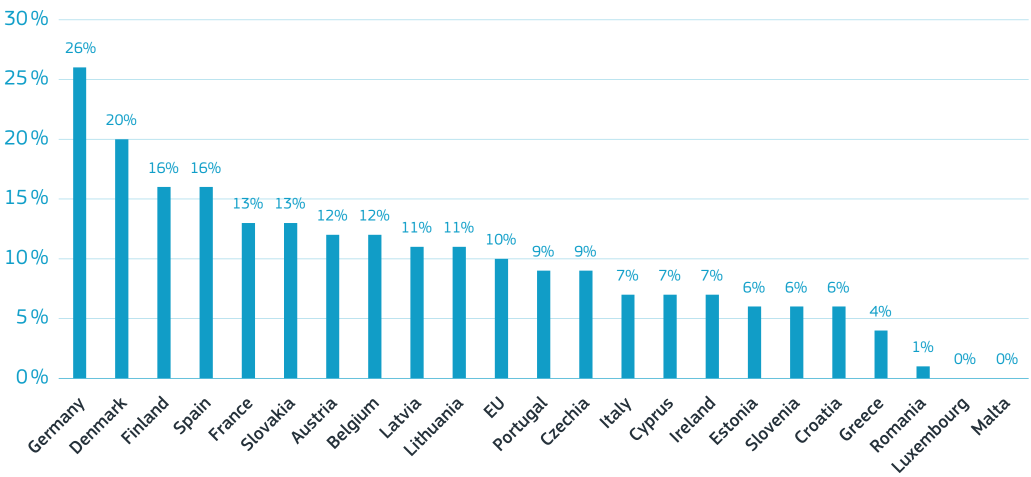


Science, research and innovation performance of the EU 2022

Source: Recovery and Resilience Scoreboard - Thematic analysis: research and innovation.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-1-16.xlsx

Figure 1-17: R&I allocation as a percentage of total allocation per Member State in Recovery and Resilience Plans



Science, research and innovation performance of the EU 2022

Source: Recovery and Resilience Scoreboard - Thematic analysis: research and innovation.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-1-17.xlsx

Box 1-2: Research and innovation in the Recovery and Resilience Plans (RRPs)

The **R&I reforms** typically plan to:

- reduce the **fragmentation of the scientific research system** through the consolidation of scientific research institutions;
- **increase the attractiveness of research careers in public institutions** through changes to the recruitment, salary and career management policies (for key areas in particular), including with increased possibility for mobility and combining public research with private activity;
- **reduce the administrative burden** related to the access to public funding for R&I activities;
- support **knowledge and technology transfer** (from public research institutions to private companies) through the creation of appropriate entities (offices, agencies) and the removal of barriers to academia-business collaboration;
- **improve the coordination between the different levels of governance** of R&I and education policies, in order to respond to skills needs and enhance employability, especially for the young.

The RRPs include both horizontal and thematic R&I investments, consisting in financial support for R&I activities and infrastructures.

The **horizontal** R&I investments account for slightly more than one third of the total R&I investments. They include a variety of cross-cutting measures such as strengthening of innovation ecosystems, upgrade of research infrastructures, grants for researchers, support for business innovation including start-ups and SMEs, facilitation of public-private R&I cooperation and the support of existing or new regional clusters.

The **thematic** R&I investments are targeted at a number of specific areas.

The green transition will be facilitated by R&I investments notably in the fields of:

- energy (17 % of total R&I expenditure; including, e.g., development of hydrogen solutions);
- environment (6 %; e.g., support for public and business R&I in the environmental field, research in innovative green technologies);
- transport/smart mobility (4 %; e.g., development of electro-mobility); and
- circular economy (3 %; e.g. development of re-use and recycling technologies).

R&I investments in **digital technologies** account for approximately 15 % of total R&I expenditure and include, for instance, development of advanced technologies (microprocessors, cloud, quantum computing, etc.), cybersecurity, 5G, as well as digital technologies of a more horizontal impact.

Another important area of R&I investments is **health** (5% of total R&I expenditure). These investments include, for example, the development of alternative production processes for nuclear medicine for cancer treatment or the establishment of a centre for precision medicine.

Several Member States also included investments to support Horizon Europe Partnerships and the funding of projects receiving a Seal of Excellence (i.e. projects which were judged to deserve funding under Horizon Europe but could not be financed due to budget limitations).

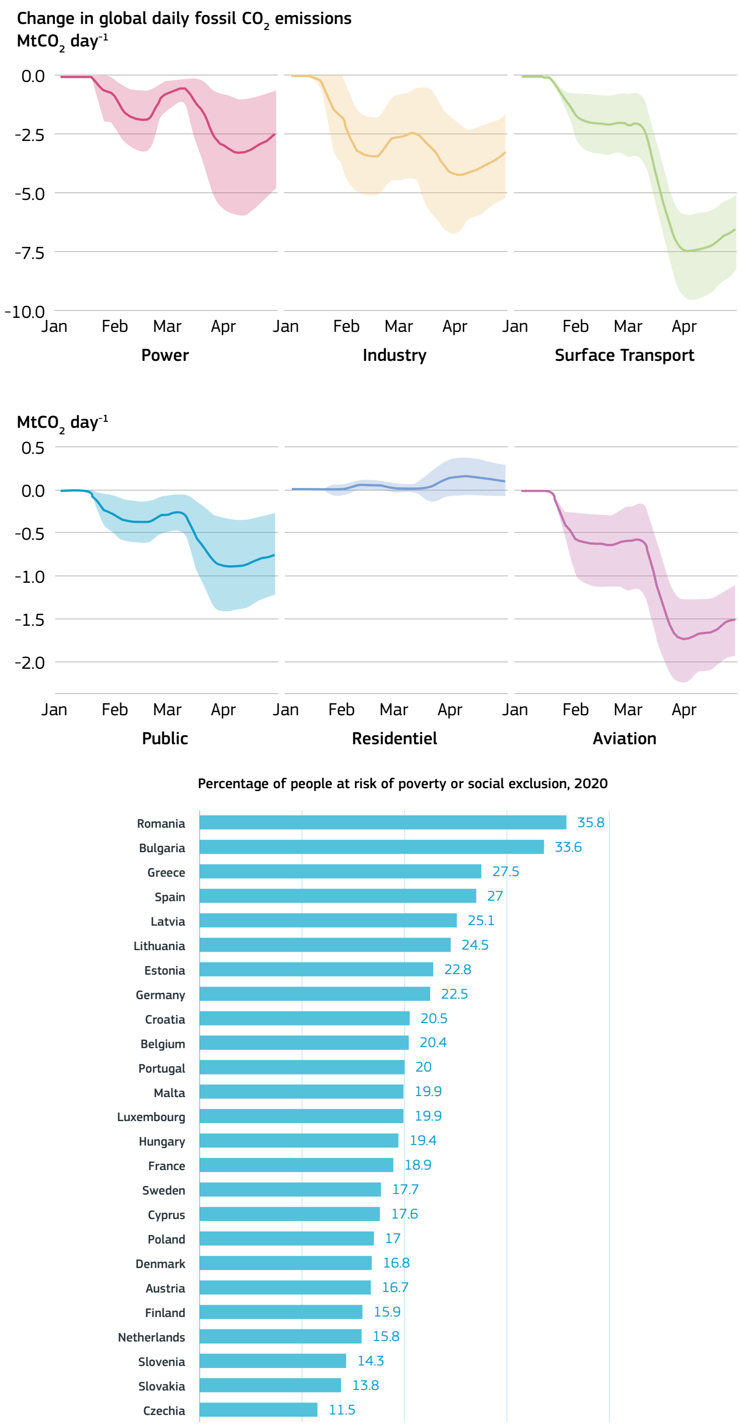
The existence of zombies can hamper the recovery. Zombie firms are financially distressed firms with unviable business models (see also Chapter 4.2). Such firms can survive for example due to inefficient credit allocation resulting from malfunctioning financial markets and inefficient solvency regimes (Schivardi et al., 2017; Azevedo et al., 2018; Caballero et al., 2008; Adalet McGowan M. et al, 2017). Labour and capital embedded in these zombie firms are inefficiently used. Overall productivity improvements can be achieved if labour and capital can be reallocated towards more efficient firms.

Education and training of employees and managers can help this reallocation process, and foster resilience. More education and functional experience by management teams of firms, as well as new knowledge and experience brought by outsider CEOs exporting firms, may reduce the probability for companies of becoming financially distressed and may contribute to enhanced productivity and resilience of the economy against shocks, such as the pandemic COVID-19 (Bloom and Van Reenen, 2010; OECD, 2021b).

5.2 Building forward better

While the pandemic has delivered a blow to our economies, it has also shown that we can change the way we live and consume very rapidly if we see the imperative to do so. During 2020, daily global CO_2 emissions decreased by 17% by early April 2020 compared with the mean 2019 levels, with just under half from changes in surface transport (see Figure 1-11). CO_2 levels were lower for all regions in the world. Emissions in individual countries decreased by 26% on average in 2020, with the largest decrease for South America, by up to approximately 40% (Le Quéré et al., 2020). While it will do little to address the issue of air pollution in the long term, it does offer an interesting perspective on discussions about the impact of a decrease in consumption on anthropocentric climate change as well as on the speed of consequences as changes take place. The EU and its Member States are now working on a common 2050 vision of sustainability (European Commission, 2018; 2019). Stepping up horizon scanning and foresight efforts and improving the uptake of partnerships with citizens will prove crucial in this respect.

Figure 1-18: Change in GHG emissions during the pandemic and percentage pf people at risk of poverty and social exclusion



Source : Le Queré et al (2020) and Eurostat (online data code: ilc_peps01n).
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-1-18.xlsx

Developing and deploying breakthrough technologies that eliminate emissions throughout the physical economy is critical. To do so, we need to tap the power of markets to fund these innovations— for example, **by finding creative ways to finance technologies or by levelling the playing field so they can compete with fossil fuels**. This can mean revising financial and tax incentives offered to industries with a large contribution to climate impacts, or offering similar support to (yet) underdeveloped industries. Furthermore, governments and corporations need to adopt policies that will make it faster and cheaper to make the transition, and leaders will need to reward those who take difficult steps (Gates, 2021). Diffusion of such green technologies will in turn stimulate the creation of sustainable jobs, such as circular economy jobs, urban and rural rewilding and preventive health services.

The pandemic has put even more pressure on the most vulnerable, including low-income households or households living in remote areas, as well as small firms, and has highlighted the extent to which the current system is falling short on social needs and the need for resilience and sustainability. For instance, the rates of food insecurity in the US got closer to 30% or higher during the pandemic, and spiked to 36% in 2020 (+20% compared to pre-Covid levels) (Bath, 2020). In Europe, in 2020, European Food Bank associations registered a surge of +34.7% of people in need and that most beneficiaries are people who have lost their job as a consequence of COVID-19. Besides, while the COVID-19 outbreak affects all segments of the population, early evidence indicates that the health and economic impacts of the virus are being borne disproportionately by poor people (UN, 2021). These deep-rooted issues need a paradigm shift that is slow to happen. Digitalisation and artificial intelligence, for example, should be optimised for social impact in order to prioritise their use for the good of people. Similarly, the design of cities and rural communities can be rethought with new models of social safety nets and creative procurement policies.

The EU needs to support a cohesive and inclusive innovation-driven growth of countries, regions and companies by fostering synergies between Horizon Europe and other EU programmes targeting R&I (such as cohesion policy and parts of InvestEU). The Commission can also support Member States and regions in designing and implementing better innovation policies and reforming national and regional research and innovation systems through the Technical Support Instrument (TSI). R&I can also be promoted through place-based policies to boost underutilised potential and strengthen regional innovation systems, by encouraging public support to R&I also for laggard firms, and by ensuring that Europeans have the skills required to effectively use the new technologies. Such an innovation system requires governance that balances experimentation and precaution and addresses the unpredictable outcomes and impacts of innovation (EEA, 2021).

This requires a multi-level, whole-of-government approach to policy. Such an integrated approach would for example allow promoting coherent investments across European and national actors, but also facilitate on-the-ground experimentation. These innovative approaches could bring better exploitation of the fruits from R&I, increased participation of civil society in R&I, and a faster and more just transition. In this optic, 'growth' should go beyond simple GDP monitoring, and evaluate the resilience and participation of citizens in building a future they feel part of (OECD, 2020b).

Experts[16] also recommended an assessment of the responses to the crisis with the objective of drawing lessons from policy responses at every level of government. It was recommended to operationalise the more successful ones into short- and long-term R&I actions capable of improving the role of R&I policy in crisis management. As such the COVID-19 pandemic has already proven fertile, as ideas have already found their way to policymakers, such as the development of rapid response capabilities for emergency data collection and organisation, critical technology mapping, and also the consideration and protection of knowledge-intensive companies as actors of European resilience. Preparedness, monitoring and evidence-based policies are also needed to address growing instabilities, disruptions and uncertainty about our future.

More generally, the COVID-19 crisis showed that Europe needs not only to prepare for the challenges we know, but needs to be ready for new ones. The rising environmental, geopolitical, economic and social instability in the world increases the likelihood of extreme events with disruptive effects, and with potentially unknown specific shape. The recent conflict in Ukraine is another illustration of this.

Extreme events have, however, shown strong signs in a foresight sense, and should, therefore, serve as a basis to complete reflections made to adjust the EU's R&I policy in light of the recent crises, i.e. resilience of the R&I systems.

The pandemic has provided us with the opportunity to 'build forward better' (ESIR, 2021; Giovannini et al., 2021; OECD, 2021a; Martin & Mullan, 2021; EEA, 2022) and aim for a more sustainable and inclusive Europe. We have learned from the past that policy objectives to combat a crisis should not only be limited to economic or public finance objectives. Furthermore, a transition to a sustainable society and economy is necessary to protect human health, and COVID-19 can be seen as a 'late lesson' from an early warning (EEA, 2022). Today there is a clear political commitment to build back better (Stern et al., 2020, 2021), and equip public and private entities with support and tools fit for a green, inclusive and resilient recovery. As the Expert Group on the Economic and Societal Impact of Research and Innovation (ESIR) puts it: 'Greater resilience by design, not by disaster'.

16 Dixson-Declève et al. (2020).

References

Aassve, A., Alfani, G., Gandolfi, F., & Le Moglie, M. (2021), 'Epidemics and trust: the case of the spanish flu', *Health economics*, 30(4), pp. 840-857.

Adalet McGowan M., Andrews D. Millot V. (June 2017), *Insolvency regimes, zombie firms and capital reallocation*, OECD economics department working papers no. 1399.

Aghion, P., Askenazy, P., Berman, N., Cette, G., & Eymard, L. (2012), 'Credit constraints and the cyclicality of R&D investment: Evidence from France', *Journal of the European Economic Association*, 10(5), pp. 1001-1024.

Agley, J. (2020), 'Assessing changes in US public trust in science amid the COVID-19 pandemic', *Public Health*, 183, pp. 122-125.

Alexandre, F., S. Cruz and M. Portela (2021), *Financial distress and the role of management in micro and small-sized firms*, OECD Productivity Working Papers, No. 27, OECD Publishing, Paris, https://doi.org/10.1787/2014873c-en.

Almeida, A., Figueiredo, H., Cerejeira, J., Portela, M., S ´a, C., and Teixeira, P. (2017), *Returns to postgraduate education in portugal: Holding on to a higher ground?*, IZA Discussion Paper No. 10676.

Anzoategui, D., Comin, D., Gertler, M., Martinez, J. (2019), 'Endogenous Technology Adoption and R&D as Sources of Business Cycle Persistence', *American Economic Journal, Macroeconomics*, 11 (3), pp. 67-110.

Azevedo N., Mateus M. Pina A. (2018), *Is bank credit going to the most productive firms? Portuguese Economic Growth.*

Barlevy, G. (2007), 'On the cyclicality of research and development', *American Economic Review*, 97(4), pp. 1131-1164.

Battiston, P., Kashyap, R., & Rotondi, V. (2021), 'Reliance on scientists and experts during an epidemic: Evidence from the COVID-19 outbreak in Italy', *SSM-population health*, 13, 100721.

Bloom N., Van den Reenen J. (2010), 'Why do management practices differ across firms and countries?', *Journal of Economic Perspectives*. Vol 24 n°1. Why Do Management Practices Differ across Firms and Countries? - American Economic Association (aeaweb.org).

Borunsky et al (2020), *Can R&I save the Day*, R&I Paper Series.

Bryan, K., J. Lemus and G. Marshall (2020), *Innovation During a Crisis: Evidence from Covid19*, SSRN Electronic Journal

Caballero R., Hoshi T., Kahsyap A.(December 2008), 'Zombie lending and depressed restructuring in Japan', *American Economic Review*, 98(5), pp. 1943-77.

Comin, D., & Gertler, M. (2006), 'Medium-term business cycles', *American Economic Review,* 96(3), pp. 523-551.

Contreras, F.; Baykal, E., and Ghulam Abid (2020), 'E-Leadership and Teleworking in Times of COVID-19 and Beyond: What We Know and Where Do We Go', *Front. Psychol.*, https://doi.org/10.3389/fpsyg.2020.590271.

Deryugina, T., Shurchkov, O., & Stearns, J. (2021, May), 'COVID-19 disruptions disproportionately affect female academics', In *AEA Papers and Proceedings*, 111, pp. 164-68).

Dixson-Declève, S., Balland, P., Bria, F., et al. (2020), *Protect, prepare and transform Europe: recovery and resilience post COVID-19*, Publications Office.

Dieckmann, N. F., & Johnson, B. B. (2019), 'Why do scientists disagree? Explaining and improving measures of the perceived causes of scientific disputes', *PLoS One*, 14(2), e0211269.

ECB (2020), April 2020 euro area bank lending survey, Press Release, 20 April 2020.

EEA (2021), *With people and for people: Innovating for sustainability*, Briefing no. 09/2021.

EEA (2022), COVID-19: *Lessons from sustainability?*, Briefing.

Eichengreen, B., Aksoy, C. G., & Saka, O. (2021), 'Revenge of the experts: Will COVID-19 renew or diminish public trust in science?', *Journal of Public Economics,* 193, 104343.

Eichengreen, B., Saka, O., & Aksoy, C. G. (2020), *The Political Scar of Epidemics* (No. w27401), National Bureau of Economic Research.

Else, H. (2020), 'How a torrent of COVID science changed research publishing-in seven charts', *Nature*, pp. 553-553.

ESIR (2021a), *Protect, prepare and transform Europe – Build forward better" ESIR virtual seminar,* European Commission (europa.eu).

Eurofound (2020a), Living, working and COVID-19: *Methodological annex to round 1*, Dublin.

Eurofound (2020b), *Living, working and COVID-19,* COVID-19 series, Publications Office of the European Union, Luxembourg.

European Commission. (2018), *A Clean Planet for all A European strategic long-term vision for a prosperous, modern, competitive and climate neutral economy*, Brussels, 28.11.2018 COM(2018) 773 final.

European Commission (2019), *The European Green Deal*, Brussels, 11.12.2019 COM(2019) 640 final.

European Commission (2020), *Europe's moment: Repair and Prepare for the Next Generation*, COM(2020) 456 final.

European Commission (2021a). *EU research and innovation in action against the coronavirus: Funding, results and impact.* Publication Office of the European Union, Luxembourg.

European Commission (2021b), Directorate-General for Employment, Social Affairs and Inclusion, *Employment and social developments in Europe 2021: towards a strong social Europe in the aftermath of the COVID-19 crisis: reducing disparities and addressing distributional impacts: annual review*, Publications Office, https://data.europa.eu/doi/10.2767/049867

European Commission (2022a), *European Economic Forecast. Winter 2022*, Institutional Paper 169.

European Commission (2022b), *European Economic Forecast. Spring 2022*, Institutional Paper 173.

European Food Banks Federation (September 2021), *COVID-19: a unique opportunity for a real change. FEBA Report 01*, FEBA_Report_Survey_COVID_Sept2021.pdf (eurofoodbank.org).

Fabrizio, K. R., & Tsolmon, U. (2014), 'An empirical examination of the procyclicality of R&D investment and innovation', *Review of Economics and Statistics*, 96(4), pp. 662-675.

Fatas, A. (2000), 'Do business cycles cast long shadows? Short-run persistence and economic growth', *Journal of Economic Growth*, 5(2), pp. 147-162.

Ferrazzi M., Savsek S. (July 2020), *COVID-19 economic update*. European Investment Bank report, COVID-19 economic update – July 17, 2020 (eib.org).

Fluckiger, M., Ludwig, M., & Sina Önder, A. (2019), ‚Ebola and state legitimacy', *The Economic Journal*, 129(621), pp. 2064-2089.

Friedman, L., & Plumer, B. (2020), *Trump's response to virus reflects a long disregard for science,* New York Times, 28.

Fry, C. V., Cai, X., Zhang, Y., & Wagner, C. S. (2020), 'Consolidation in a crisis: Patterns of international collaboration in early COVID-19 research', *PLoS One*, 15(7), e0236307.

Gates B. (Avril 23rd 2021), *My climate message for world leaders*, Bill Gates (gatesnotes.com).

Gauchat, G. (2012), 'Politicization of science in the public sphere: A study of public trust in the United States', 1974 to 2010, *American sociological review*, 77(2), pp. 167-187.

Gewin, V. (2020), 'The career cost of COVID-19 to female researchers, and how science should respond', *Nature*, 583(7818), pp. 867-869.

Gibson, E.M. et al. (2020), 'How support of early career researchers can reset science in the post-COVID19 world', *Cell*, 181(7), pp. 1445-1449.

Giovannini, E., Hidalgo, C., Huang, A., et al. (2021), *Transformation post-COVID: the future of European universities*, Publications Office.

Grassano, N., Hernandez Guevara, H., Fako, P., Tuebke, A., Amoroso, S., Georgakaki, A., Napolitano, L., Pasimeni, F., Rentocchini, F., Compano, R., Fatica, S. and Panzica, R., (2021), *The 2021 EU Industrial R&D Investment Scoreboard*, EUR 30902 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-44399-5, doi:10.2760/559391, JRC127360.

Gupta, S., Cantor, J., Simon, K. I., Bento, A. I., Wing, C., & Whaley, C. M. (2021), 'Vaccinations Against COVID-19 May Have Averted Up To 140,000 Deaths In The United States: Study examines role of COVID-19 vaccines and deaths averted in the United States', *Health Affairs*, 40(9), pp. 1465-1472.

Harris, M., Bhatti, Y., Buckley, J. and Sharma, D. (2020), 'Fast and frugal innovations in response to the COVID-19 pandemic', *Nature Medicine*, 26, pp. 814–817.

He, S., Lai, D., Mott, S., Little, A., Grock, A., Haas, M. R., et al. (2020), 'Remote e-work and distance learning for academic medicine: best practices and opportunities for the future', *J. Grad. Med. Educ*, 12, 256–263. doi: 10.4300/JGME-D-20-00242.1.

CHAPTER 1

Howell, S. T., Lerner, J., Nanda, R., & Townsend, R. R. (2020), *Financial distancing: How venture capital follows the economy down and curtails innovation* (No. w27150), National Bureau of Economic Research.

JRC (June 2021), *The impact of COVID-19 on top R&D investors: first insight into 2021 EU Industrial R&D Investment*, JRC125712. .sb2021_pb_21june2021.pdf (europa.eu).

Juchnowicz, M.; Kinowska, H. (2021), *Employee Well-Being and Digital Work during the COVID-19 Pandemic*, Information, 12, 293. https://doi.org/10.3390/info12080293.

Kambhampati, S. B., Vaishya, R., & Vaish, A. (2020), 'Unprecedented surge in publications related to COVID-19 in the first three months of pandemic: A bibliometric analytic report', *Journal of clinical orthopaedics and trauma*, 11(Suppl 3), S304.

Kelly Servick, A. C., & Giorgia Guglielmi, G. V. (2020), 'Labs go quiet as researchers brace for long-term coronavirus disruptions', *Science*.

Kleine-Rueschkamp, L., and Adrjan, P. (2021), *After the Boom? COVID-19 and European City Labour Markets: Shortage of lower paid and non-remote job postings risks widening urban inequality*, https://www.oecd.org/local-forum/blog/.

Le Quéré C., JacksonR., Jones M., Smith A., Abernethy S., AndrewR., De-Gol A., Willis D., Shan Y., Canadell J., Friedlingstein P., Creutzig F., Peters G. (July 2020) 'Temporary reduction in daily global CO_2 emissions during the COVID-19 forced confinement', *Nature Climate Change*, Vol 10. 647-653. https://doi.org/10.1038/s41558-020-0797-x.

Ledford, H. (2020), 'Coronavirus shuts down trials of drugs for multiple other diseases', *Nature*, 580(7801), pp. 15-17.

Longhitano, G. A., Bitencourt Nunes, G., Candido, G., Lopes da Silva, J., V. (2021). *The role of 3D printing during COVID-19 pandemic: a review*, Progress in Additive Manufacturing 6, pages 19–37, https://doi.org/10.1007/s40964-020-00159-x.

López Peláez, A., Erro-Garcés, A., Pinilla García, F.J., Kiriakou, D. (2021), 'Working in the 21st Century. The Coronavirus Crisis: A Driver of Digitalisation, Teleworking, and Innovation, with Unintended Social Consequences. Information', 12(9), 377.

Martin, K., Mullan, Z. (2021), 'Building forward better', *The Lancet Global Health*, 9, Supplement 1, pp. S1-S2.

Mugabushaka, A. (2021), *Meeting the pandemic challenges : contribution of EU R&I funding to COVID-19 related research*, European Commission Publications Office.

Muoio D. (May 2020), *COVID-19's 'unprecedented stress' on social services drives demand for innovative SDOH programs*, MobilHealthNews.

Myers, K. R., et al. (2020), 'Unequal effects of the COVID-19 pandemic on scientists', *Nature human behaviour,* 4(9), pp. 880-883.

Negreiro Achiaga, M. (2021), *The rise of digital health technologies during the pandemic,* European Parliamentary Research Service.

OECD (2020a), *Responses to the crisis have drawn upon the innovative potential of businesses, Responses to the crisis have drawn upon the innovative potential of businesses*, OECD Publishing, Paris.

OECD (2020b), *Beyond Growth: Towards a New Economic Approach*, New Approaches to Economic Challenges, OECD Publishing, Paris, https://doi.org/10.1787/33a25ba3-en.

OECD (2020c) *Building forward better by strengthening resilience*, OECD Publishing, Paris.

OECD (2021a), *Before the COVID-19 crisis, OECD countries stepped up R&D investments*, https://www.oecd.org/sti/msti-highlights-march-2021.pdf.

OECD (2021b), OECD *Science, Technology and Innovation Outlook 2021: Times of Crisis and Opportunity*, OECD Publishing, Paris.

OECD, (February 2021c). *Business dynamism during the COVID-19 pandemic: Which policies for an inclusive recovery*? OECD Publishing, Paris.

Pai, M. (2020), 'Covidization of research: what are the risks?', *Nature medicine*, 26(8), pp. 1159-1159.

Paunov, C. and Planes-Satorra, S. (2021), *Science, technology and innovation in the time of COVID-19*, OECD Science, Technology and Industry Policy Papers 99, OECD Publishing.

Pollin R., Garrett-Peltier H., Heintz J., Scharber H. Green Recovery: *A Program to Create Good Jobs and Start Building a Low-Carbon Economy*, Center for American Progress (2008), Green Recovery: A Program to Create Good Jobs & Start Building a Low-Carbon Economy (repec.org).

Rafferty, M. C. (2003), 'Do business cycles influence long-run growth? The effect of aggregate demand on firm-financed R&D expenditures', *Eastern Economic Journal*, 29(4), pp. 607-618.

Sachini, E., Labrianidis, L., Sioumalas-Christodoulou, K., Chrysomallidis, C., Siganos, G., Belouli, A., & Karampekios, N. (2021), 'Research on Researchers. Coping during COVID-19. Results on a Nation-Wide Survey', *Science & Public Policy*, 48(4), pp. 451–461.

Schivardi F. Sette E., Tabellini G. (July 2017), *Credit misallocation during the European financial crisis,* Voxeu.org Credit misallocation during the European financial crisis, VOX, CEPR Policy Portal (voxeu.org).

Sedgley, N. H., Burger, J. D., & Tan, K. M. (2019), 'The symmetry and cyclicality of R&D spending in advanced economies', *Empirical Economics*, 57(5), pp. 1811-1828.

Si, S, Cullen, J., Ahlstrom, D. and Jiang Wei (2018), 'Special Issue: Business, Entrepreneurship and Innovation Toward Poverty Reduction', *Entrepreneurship & Regional Development*, 30:3-4, pp. 475-477.

Squazzoni, F., Bravo, G., Grimaldo, F., García-Costa, D., Farjam, M., & Mehmani, B. (2021), 'Gender gap in journal submissions and peer review during the first wave of the COVID-19 pandemic. A study on 2329 Elsevier journals', *PloS one*, 16(10), e0257919.

Stern N., Valero A. (November 2021), 'Innovation, growth and the transition to net-zero emissions', *Research Policy*. Vol 50. Issue 9. 104293. https://doi.org/10.1016/j.respol.2021.104293.

Stern, N. Unsworth S., Valero A., Zenghelis D., Rydge J., Robins N. (July 2020), *Strategy, investment and policy for a strong and sustainable recovery: An action plan*, Centre for Economic Performance. A CEP COVID-19 analysis Paper No.005. cepCOVID-19-005.pdf (lse.ac.uk).

Sturgis, P., Brunton-Smith, I., & Jackson, J. (2021), 'Trust in science, social consensus and vaccine confidence', *Nature Human Behaviour*, 1-7.

UN (April 2020), *The social impact of COVID-19. The Social Impact of COVID-19*, DISD (un.org).

Viglione, G. (2020), 'Are women publishing less during the pandemic? Here's what the data say', *Nature*, 581(7809), pp. 365-367.

Vincent-Lamarre, P., Sugimoto, C. R., & Larivière, V. (2020), 'The decline of women's research production during the coronavirus pandemic', *Nature index*, 19.

Woolston, C. (2020a), 'Junior researchers hit by coronavirus-triggered hiring freezes', *Nature*, 582(7812), pp. 449-450.

Woolston, C. (2020b), 'Pandemic darkens postdocs' work and career hopes', *Nature*, 585(7824), pp. 309-312.

Woolston, C. (2020c), 'Seeking an exit plan for leaving academia amid coronavirus worries', *Nature*, 583(7817), pp. 645-647.

CHAPTER 2

ZOOM OUT, ZOOM IN – THE GEOGRAPHY OF R&I

CHAPTER 2.1

ZOOM OUT – TECHNOLOGY AND GLOBAL LEADERSHIP

KEY FIGURES

1/5
of worldwide R&I output comes from the EU

9 %
of worldwide patents in semiconductors come from the EU

28 %
of worldwide patents in low-carbon technologies come from the EU

KEY QUESTIONS WE ARE ADDRESSING

- What is the overall position of the EU in the world in terms of R&I?
- What are the technological strengths and weaknesses of the EU on the global stage?
- Is the technological sovereignty of the EU at risk?

KEY MESSAGES

What did we learn?

- The changing geopolitical context increased uncertainties linked to the global and security outlook, calling for a reduction of industrial dependencies in strategic sectors through economic restructuring.
- The EU accounts for about one-fifth of worldwide R&I activities, with less than 7 % of the world's population.
- Major EU trading partners have improved their innovation performance at a faster pace in recent years.
- While the EU shows strengths in technological areas related to advanced manufacturing and advanced materials, its technological sovereignty is at risk in fields, including AI, big data, cloud computing, cybersecurity, robotics and micro-electronics.
- The EU is the international leader in clean energy innovation.

What does it mean for policy?

- Changes in the EU energy system induced by the Green Deal and accelerated by the Russian invasion of Ukraine are expected to have important geopolitical implications.
- Reducing strategic dependencies in key technological areas and value chains is necessary to strengthen the resilience of the EU.
- Increased efforts to commercialise research results will help the EU strengthen its technological leadership
- A reinvigorated multilateral approach would help the EU reinforce its open strategic autonomy, strengthening its role as a leading actor to foster international cooperation.

On the global stage, the EU is a key actor when it comes to R&I activities. It accounts for about one-fifth of worldwide R&I activities, with less than 7% of the world's population. The EU is an open research and innovation area that welcomes research organisations worldwide, and collaborates extensively with international partners on joint programmes. Europe is at the forefront of scientific advances. The EU leads in the fields of low-carbon technologies and renewable energies, and holds a strong position in industrial sectors such as pharmaceuticals, chemicals and mechanical engineering. At the same time, there is a need to reduce strategic dependencies on our main international partners. In its Communication of February 2020 Shaping Europe's digital future, the European Commission renewed its commitment to the creation of a stronger digital Europe, able to withstand the competitive pressure from its international partners, while protecting EU values and fundamental rights.

The need to strengthen European leadership in key technological domains has become more urgent with the outbreak of the COVID-19 pandemic. The acceleration of digitalisation and the significant supply chain disruptions caused by the COVID-19 pandemic have intensified the political discourse on EU technological and data sovereignty. To preserve and strengthen the EU's technological leadership, efforts are needed to increase R&D expenditure critical to the development of innovative solutions, improve access to materials along strategic value chains, and create a more efficient regulatory framework to develop and deploy advanced technologies (Csernatoni, 2021). Analysing the patterns of technological specialisation at global level is essential to identify critical emerging technological areas, assess the EU's global competitive position, and understand how to steer EU policy action accordingly (Confraria et al., 2021).

Furthermore, **the changing geopolitical context has increased uncertainties linked to the global and security outlook**. The Commission's recent Communication *Towards a green, digital and resilient economy: our European Growth Model* reinforces the commitment to strengthen the EU's long-term sustainable growth agenda, by leveraging international EU partnerships. The deterioration of Ukraine-Russia relationship, which culminated in the invasion of Ukraine, revealed important vulnerabilities, confirming the need to further accelerate EU economic transformation (European Commission, 2022d). The unprovoked Russian invasion of Ukraine is expected to affect global geopolitical relations, requiring **a reduction of industrial dependencies in strategic sectors through economic restructuring**, which will likely affect innovation. At the same time, the war will negatively impact the vibrant tech ecosystem in Ukraine, accelerate reshoring trends and worsen the global chips shortage (Ravet et al., 2022).

1. The position of the EU in the world: overview

The EU shows both strengths and weaknesses in terms of scientific performance (Table 2.1-1). In terms of overall scientific performance (total share of scientific publications and co-publications), the EU shows a strong position compared with the US, Japan and South Korea (see also Chapter 6.1 – Scientific performance). Nevertheless, the EU lags behind the US and China in terms of overall scientific excellence (i.e. share of 10% most cited publications), and other R&I indicators, including investments in intangibles (see Chapter 5.1 - Introduction: tangible and intangibles assets) and patent activities in several fields (e.g., the ICT sector, where it falls considerably behind all its main international competitors) (see also Chapter 6.3 - Innovation output, societal and market uptake and knowledge valorisation).

The EU performs well in fields related to health and environment. The EU leads in terms of the share of scientific publications in the health sector and, although behind the US in terms of patent applications related to health, it remains well above both Japan and China. Furthermore, the EU is strong in areas related to the green transition, outperforming both the US and China in terms of patent applications.

Major EU trading partners have improved their innovation performance at a faster pace in recent years. Despite its strengths, the EU risks falling behind in areas where it is exposed to global competition. The risk is particularly high considering the faster rate at which the EU's main competitors have been evolving. It is therefore important **to keep strengthening the EU's capacity to develop and implement advanced technologies, to stay competitive and avoid future strategic dependencies** (see section 2).

The EU lags behind the US and other competing international economies in terms of private sector R&D expenditure (EIB, 2021). The share of BERD in total R&D expenditure is around 67% in the EU, well below that of the US (73%), and China, Japan and South Korea, whose shares range between 78% and 80% (EIB, 2021; Confraria et al., 2021). The EU also underperforms in terms of number of firms investing in R&D. The EU share of top 2 500 R&D investors has decreased over time, mostly due to the rise of Chinese tech companies (Grassano et al., 2021). Although the US keeps its position as leading innovator, the number of Chinese firms allocating resources to R&D has increased significantly. Between 2006 and 2018, Chinese R&D investors in the top 2 500 increased from 0.5% to 20%, overtaking the EU (See Chapter 5.2 – Investment in R&D). Over the past decade, the EU's top R&D spenders have maintained a stable sectoral composition, with a heavy reliance on the automotive sector, while the US and China have specialised further in ICT sectors (EC R&D scoreboard 2021).

Table 2.1-1: Overall global position of EU in R&I

	Indicators	Last available year	EU	Trend	United States	Trend	China	Trend	Japan	Trend	South Korea	Trend
General Indicators	GDP per capita, PPP (constant 2017 international $)	2020[1]	41504	↗	60236	↗	16411	↗↗	41380	↗	42251	↗↗
	Share of population aged 65+ (%)	2020	20.6	↗↗	16.6	↗↗	12.0	↗↗	28.4	↗↗	15.8	↗↗
	Gini coefficient of equivalised disposable income	2019[2]	0.31	→	0.39	→	0.51	n/a	0.33	n/a	0.35	↘
	CO_2 emissions (metric tons per capita)	2018	6.4	↘	15.2	↘	7.4	↗	8.7	→	12.2	↗
R&D Invesment	R&D investment as % of GDP	2019	2.20	↗	3.07	↗	2.23	↗↗	3.24	→	4.64	↗↗
	Business spending on R&D as % GDP	2019	1.46	↗	2.27	↗↗	1.71	↗↗	2.57	↗	3.73	↗↗
	Public spending on R&D as % of GDP	2019	0.73	→	0.66	↘	0.53	↗	0.63	↘	0.85	↗
Human Resources	Researchers employed per million population	2019	4157	↗↗	4414	↗	1340	↗↗	5360	↗	7913	↗↗
	Population aged 25-34 with tertiary education (%)	2019[3]	40.5	↗↗	50.4	↗	14.0	↗↗	61.5	↗	69.8	↗
Scientific Performance	Scientific publications (world share %)	2020	19.6	↘	15.6	↘↘	22.4	↗↗	3.3	↘↘	2.4	→
	Scientific excellence (% of publications within 10% most cited) (*)	2018	9.9	→	13.3	↘	11.1	↗↗	5.8	↘	7.8	→
	International scientific co-publications /million population	2020	783	↗↗	759	↗↗	126	↗↗	335	↗↗	549	↗↗
	Share of public-private co-publications (%)	2020	9.1	↗	8.4	↘	7.7	↗↗	10.7	→	7.9	↘
Innovation Performance	PCT patent applications (world share %)	2018	19.4	↘↘	22.0	↘↘	20.9	↗↗	18.3	→	6.5	↗
	PCT patent applications /million population	2018	106.4	↗	165.1	↗↗	36.7	↗↗	353.9	↗↗	308.7	↗↗
	European Innovation Scoreboard (index)	2021[4]	113	↗	120	↗↗	84	↗↗	114	↗↗	136	↗↗
	Number of unicorns	Jul 2021	60	n/a	392	n/a	157	n/a	6	n/a	11	n/a
	Number of companies in Top 100 of the R&D Industrial Scoreboard	2020	26	n/a	35	n/a	10	n/a	15	n/a	4	n/a
Export Capacity	Share of High-Tech and Medium High-Tech Exports (%)	2021[4]	57.1	↗	53.7	↗	58.1	↗	73.6	→	72.3	↗
	Share of Knowledge-Intensive Services Exports (%)	2021[4]	67.3	↗	70.8	→	65.9	→	69.3	↘	58.6	→
ICT Sector	Scientific publications (world share %)	2020	17.8	↘↘	10.3	↘↘	25.9	↘↘	2.7	↘↘	2.3	↘
	Scientific excellence (% of publications within 10% most cited) (*)	2018	9.7	↘	12.1	↘↘	11.6	↗↗	4.9	↗↗	8.1	↘
	PCT patent applications /million population	2017	17.9	↗	51.1	↗↗	17.4	↗↗	80.0	→	101.4	↗↗
	PCT patent applications (world share %)	2017	11.0	↘↘	22.9	↘↘	33.2	↗↗	14.0	↘↘	7.2	↘
	Business R&D intensity in ICT sector (%)	2019[5]	5.6	→	10.1	→	6.0	↗↗	7.6	↘	21.4	↗↗
Climate & Environment Sector	Scientific publications (world share %)	2020	19.8	↘↘	10.7	↘↘	25.1	↗↗	1.8	↘↘	2.1	↗
	Scientific excellence (% of publications within 10% most cited) (*)	2018	13.5	→	15.2	↘↘	15.7	↗↗	7.8	↘	11.0	↘
	PCT patent applications /million population	2018	0.98	→	1.22	→	0.24	↗↗	1.91	↗↗	2.77	↗↗
	PCT patent applications (world share %)	2018	22.5	↘↘	20.5	↘↘	16.9	↗↗	12.4	↘	7.3	↗
Health Sector	Scientific publications (world share %)	2020	21.0	↘	20.8	↘↘	16.6	↗↗	3.9	↘↘	2.5	↗
	Scientific excellence (% of publications within 10% most cited) (*)	2018	9.9	↗	13.6	↘	10.8	↗↗	5.9	→	8.0	↗
	PCT patent applications /million population	2018	4.7	↗↗	13.1	↗↗	0.9	↗↗	15.0	↗↗	13.8	↗↗
	PCT patent applications (world share %)	2018	17.4	↘↘	35.4	↘↘	10.3	↗↗	15.7	↗↗	5.9	↗↗

Best — Worst

→	Annual growth between -0.5% and 0.5% (inclusive)
↗ or ↘	Annual growth between 0.5% and 2% or between -0.5% and -2% (inclusive)
↗↗ or ↘↘	Annual growth above 2% or below -2%

Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Unit Common R&I Strategy & Foresight Service – Chief Economist Unit based on Eurostat, OECD, World Bank, DG R&I, DG JRC, Science-Metrix based on Scopus database and PATSTAT, EIS 2021.

Notes: (1) JP figure corresponds to 2019. (2)US figure corresponds to 2017 and CAGR 2013-2017. CN figure corresponds to 2011. JP figure corresponds to 2018. KR figure corresponds to 2018 and CAGR 2015-2018. (3)EU figure corresponds to 2020. CN figure corresponds to 2018 and CAGR: 2011-2018. (4)CAGR: 2014-2021. (5)JP figure corresponds to 2018 and CN to 2017 (6)Trend is defined by calculating the average annual growth (CAGR) between 2010 and the latest available year. (*)Definition: ratio between the number of scientific publications of the country among the top 10 % most cited worldwide by the total number of scientific publications of the country.

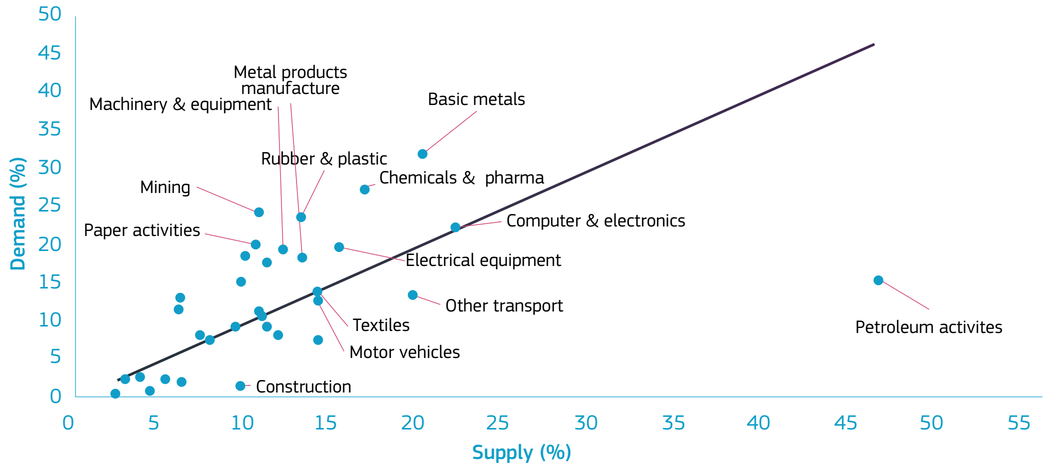
2. Industrial leadership and dependencies

The EU wants to strengthen its technological sovereignty. Technological sovereignty can refer to 'a state's or a supranational union's ambition to shape and direct (parts of) the global technological system' (Edler et al., 2021). Achieving technological sovereignty hinges on the ability to provide the necessary technologies without creating one-sided dependencies, thereby ensuring future economic wellbeing (Edler et al., 2021). The pace at which the technological performance of the EU's main competitors is evolving calls for increasing efforts to boost EU companies' ability to compete globally. The disruptions produced by the COVID-19 pandemic and recent geopolitical tensions have fuelled the debate on reducing strategic dependencies and achieving technological sovereignty.

EU industry plays an important role in realising the EU's global ambitions, safeguarding essential elements of EU strategic value chains (European Commission, 2020c). Production processes and supply chains have become increasingly interlinked in the last decades. The progressive integration of global value chains (GVCs) created huge economic benefits, and challenges. If, on the one hand, GVCs have improved companies' market position by increasing production diversification and reducing costs (OECD, 2020), they also made companies more vulnerable to external demand and supply shocks (European Commission, 2021a). The digital revolution has been accompanied by a gradual increase in market concentration and imbalances in revenue distribution. Already before the outbreak of the coronavirus, some vulnerabilities associated with GVCs became apparent. The increased integration of GVCs yielded important efficiency gains, but failed to prepare the global economy for unforeseen disturbances. It also prevented incorporation of sustainable practices crucial for long-term economic resilience (European Commission, 2021d). The COVID-19 crisis has exacerbated these aspects and reinforced the debate about the trade-off between the costs and benefits of international specialisation in GVCs, which are vulnerable to rapid and widespread global transmission of demand and supply shocks (OECD, 2021).

Reducing strategic dependencies in key technological areas and value chains is necessary to strengthening EU resilience in the post-COVID-19 scenario. Computers and electronics, chemicals and pharmaceuticals, basic metals and electrical equipment are the sectors in which the EU shows the highest foreign dependencies, both in terms of supply and demand (Figure 2.1-1). The EU is a net recipient of foreign direct investment (FDI), representing an important channel of growth for the European economy. FDI helps the EU enhance its competitiveness, create new jobs and open new markets for exporters (European Commission, 2020b). However, the disruptions to GVCs during the COVID-19 pandemic have increased the risks of strategic industries being acquired by foreign investors. This is particularly relevant (but not limited) to the health industry and acquire strategic industrial segments (such as those related to the production of medical equipment and/or research establishments) (European Commission, 2020a). This calls for action intended to screen FDI targeting EU countries. In March 2020, the European Commission published its Communication Coordinated economic response to the COVID-19 Outbreak, in which it calls for increased vigilance regarding FDI by all Member States.

Figure 2.1-1: Downstream and upstream exposure of EU industry to extra EU markets



Science, Research and Innovation Performance of the EU 2022

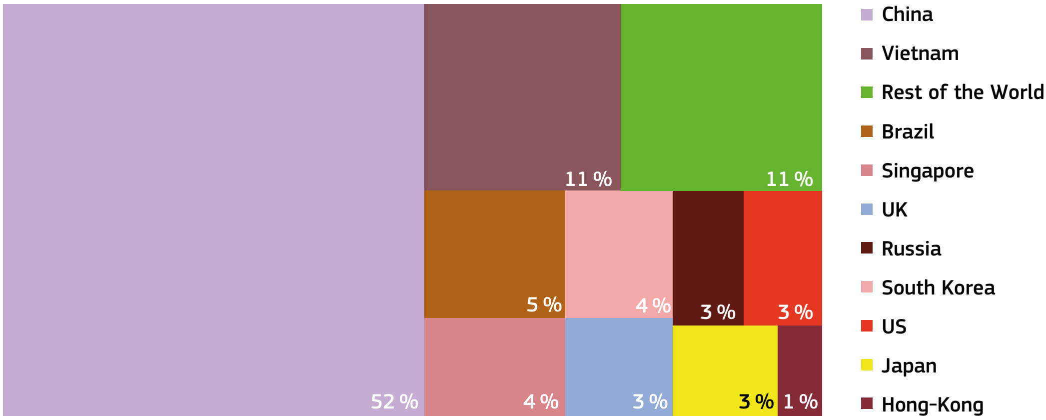
Source: European Commission SWD on Strategic Dependencies and Capacities, based on OECD 2016-AMNE data.
Note: The horizontal axis measures the share of value added for each EU sector that depends on intermediate inputs generated by extra-EU supply chains. The vertical axis measures the share of final demand absorbed by exports to extra-EU countries, for each EU sector.
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-2-1-1.xlsx

The EU is heavily dependent on trading partners in non-EU countries for several strategic products[1]. These include **raw/processed materials (e.g. semiconductors) and chemicals, health and medical products** (such as active pharmaceutical ingredients (APIs), and **renewable energy production, green mobility and digital/electronics** (European Commission, 2021a). China accounts for more than half of the EU's strategic imports related to almost all types of products (Figure 2.1-2).

Vietnam follows with 11 %, exporting to the EU strategic chemicals such as red phosphorus (critical for the production of semiconductors), and tungstates (mostly used in high-temperature industrial applications) (European Commission, 2022c).

1 Dependencies are identified using data on external trade flows for more than 5,000 products. Overall, The EU results to be highly dependent on third countries for 137 products (accounting for about 6% of the extra-EU import value of goods) (European Commission, 2021a).

Figure 2.1-2: Share of EU imports value for identified dependent product[1] (critical materials) by country of origin



Science, Research and Innovation Performance of the EU 2022

Source: European Commission (2021a) based on BACI database.

Note: [1]Data on more than 5 000 products across all industrial ecosystems.

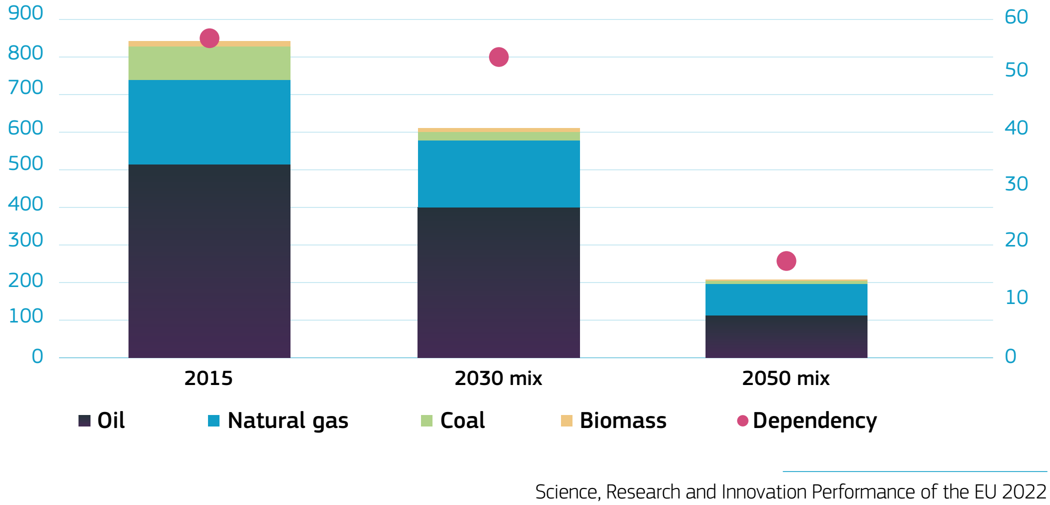
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-2-1-2.xlsx

Furthermore, implementation of the European Green Deal will produce significant changes in the EU's energy system and energy dependencies. Currently, about three-quarters of the EU energy system relies on fossil fuels (Leonard et al., 2021). In 2020, oil accounted for the largest share of gross available energy[2] in the EU, followed by natural gas with 23.7 % (Eurostat, 2022). Coal represented about 10 % of the energy mix, and has been on a decreasing trend since 2015. The importance of renewable energy (including biofuels) is increasing, although it still accounts for only about 17.4 % (Eurostat, 2020).

The successful implementation of the Green Deal will mark a radical change in the EU's energy mix by 2050. From 2030, a considerable reduction in the use of oil, gas and coal is expected, with consequent effects on EU energy imports. Projections for the period 2015-2030 estimate a reduction of between 71 % and 77 % in EU coal imports (Leonard et al., 2021). Similarly, EU imports of oil and natural gas are expected to drop by 23 %-25 % and 13 %-19 % respectively over the same time horizon. This reduction is expected to significantly accelerate in the post-2030 period, towards the 2050 net-zero objective (Figure 2.1-3).

2 Gross available energy represents the quantity of energy necessary to satisfy the energy needs of a country or a region (Eurostat, 2022).

Figure 2.1-3: Evolution of EU energy imports (55% lower emissions in 2030 compared with 1990 and climate neutrality in 2050)

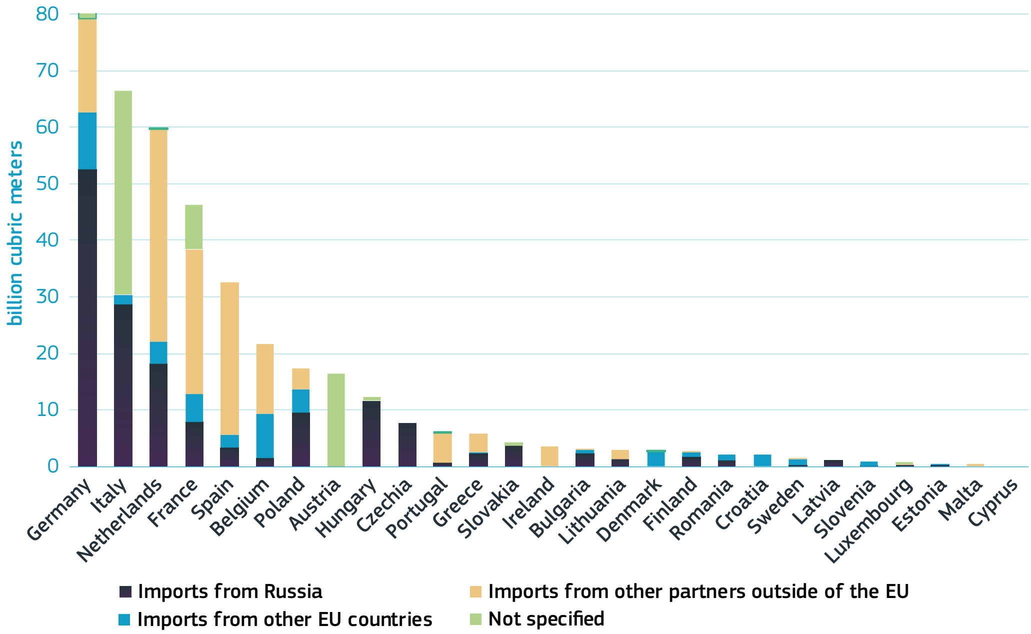


Source: Leonard et al. (2021).
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-2-1-3.xlsx

Changes in the EU energy system induced by the Green Deal are expected to have important geopolitical implications. As the need for oil and gas decreases, EU imports from oil- and gas-producing countries in the EU neighbourhood will also decline (Leonard et al., 2021). This will change EU energy resource trade relationships. Notably, the implementation of the European Green Deal is likely to result in a considerable increase in trade of green electricity and green hydrogen, potentially increasing the importance of North Africa and Middle Eastern countries that benefit from extensive access to solar and wind energy (Leonard et al., 2021).

The achievement of the 2050 climate targets poses important challenges for EU energy security, especially in light of the increasing geopolitical tensions in Europe. The EU imports 92% of the natural gas it consumes. The total 155 bcm imported from Russia accounted for around 45% of the EU's gas imports in 2021 and almost 40% of its total gas consumption (IEA, 2022). In 2020, Germany and Italy imported most of their natural gas from Russia. France and the Netherlands rely less on Russia. Other countries rely almost fully on Russia for their natural gas imports, such as Hungary, Slovakia and Latvia. Portugal and Spain have low dependency while Ireland and Malta have almost no dependency on Russian gas (Figure 2.1-4).

Figure 2.1-4: Total natural gas imports and imports from Russia per country, 2020



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Unit Common R&I Strategy & Foresight Service – Chief Economist Unit based on Eurostat [online code: NRG_TI_GAS__custom_2309441].

Note: The labels on the graph are the share of natural gas imported from Russia over the total natural gas imported (= percentage of dependency to Russian gas).

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-2-1-4.xlsx

Cutting imports from Russia would have a negative impact on the European economy, although the effects would differ across Member States. The need to reduce EU dependency on Russian gas risks forcing European countries to resort to fossil fuels to meet their energy needs, even if other options are possible[3]. This would mean a significant setback for the EU's climate goals, putting into question the successful implementation of the EU decarbonisation process (Ravet et al., 2022).

In this regard, the EU's green transition will strongly rely on the deployment of new and advanced green technologies and on imports of the minerals and critical materials underpinning them.

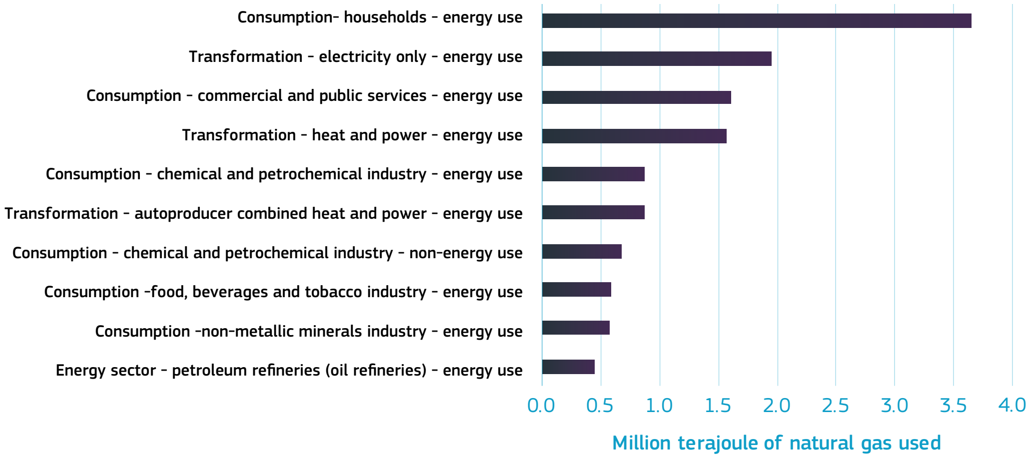
R&I investments and efforts should be strengthened to accelerate the development and deployment of energy efficient and clean energy technologies, thereby securing both EU independence and competitiveness.

3 For example, the IEA has proposed a 10-point plan for the EU to reduce reliance on Russian gas: https://www.iea.org/reports/a-10-point-plan-to-reduce-the-european-unions-reliance-on-russian-natural-gas

Some sectors rely specifically on natural gas, such as energy consumption in buildings and infrastructures (Figure 2.1-5). In these and other sectors, it is critical to foster R&I to ensure more independence. Furthermore, with RePowerEU, the Commission recently proposed an outline of a plan to make Europe independent of Russian fossil fuels well before 2030, starting with gas.

The Communication *Safeguarding food security and reinforcing the resilience of food systems* illustrates the need to address global food security in light of dependencies, with Russia and Ukraine being responsible for 30% of world wheat exports (European commission, 2022f).

Figure 2.1-5: Top 10 sectors in the EU for transformation and consumption of natural gas, 2020



Science, Research and Innovation Performance of the EU 2022

Source: Eurostat [online code: NRG_CB_GAS__custom_2310132].
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-2-1-5.xlsx

3. Technological leadership and vulnerabilities in the context of the green and digital transition

The EU must strengthen its position in technological fields critical to the achievement of EU policy objectives. Six key enabling technologies (KETs) have been identified as essential to boost EU growth and preserve EU leadership: advanced manufacturing, advanced (nano) materials, life-science technologies, micro- and nano-electronics, photonics, AI, and security and connectivity technologies (European Parliament, 2021). The EU ranks

Table 2.1-2: EU global position by Key Enabling Technologies (KETs)

KET	Indicator	Last Available Year	EU	Trend	United States	Trend	China	Trend	Japan	Trend
Advanced Manufacturing	Total Publications (world share %)	2020	24.0	↗↗	11.6	↗↗	25.5	↗↗	2.4	↙
	Top 10% Cited Publications (world share)	2018	22.2	↗↗	18.2	↗↗	25.0	↗↗	1.7	↗↗
	PCT Patent Applications (world share %)	2018	17.8	↗	25.0	↗↗	14.9	↗↗	23.7	↗↗
Advanced Materials	Total Publications (world share %)	2020	15.0	↗↗	8.8	↗↗	34.6	↗↗	3.1	↙
	Top 10% Cited Publications (world share)	2018	12.5	↗↗	12.7	↗	41.8	↗↗	1.9	↙
	PCT Patent Applications (world share %)	2018	18.1	↗	17.2	↗↗	12.3	↗↗	36.1	↗↗
Industrial Biotechnology	Total Publications (world share %)	2020	22.1	↗↗	11.2	↗	20.8	↗↗	2.2	↗
	Top 10% Cited Publications (world share)	2018	14.3	↗	13.4	↙	39.4	↗↗	2.0	↙↙
	PCT Patent Applications (world share %)	2018	18.4	↙	36.9	↗↗	12.5	↗↗	12.2	↗↗
Micro- and Nano-electornic	Total Publications (world share %)	2020	12.9	↙↙	8.7	↙↙	33.9	↙↙	3.0	↙↙
	Top 10% Cited Publications (world share)	2018	24.2	↗↗	15.9	↙↙	22.5	↗↗	1.9	↗↗
	PCT Patent Applications (world share %)	2018	9.8	→	16.3	↙	29.2	↗↗	28.6	↗
Nanotechnolgy	Total Publications (world share %)	2020	14.0	↗↗	9.3	→	34.8	↗↗	3.2	↙
	Top 10% Cited Publications (world share)	2018	13.5	↗	16.5	↙	37.9	↗↗	2.4	↙↙
	PCT Patent Applications (world share %)	2018	17.2	↙↙	32.2	↙↙	16.5	↗↗	13.3	↙↙
Photonics	Total Publications (world share %)	2020	15.5	↗	10.7	↙	33.1	↗↗	3.9	↙
	Top 10% Cited Publications (world share)	2018	11.8	↗	12.2	↙	43.1	↗↗	1.7	↙↙
	PCT Patent Applications (world share %)	2018	15.3	→	19.8	↗	22.2	↗↗	25.5	↗↗

Best — Worst

→	Annual growth between -0.5% and 0.5% (inclusive)
↗ or ↘	Annual growth between 0.5% and 2% or between -0.5% and -2% (inclusive)
↗↗ or ↘↘	Annual growth above 2% or below -2%

Source: DG Research and Innovation - Unit Common R&I Strategy & Foresight Service – Chief Economist Unit based on Science-Metrix using data from Scopus and PATSTAT database.

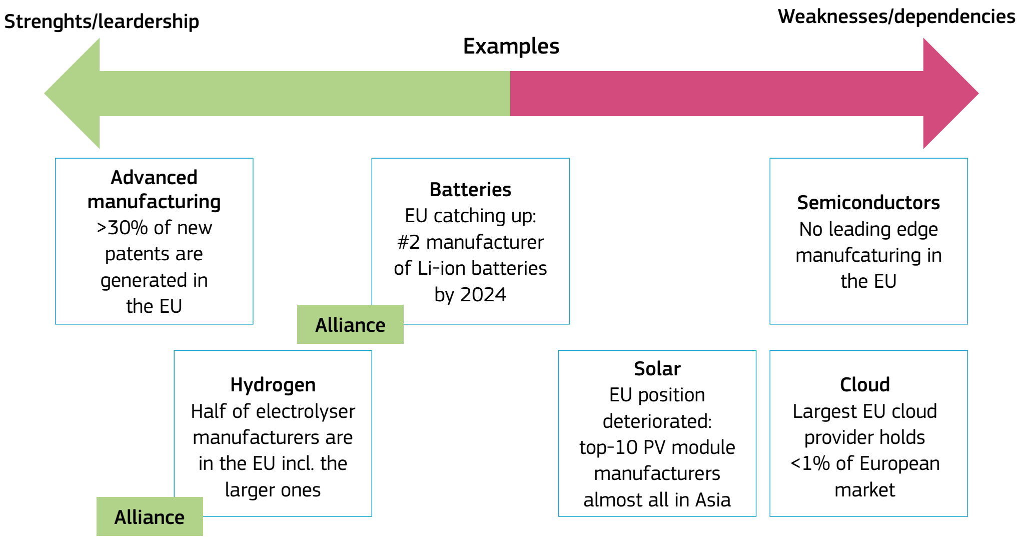
Notes: Trend is defined by calculating the average annual growth rate (CAGR) between 2010 and the latest available year.

second after the US in patent applications in the fields of advanced materials, industrial biotechnologies and nanotechnologies. However, the EU is significantly behind Japan, the US and China in micro- and nano-electronics and photonics, where its share of patent applications is 9.8 % and 15.3 % respectively (Table 2.1-2).

While the EU shows strong performance in advanced manufacturing and advanced materials (either in terms of publications or patent applications), **its technological sovereignty is at risk in other fields, including AI, big data, cloud computing, cybersecurity, robotics and micro-electronics** (European Commission, 2021a). Contributing to this low performance is the **scarce availability of high-quality data** at EU level, and **a lack of digital skills**, both representing important resources for the development and deployment of advanced technologies, in particular AI technologies (European Parliament, 2021). The EU also remains significantly **dependent on foreign suppliers** in micro- and nano-electronics, photonics, and life-science technologies, which exposes it to geopolitical challenges (European Parliament, 2021).

Nevertheless, the EU has tools at its disposal to build capacity. **Industrial alliances, Important Projects of Common European Interest (IPCEIs) and EU funding programmes, notably Horizon Europe, play an instrumental role in supporting EU capacity-building**. Initiatives such as the European Battery Alliance and the European Clean Hydrogen Alliance strengthen the EU's global position in

Figure 2.1-6: EU strategic capacity: strong in some technologies, highly dependent in others



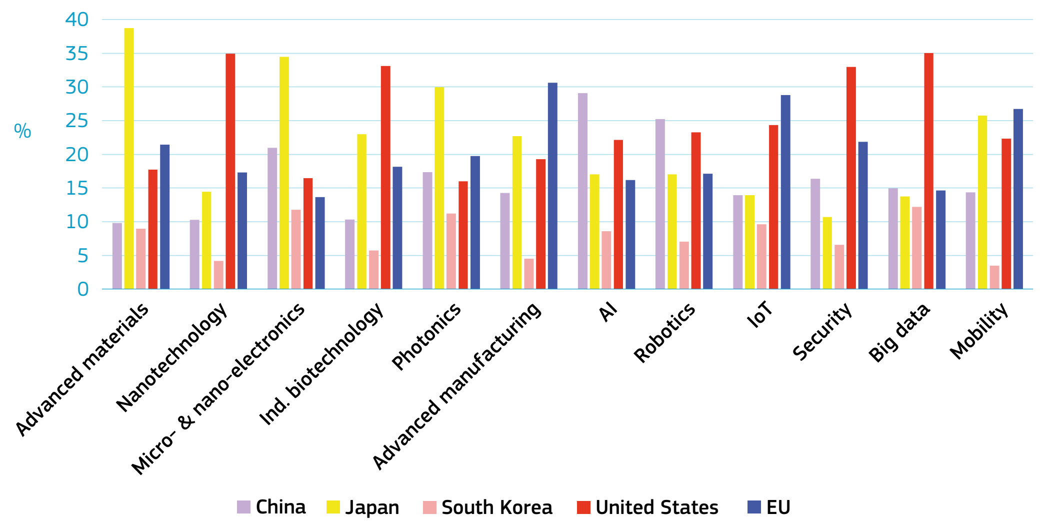
Source: European Commission, DG Internal Market, Industry, Entrepreneurship and SMEs.
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-2-1-6.xlsx

these fields, and mitigate foreign dependencies (Figure 2.1-6). Similarly, Horizon Europe will play a key role in boosting project pipelines in strategic areas, through the implementation of several European partnerships, for instance the Batteries Partnership. IPCEIs also represent an important tool to promote research and innovation activities. Ongoing IPCEIs on batteries and semiconductors are delivering results, and new IPCEIs on cloud computing, hydrogen and a second one on semiconductors are under discussion.

Security and connectivity technologies are critical to EU technological leadership. With the acceleration in digitalisation and the COVID-19 crisis, increasing the resilience and security of connectivity infrastructures has become a pressing issue. The EU is increasing its efforts to build a cybersecure digital economy, building a solid legislative framework to safely process and store digital data and to reduce the risks of human rights violations associated with the development of sensitive cyber surveillance technologies (Csernatoni, 2021) (See Chapter 7.2 – Other framework conditions). Furthermore, the geopolitical tensions resulting from Ukraine's invasion make it even more urgent to further develop strategic capacities in areas such as defence and cyber (European Commission, 2022d). In March 2022, the Commission published a Communication on the European growth model, acknowledging the necessity for European countries to increase their investments in the defence and space industries (including cyber defence) to strengthen EU industrial resilience, critical to fulfilling EU policy objectives.

For Europe to remain an economic power at global level, ensuring leadership in 'green' and 'digital' solutions is essential. While in some areas, such as advanced manufacturing and green technologies, the EU performs well, more efforts are needed to maintain and further build a strong global position in digital technologies. The EU falls significantly behind the US and

Figure 2.1-7: Share of global patent applications in digital/manufacturing technologies, 2018



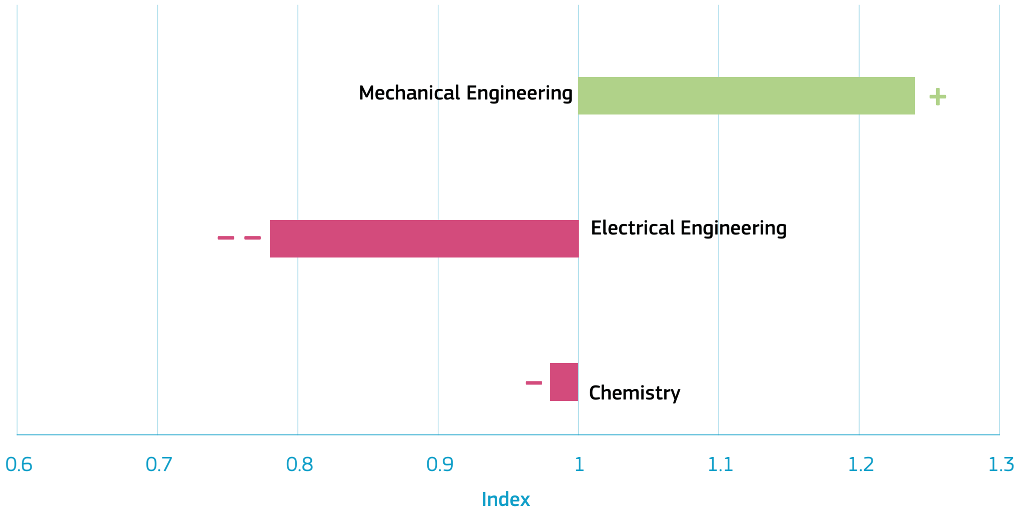
Source: ATI Project.
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-2-1-7.xlsx

struggles to keep up with China in many digital technologies, such as nanotechnologies, AI and big data (Figure 2.1-7). Current levels of funding will likely be inadequate for the EU to match or overtake the US and China in such key sectors, calling for increasing resources to strengthen the European research and innovation capacities.

The EU is highly specialised in the field of mechanical engineering. In 2018, the EU reported a specialisation index[4] well above 1 in the field of mechanical engineering (Figure 2.1-8). As reported in Table 2.1-3 the EU ranks first in patent applications in almost all related sub-fields, with a share of patent applications ranging between 29% and 34.5%. The only sub-fields in which the EU does not rank first are those related to textile and paper machines, and thermal processes where Japan is first with a share of patent applications of 25.5% and 29.3%, respectively.

In contrast, the EU reports a lower degree of specialisation in the fields of chemistry and electrical engineering. In the chemistry sector, the EU reports a specialisation index close to 1, and a strong relative performance in terms of patent applications. Ranking second in most of the chemistry sub-fields, the EU leads in chemistry engineering, environmental technology, and food chemistry with a share of patent applications of 26%, 23.6% and 24.2%, respectively (Table 2.1-3). Electrical engineering

Figure 2.1-8: EU Specialisation Index in patent applications, by technological field, 2018



Science, Research and Innovation Performance of the EU 2022
Source: DG Research and Innovation - Unit Common R&I Strategy & Foresight Service – Chief Economist Unit based on Science-Metrix using data from PATSTAT database.
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-2-1-8.xlsx

4 The specialisation index here is defined as a country's share of EPO patents in a particular technology field over the country's share in all patent fields, relative to the world share. An index of 0 indicates that the country does not hold any patent in a given sector. An index equal to 1 indicates no specialisation, i.e. the country's share in the sector equals its share in all fields. A value greater than 1 signals a positive specialisation.

is the technological field in which the EU has the lowest specialisation index (less than 0.8). When compared with other economies, the EU underperforms in all the relevant sub-fields, positioning itself well below China and the US, especially in the areas related to digitalisation, such as audio-visual technology, telecommunications, computer technology, and digital communication (Table 2.1-3). For digital communication technologies, the gap with China is particularly striking (40.3% of patent applications against 14.3%).

The EU has some strengths in the field of semi-conductors, but remains weak in

Table 2.1-3: PCT patent applications (world share %) in 2018, by technological field

	Technological Field	Indicator	Last Available Year	EU	Trend	United States	Trend	China	Trend	Japan	Trend	South Korea	Trend
Chemistry	Basic materials chemistry	PCT Patent Applications (world share %)	2018	20.6	↙	24.0	↙	9.7	↗↗	23.3	↗↗	5.8	↗↗
	Biotechnology	PCT Patent Applications (world share %)	2018	19.0	↙	35.2	↗	13.9	↗↗	13.0	↗↗	6.1	↗↗
	Chemical engineering	PCT Patent Applications (world share %)	2018	26.0	↗	23.2	↗	13.4	↗↗	14.3	↗↗	6.5	↙↙
	Environmental technology	PCT Patent Applications (world share %)	2018	23.6	↙	19.0	↙	19.0	↗↗	14.5	↙	7.6	↗↗
	Food chemistry	PCT Patent Applications (world share %)	2018	24.2	↙	17.3	↙↙	9.7	↗↗	18.5	↗	11.6	↗↗
	Macromolecular chemistry, polymers	PCT Patent Applications (world share %)	2018	21.9	↗	18.2	↗	10.9	↗↗	33.1	↗↗	8.1	↗↗
	Materials, metallurgy	PCT Patent Applications (world share %)	2018	22.0	↗	14.9	↗	13.0	↗↗	29.7	↗↗	9.4	↗↗
	Micro-structural and nano-technology	PCT Patent Applications (world share %)	2018	21.2	↗	30.8	↙	13.5	↗↗	15.6	↗↗	4.0	↙↙
	Organic fine chemistry	PCT Patent Applications (world share %)	2018	21.8	↙↙	28.7	↙	15.1	↗↗	12.7	↙	5.3	↗↗
	Pharmaceuticals	PCT Patent Applications (world share %)	2018	17.5	↙	39.8	↗↗	8.8	↗↗	8.6	↗	8.2	↗↗
	Surface technology, coating	PCT Patent Applications (world share %)	2018	20.1	↗↗	16.9	→	11.9	↗↗	33.2	↗↗	7.8	↗↗
Electrical Engineering	Analysis of biological materials	PCT Patent Applications (world share %)	2018	26.9	↗↗	20.2	↙	25.0	↗↗	3.9	↗↗	8.4	↗↗
	Audio-visual technology	PCT Patent Applications (world share %)	2018	10.1	↙	11.8	↗	40.1	↗↗	22.2	↗↗	5.8	↗↗
	Basic communication processes	PCT Patent Applications (world share %)	2018	17.8	↗	24.2	↗	18.7	↗↗	24.2	↗↗	4.0	↗↗
	Computer technology	PCT Patent Applications (world share %)	2018	9.6	→	30.3	↗↗	31.7	↗↗	12.1	↗	5.6	↗↗
	Control	PCT Patent Applications (world share %)	2018	17.2	↗↗	19.3	↗↗	24.9	↗↗	23.9	↗↗	3.4	↗↗
	Digital communication	PCT Patent Applications (world share %)	2018	14.3	↗	24.4	↗↗	40.3	↗↗	5.3	↗↗	6.6	↗↗
	Electrical machinery, apparatus, energy	PCT Patent Applications (world share %)	2018	20.6	↗↗	12.9	↗	18.5	↗↗	28.2	↗↗	8.9	↗↗
	IT methods for management	PCT Patent Applications (world share %)	2018	7.3	↗↗	27.0	↗↗	29.0	↗↗	13.3	↗↗	8.5	↗↗
	Measurement	PCT Patent Applications (world share %)	2018	23.2	↗	22.6	↗↗	14.9	↗↗	20.2	↗↗	4.9	↙↙
	Medical technology	PCT Patent Applications (world share %)	2018	17.8	↗	35.6	↗↗	10.2	↗↗	14.8	↗↗	5.7	↗↗
	Optics	PCT Patent Applications (world share %)	2018	12.8	↗↗	17.4	↗↗	26.6	↗↗	27.7	↗↗	6.5	↗↗
	Semiconductors	PCT Patent Applications (world share %)	2018	9.4	↙↙	18.8	↙	27.8	↗↗	27.7	→	8.6	↗↗
	Telecommunications	PCT Patent Applications (world share %)	2018	13.7	↙	21.9	↗	31.3	↗↗	14.0	↗	9.2	↙↙
Mechanical Engineering	Engines, pumps, turbines	PCT Patent Applications (world share %)	2018	32.4	↙	15.5	→	11.0	↗↗	23.4	↗↗	3.6	↗↗
	Handling	PCT Patent Applications (world share %)	2018	29.1	↗	17.4	↗	13.6	↗↗	20.0	↗↗	4.8	↙↙
	Machine tools	PCT Patent Applications (world share %)	2018	30.7	↗	14.1	↗	15.6	↗↗	23.4	↗↗	4.6	↗↗
	Mechanical elements	PCT Patent Applications (world share %)	2018	34.5	↗	14.8	↗	11.7	↗↗	23.8	↗↗	3.4	↗↗
	Other special machines	PCT Patent Applications (world share %)	2018	30.5	↗↗	21.6	↗↗	9.6	↗↗	17.7	↗↗	4.9	↗↗
	Textile and paper machines	PCT Patent Applications (world share %)	2018	24.5	→	21.2	↗↗	13.2	↗↗	25.5	↗↗	4.3	↗↗
	Thermal processes and apparatus	PCT Patent Applications (world share %)	2018	23.9	↙	13.5	↙	14.9	↗↗	29.3	↗↗	5.5	↗↗
	Transport	PCT Patent Applications (world share %)	2018	34.4	↗↗	12.8	↗↗	13.9	↗↗	24.0	↗↗	3.6	↙↙

Best | | | | Worst

→	Annual growth between -0.5% and 0.5% (inclusive)
↗ or ↘	Annual growth between 0.5% and 2% or between -0.5% and -2% (inclusive)
↗↗ or ↘↘	Annual growth above 2% or below -2%

Source: DG Research and Innovation - Unit Common R&I Strategy & Foresight Service – Chief Economist Unit based on Science-Metrix using data from PATSTAT database.

Notes: Trend is defined by calculating the average annual growth rate (CAGR) between 2010 and the latest available year.

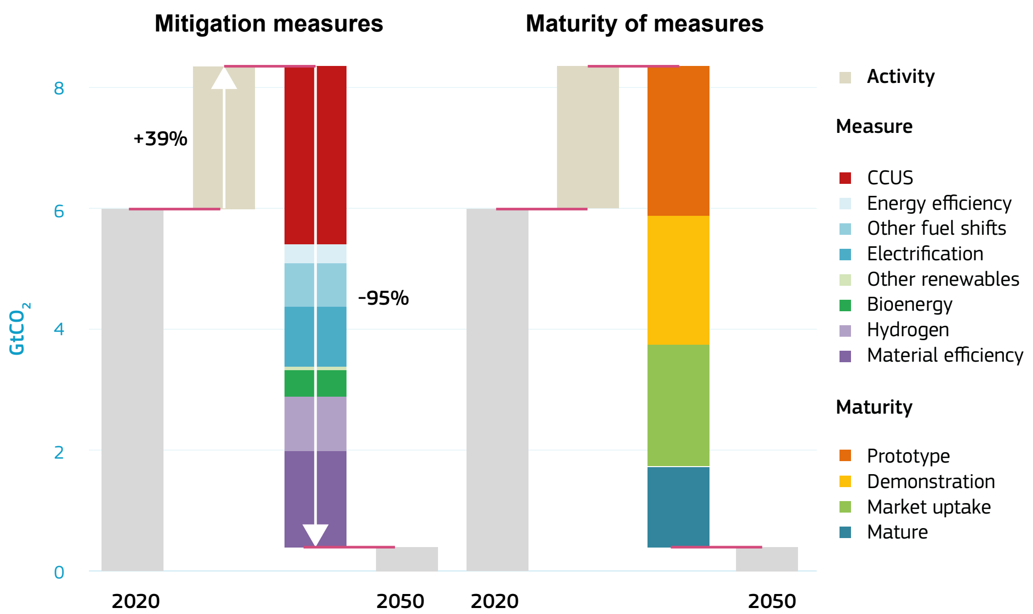
terms of total patent applications, with a share of 9.4% against 27.8% and 18.8% for China and the US, respectively (Table 2.1-3). The EU is strong in R&D in the field of semi-conductors, hosting world-leading research and technology organisations (RTOs) pioneering the production techniques of advanced chips (European Commission, 2022b). The EU is also specialised in the design of specific chips for power electronics and in industrial segments related to equipment manufacturing and raw materials, crucial for the production of advanced chips. Nevertheless, the EU accounts for only 10% of the global revenue share of semi-conductor chips (European Commission, 2022b).

Global demand for semi-conductor chips is expected to double by 2030 as a result of the acceleration in the digital transition. Given the key role played by semi-conductor chips in the production of digitalised products, they represent a strategic area in the race towards technological sovereignty (European Commission, 2022b). In its Communication of February 2022, the European Commission proposed the **European Chips Act**, to create a resilient and competitive EU semi-conductor ecosystem, reducing excessive dependencies and strengthening the EU's capacity to react to future supply chain disruptions (European Commission, 2022b). In this regard, **the Russia-Ukraine conflict is expected to accelerate the reduction of industrial dependencies in strategic sectors through economic restructuring**. Potential closer alignment between China and Russia will profoundly modify the exchange of energy, raw materials, industrial parts and goods between the West, China, and Russia (Simchi-Levi and Haren, 2022). EU industries, including semi-conductors, automotives, and medical equipment, will need to **reorganise and re-diversify their supply chains**, while fostering local supply chain strategies. In this direction, both the US Chips Act and the European Chips Act are examples of government efforts to reduce dependence on Asia in strategic technological sectors.

Such a shift in the focus of global trade policy, from mutual economic benefits of open trade policies to geopolitical considerations limiting interdependence, will likely have implications for innovation and economic growth. As an example, Góes & Bekkers (2022) estimate that a hypothetical decoupling of the global trading system into a US- and a China-centric bloc, would reduce total welfare in 2040 (compared to a baseline without decoupling) by about 5% worldwide, around 4% in the West and 10% in the East. Low-income regions would be the most affected, as they benefit most from the positive technology spillovers of trade. By cutting ties with richer and innovative markets, less productive countries are likely to shift their supply chains towards lower-quality inputs, which, in turn, induce less innovation. In contrast, richer western countries, even if they were to suffer welfare losses, would see their innovation path less affected (Ravet et al., 2022).

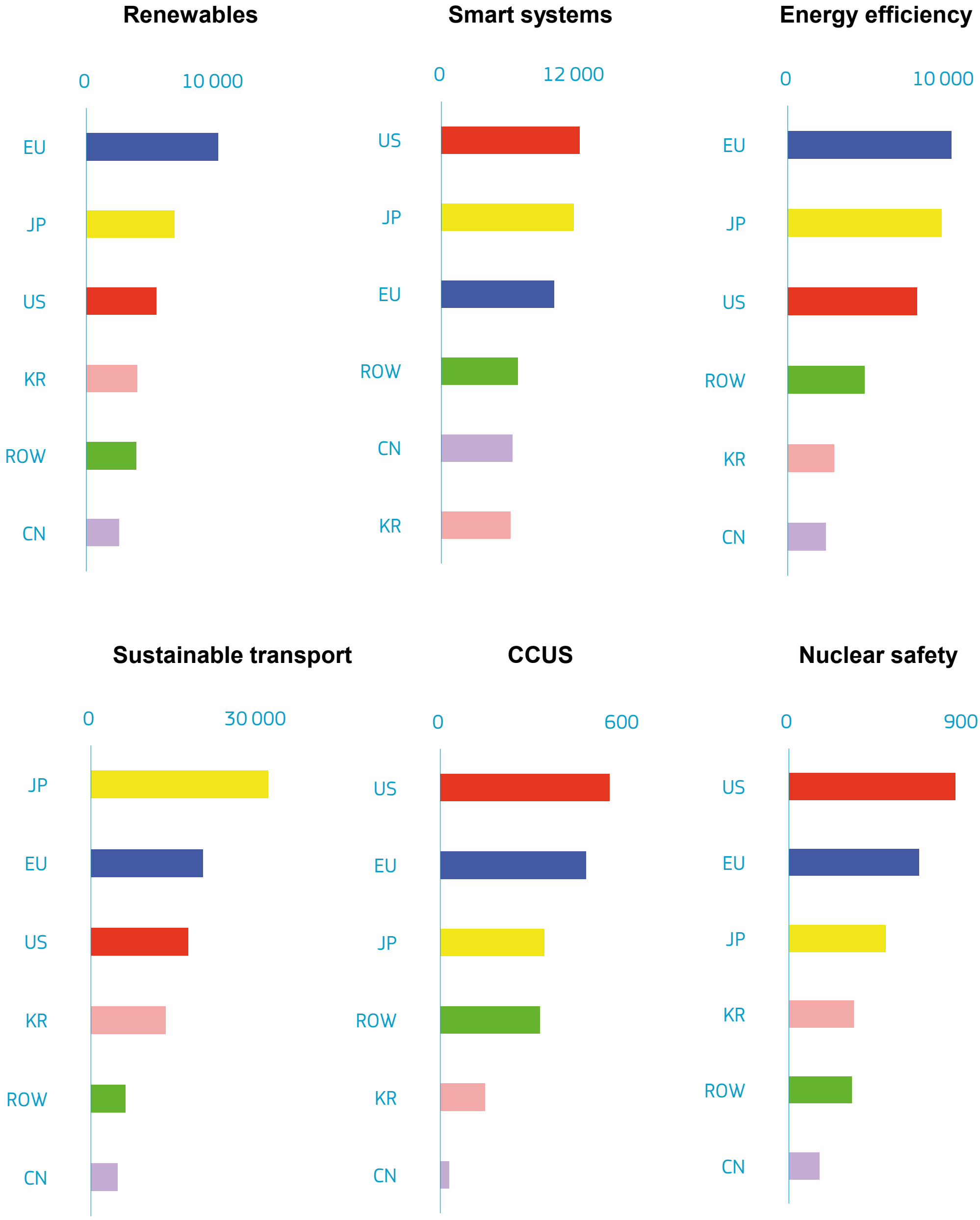
An acceleration in clean energy innovation is necessary to meet the EU net-zero emission target. The net-zero emissions by 2050 scenario (NZE), presented by the IEA (2021), investigates the actions needed for the global energy sector to achieve net-zero CO_2 emissions by 2050. The successful decarbonisation of the global energy system over the next decades hinges on the use of different technologies (mostly related to energy efficiency, electrification, renewables, hydrogen and hydrogen-based fuels, bioenergy, and carbon capture, utilisation and storage (CCUS)), and the ability to make market behaviours more sustainable (IEA, 2021). The industrial sector represents the second-largest source of CO_2 emissions globally. In 2020, industrial CO_2 production amounted to around 8.4 Gt (Figure 2.1-9). Meeting the net-zero target by 2050 would require a 95 % reduction of global CO_2 emissions from heavy industry, relying on the implementation of technologies currently under development (Figure 2.1-9) (IEA, 2021). As such, **ensuring that innovative clean energy technology will reach maturity in the next decade is among the main challenges in the EU's race towards climate neutralit**y (European Commission, 2022a).

Figure 2.1-9: Global CO_2 emissions in heavy industry and reductions by technological options (mitigation measures) and technology maturity level, in the net-zero emissions scenario of the IEA



Source: IEA, Net zero by 2050 (2021).
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-2-1-9.xlsx

Figure 2.1-10: EU positioning in high-value patents in the energy union R&I priorities (total over 2005-2018)

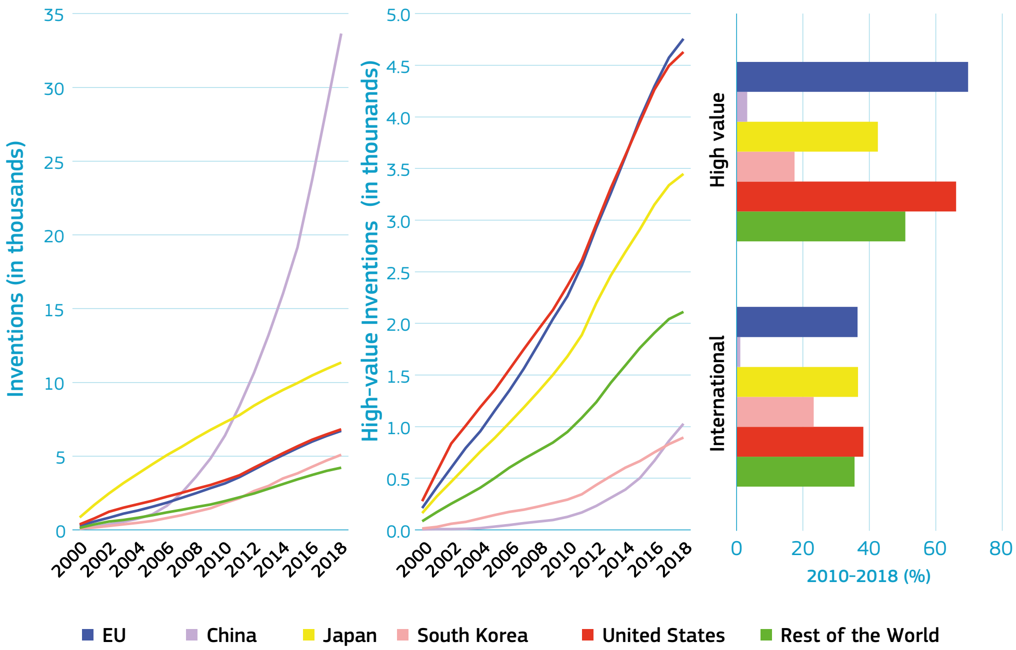


Source: European Commission (2020), Progress on competitiveness of clean energy technologies, COM(2020) 953 final.
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-2-1-10.xlsx

Worldwide innovation output in low-carbon technologies has been increasing over time. At global level, the number of patents in low-carbon technologies has been rising over the past 20 years (EPO-IEA, 2021). Nevertheless, the pace at which new low-carbon energy patents have been issued has significantly decreased over time. Between 2000 and 2013, patents related to low-carbon technologies reported an annual growth rate of 12.5 %, while annual growth rates reported in recent years are about three-quarters lower. This calls for intensified policy actions to accelerate clean energy innovation (EPO-IEA, 2021).

The EU leads the international scene in terms of clean energy innovation. The share of EU patents in low-carbon technologies has remained around 28 % over the period 2010-2019 (EPO-IEA, 2021). Japan and the US follow closely with a share of 25 % and 20 % respectively, while China lags significantly behind with only 8 % of the world share. Europe is particularly strong in the rail and aviation sectors, while Japan leads in electric vehicles, batteries and hydrogen. The US performs particularly well in technological fields related to biofuels and carbon capture, while China's greatest strength remains the ICT sector (EPO-IEA, 2021). When looking at green, high-value inventions (i.e. inventions protected by more than one patent office), the EU leads in areas related to renewable energies and energy efficiency (Figure 2.1-10). Furthermore, over the last 5 years, the EU has given home to around 25 % of the top 100 companies with high-value patents in clean energy (European Commission, 2022e).

Figure 2.1-11: Trends in green inventions in energy-intensive industries, accumulated over 2000-2018 and 2010-2018



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Source: European Commission (2020), Progress on competitiveness of clean energy technologies, COM(2020) 953 final.

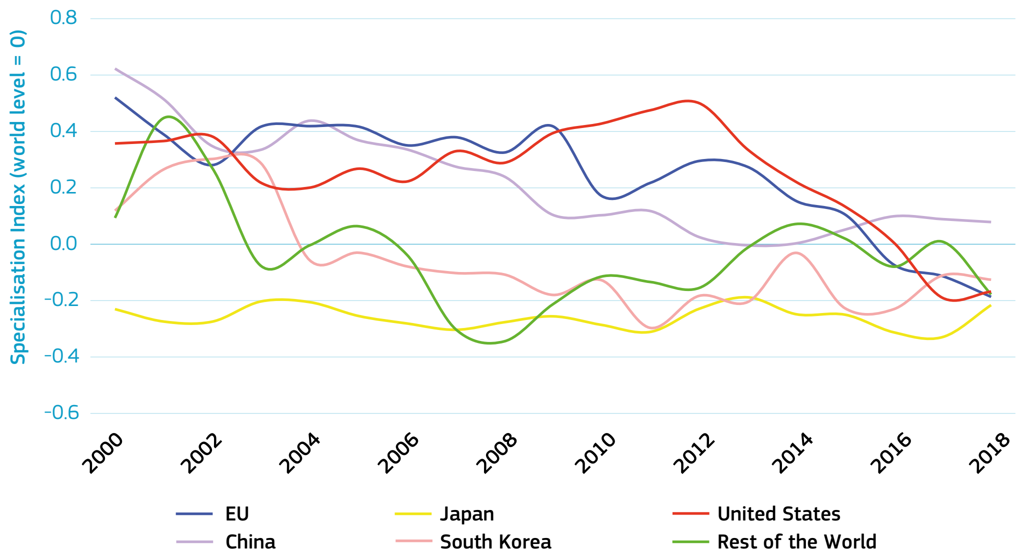
Note: Cumulative inventions (left), high-value inventions (centre), and share of high-value and international inventions (i.e. patent applications protected in a country different to the residence of the applicant) (right) for major economies in the period 2010-2018.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-2-1-11.xlsx

The decarbonisation of energy-intensive industries (EIIs)[5] is critical to the achievement of the EU's climate goals. Between 2010-2018, 17% of total green inventions implemented in the production and processing of goods came from EIIs (European Commission, 2022e). China ranks first in terms of overall inventions in EIIs. Nevertheless, the EU and the US lead in terms of high-value inventions[6], followed by Japan (Figure 2.1-11).

China surpassed the EU and US in terms of specialisation in EIIs. The EU and US reported the highest specialisation indexes in green innovations for EIIs until 2015 (Figure 2.1-12). Since then, both have lost their relative advantage in the field (with the specialisation index falling below the world average), and have been outperformed by China since 2016 (Figure 2.1-12).

Figure 2.1-12: Specialisation index in green inventions for energy intensive industries[(1)]



Science, Research and Innovation Performance of the EU 2022

Source: European Commission (2020), Progress on competitiveness of clean energy technologies, COM(2020) 953 final - Joint Research Centre elaboration based on EPO Patstat.

Note: [(1)]The figure reports the share of inventions relevant to EIIs within Climate Change Mitigation Technologies (CCMTs), for the production and processing of goods.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-2-1-12.xlsx

5 Energy Intensive industries include cement, chemicals, ceramics, steel and fertilisers industries

6 i.e. inventions protected by more than one patent office

4. Conclusions: R&I in a globally connected world

The COVID-19 crisis highlighted the importance for the EU to strengthen its resilience, and seize its role as a leader in the post-recovery global framework (European Commission, 2020a). In the context of the Green Deal implementation, it is essential for the EU to secure access to critical materials necessary for the production of advanced green technologies. In doing so, the EU must find a balance between its technological ambitions and the need to reduce its dependencies on international competitors. **Import portfolio diversification** is one of the possible strategies for the EU to mitigate reliance on a single supplier, along with the **implementation of recycling and substitution strategies** (Leonard et al., 2021). Furthermore, the EU has long relied on its **soft power to shape international standards and norms**. Leveraging the single market and its ability to build and enforce a solid regulatory framework, the EU has been able to exercise considerable influence at global level (UNESCO, 2021). In this regard, EU trade policy represents an important tool through which the EU can promote sustainability practices by setting both digital and green global standards (European Commission, 2020a). Thanks to its strong regulatory power, the EU confirms its key role in driving the transition towards a more circular economy and its capacity to lead by example, enforcing environmental norms and practices emulated by other regions (European Commission, 2020a).

Reducing EU strategic dependencies requires diversifying supply, notably by reshoring the production of some inputs, and increasing circularity. The EU would need to step up **commercialisation of its research results**. Although the EU is still strong in the production of scientific knowledge, challenges persist in translating scientific results into market products (see Chapter 6.3 - Innovation output, societal and market uptake and knowledge valorisation). Firms outside the EU often benefit from the EU's scientific results and successfully commercialise them (European Parliament, 2021). Furthermore, **the EU must play a leading role in the revival of multilateral governance structures**. In this regard, research and innovation will play a crucial role in realising the EU's global ambitions.

Furthermore, the Russian invasion of Ukraine has revealed the vulnerabilities of the EU energy sector. The new emphasis reducing EU dependency on Russian gas requires strengthening R&I investments and efforts to accelerate the development and deployment of energy efficient and clean energy technologies. Achieving this will **secure the green transition and the independence and competitiveness of the EU**. R&I policy can play a major role in shaping the direction of innovations and the portfolio of energy technologies. **The innovation policy of the future will have to be developed in a complex triangle of transformation policies, competitiveness policies and technology sovereignty considerations**. However, in doing so, the EU should avoid sacrificing international welfare gains through free trade and division of labour for shortsighted technology sovereignty policies driven by domestic interest groups (Edler et al, 2021).

To build 'a stronger Europe in the world', the European Commission aims to **reinforce the role of the EU as a leading actor to foster international cooperation**. With the Communication *Europe's global approach to cooperation in R&I*, the European Commission reaffirms EU's commitment to leading by example, preserving openness in international R&I cooperation, while promoting a level playing field and safeguarding fundamental EU values. Building on the lessons learned from the COVID-19 pandemic, **the new EU strategy on international R&I cooperation calls for a reinvigorated multilateral approach**, essential for achieving the SDGs and for establishing mutually beneficial relationships with international partners to deliver solutions to green, digital, health, social and innovation challenges (European Commission, 2021b). To strengthen the EU's open strategic autonomy, it is necessary to leverage the EU's capacity to develop and take up strategic technologies, thereby increasing EU competitiveness and avoiding future dependencies.

Box 2.1-1: Foreign interference

Research and innovation activities have become increasingly internationalised. Scientific research is a collaborative process, leveraging the relationships that researchers and scientists have built across disciplines over time. Nevertheless, research activities also embed a high level of competition between different actors. Europe's higher education institutions (HEI) and research performing organisations (RPO) have a strong record of internationalisation (European Commission, 2022a).

The EU strategy on international cooperation in R&I needs to balance the benefits of research collaboration with the risks related to foreign interference. International interference '*occurs when activities are carried out by, or on behalf of, a foreign state-level actor, which are coercive, covert, deceptive, or corrupting and are contrary to the sovereignty, values, and interests of the EU*' (European Commission, 2022a). Foreign interference may pursue different objectives, from the unlawful retrieval of information, to securing the power to influence decisions in favour of the foreign actor (European Commission, 2022a). Given the essential role played by HEIs and RPOs in fostering international research, and supporting knowledge creation and diffusion, the European Commission published a set of guidelines and best practices to support these entities in safeguarding their fundamental values (including academic freedom, integrity and institutional autonomy, as well as the protection of researchers, students and staff). As such, the Commission's *Staff Working Document on Foreign Interferences* informs HEIs and RPOs on the measures at their disposal to mitigate the risks of foreign interference and encourage the adoption of existing best practices.

References

Confraria, H., Ferreira, V. H., & Godinho, M. M. (2021), *Emerging 21st century technologies: is Europe still falling behind?*

Csernatoni, R. (2021), *The EU's Rise as a Defense Technological Power: From Strategic Autonomy to Technological Sovereignty,* Carnegie Europe.

EIB (2021), *Intangible investment, innovation and digitalisation*, in: Shaw, C., Barron, K., Lefort, J.S. (Eds.), European Investment Bank Investment Report: Building a Smart and Green Europe in the COVID-19 Era. European Investment Bank, doi:www.doi.org/10.2867/904099.

EPO-IEA (2021), *Patents and the energy transition Global trends in clean energy technology innovation*, April 2021.

European Commission, Progress on competitiveness of clean energy technologies, COM(2020) 953 final, *ERA industrial technology roadmap on low-carbon technologies - For energy-intensive industries.*

European Commission (2020a), 2020 Strategic Foresight Report – Charting the course towards a more resilient Europe, COM(2020) 493 final.

European Commission (2020b), Guidance to the Member States concerning foreign direct investment and free movement of capital from third countries, and the protection of Europe's strategic assets, ahead of the application of Regulation (EU) 2019/452 (FDI Screening Regulation), C(2020) 1981 final.

European Commission (2021a), Strategic dependencies and capacities, SWD (2021) 352 final.

European Commission (2021b), Global Approach to Research and Innovation, Europe's strategy for international cooperation in a changing world, COM(2021) 252 final.

European Commission, Directorate-General for Research and Innovation, (2021c), *Science, research and innovation performance of the EU, 2020 : 11 recommendations for a fair, green and digital Europe*, Publications Office, https://data.europa.eu/doi/10.2777/520136.

European Commission, Directorate-General for Research and Innovation, Dixson-Declève, S., Bria, F., Charveriat, C. (2021d), *Transformation post-COVID: global value chains : harnessing innovation to protect and transform the backbone of global trade*, Publications Office, https://data.europa.eu/doi/10.2777/360812.

European Commission, Directorate-General for Research and Innovation (2022a), *Tackling R&I foreign interference: staff working document*, https://data.europa.eu/doi/10.2777/513746.

European Commission (2022b), A Chips Act for Europe, COM(2022) 45 final.

European Commission (2022c), Strategic dependencies and capacities: second stage of in-depth reviews, SWD (2022) 41 final.

European Commission (2022d), Towards a green, digital and resilient economy: our European Growth Model, COM(2022) 83 final.

European Commission, Directorate-General for Research and Innovation (2022e), *ERA industrial technology roadmap on low-carbon technologies - For energy-intensive industries*.

European Commission (2022f), Safeguarding food security and reinforcing the resilience of food systems, COM(2022) 133 final.

European parliament (2021), S*tudy on Key enabling technologies for Europe's technological sovereignty*, EPRS - European Parliamentary Research Service Scientific Foresight Unit (STOA).

Góes, C., & Bekkers, E. (2022), *The Impact of Geopolitical Conflicts on Trade, Growth, and Innovation*, arXiv preprint arXiv:2203.12173.

IEA (2021), *Net Zero by 2050 A Roadmap for the Global Energy Sector.*

IEA (2022), *A 10-Point Plan to Reduce the European Union's Reliance on Russian Natural Gas*, IEA Publications.

Leonard, M., J.Pisani-Ferry, J. Shapiro, S. Tagliapietra and G. Wolff (2021), *The geopolitics of the European Green Deal*, Policy Contribution 04/2021, Bruegel.

OECD (2020), *Shocks, risks and global value chains: insights from the OECD METRO model*, https://www.oecd.org/trade/documents/shocks-risks-gvc-insights-oecd-metro-model.pdf.

OECD (2021), *Global Value Chains: Efficiency and Risks in the Context of COVID-19*, https://www.oecd.org/coronavirus/policy-responses/global-value-chains-efficiency-and-risks-in-the-context-of-covid-19-67c75fdc/.

Ravet, J., Di Girolamo, V., Mitra, A., Peiffer-Smadja O, Canton E, Hobza A. (2022), *EU research and innovation and the invasion of Ukraine : main channels of impact*, European Commission, Directorate-General for Research and Innovation, https://data.europa.eu/doi/10.2777/54321.

Simchi-Levi and Haren (2022), 'How the War in Ukraine Is Further Disrupting Global Supply Chains', *Harvard Business Review*, https://hbr.org/2022/03/how-the-war-in-ukraine-is-further-disrupting-global-supply-chains.

UNESCO (2021), UNESCO *Science Report: the Race Against Time for Smarter Development*. S. Schneegans, T. Straza and J. Lewis (eds). UNESCO Publishing: Paris.

CHAPTER
2.2

ZOOM IN – REGIONAL ANALYSIS

KEY FIGURES

1 region
concentrates 9 % of total EU business R&I expenditure

43 %
of ICT patents filed in Europe are from 10 European regions

More than 3/4
of collaborations on patents were intraregional over 2012-2016

9 in 10
M&A innovative deals in Europe target a company in a more-developed region

56 of 73
less-developed EU regions increased their contribution to total EU scientific publications over 2010-2018

KEY QUESTIONS WE ARE ADDRESSING

- What are the R&I trends across EU regions?
- What is the regional specialisation pattern of R&I activities in the EU?
- What is the relationship between productivity and innovation at the regional level?

KEY MESSAGES

What did we learn?

- R&D expenditure, scientific publications and patent applications are concentrated in more-developed regions.
- The least-innovative regions recorded low and declining growth in patent applications over 2013-2018, putting into question technology production convergence across EU regions.
- Regions with lower or moderate innovation capacity rely more on the public sector for R&D investments than those with strong innovation capacity.
- About 75 % of patent collaborations in the EU have been intra-regional and only 3-5 % interregional across national borders.
- Patenting activity in health, ICT and climate mitigation technologies is highly concentrated in only a few EU regions.
- While most regions in central and eastern Europe (CEE) experienced significant catching up in productivity, much of the growth has been fuelled by a combination of factors such as rapid expansion of global supply chains and foreign direct investment. There has been a smaller role for innovation-driven productivity growth.
- Many transition regions are characterised by low R&I performance and have also not done well in productivity growth.

What does it mean for policy?

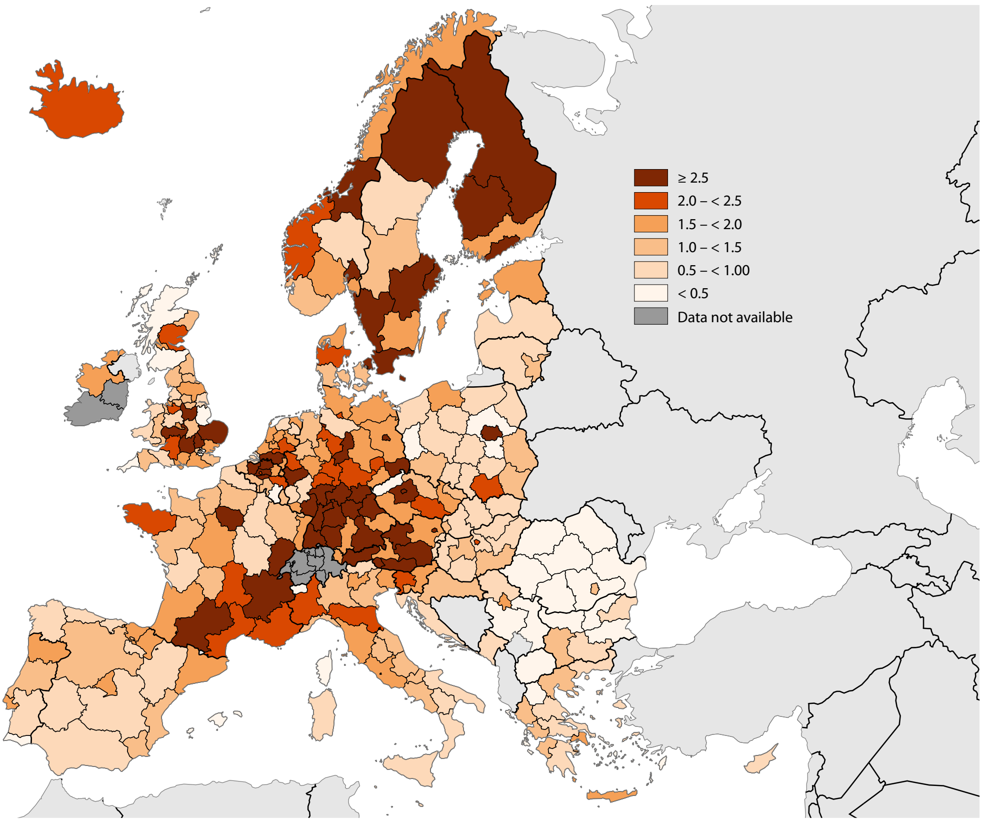
- Promoting innovation diffusion and transfer in less-developed and transition regions to trigger economic dynamism would help to close the innovation divide and increase the competitiveness of the EU as a whole.
- European R&I policies could target different types of innovation (product, process, social, ecological, etc.) according to territorial specificities, local needs and assets.
- Cross-border collaboration on R&I activities could optimise efforts and accelerate joint learning for the twin transition.
- Complementarities in R&I activities between EU regions in terms of industrial specialisation and knowledge transfer could be also strengthened at EU level to ensure a smooth integration of the latest research inputs and inventions across regions and countries.
- To maintain growth, regions, in particular less-developed ones, could shift to a knowledge-based and innovation-driven growth model in order to continue catching up.

1. EU regional disparities and trends in R&I

State of play of R&I dynamics at regional level

There is a pronounced regional concentration of R&D investments in the EU (Figure 2.2-1). In particular, western and northern Europe feature high R&D intensity, although well-performing regions can be found in other parts of Europe, too. Within countries, there is a concentration of R&D expenditure per capita in a few regions, typically capital regions or regions with large urban agglomerations. In the last decade, some regions with high R&D intensity continued to increase their R&D expenditures further. Only some regions with lower R&D intensities managed to catch up, and the gap with the top-performing regions remains significant.

Figure 2.2-1: R&D intensity (Gross R&D investment as % of GDP), 2019 or latest year available



Science, Research and Innovation Performance of the EU 2022

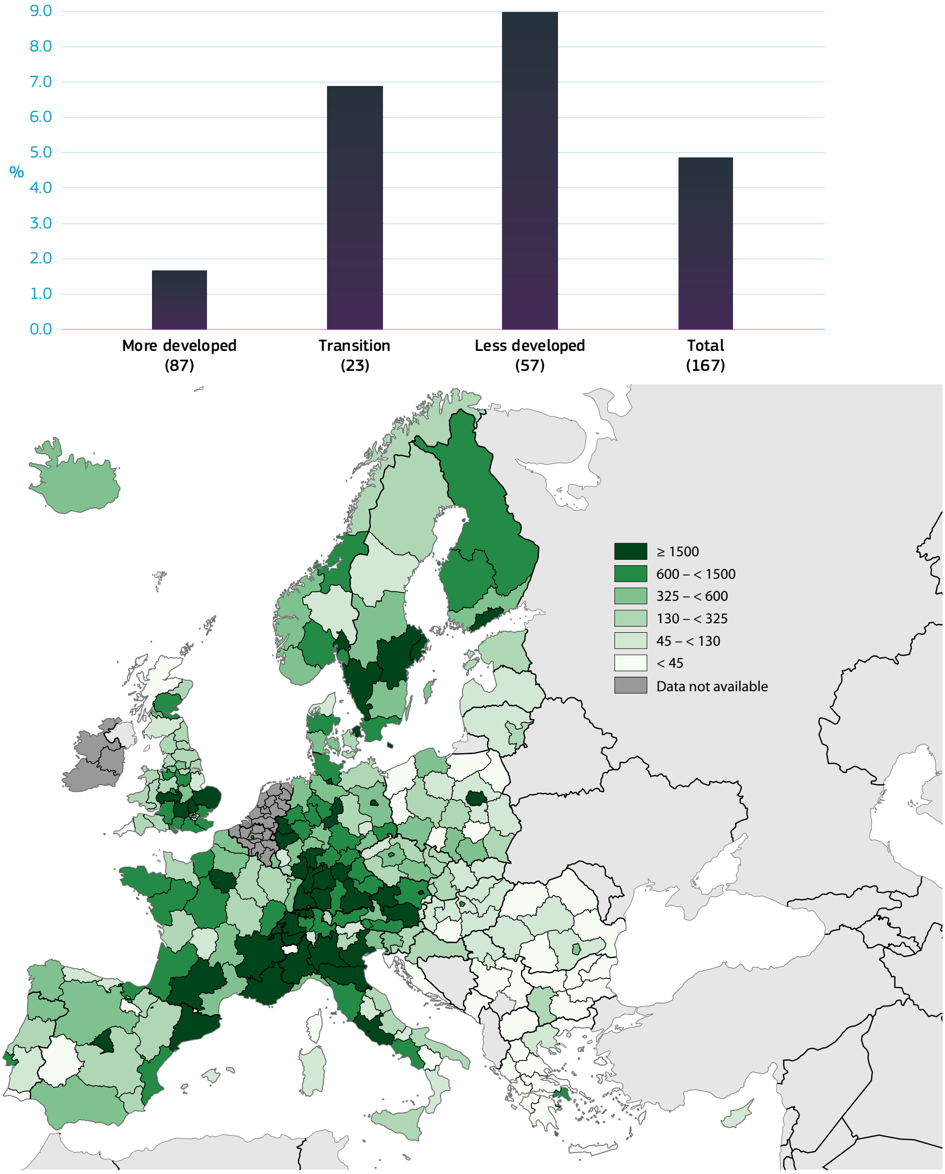
Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Eurostat (online data code: rd_e_gerdreg).

Note: BE, 2017; FR, 2013; NL, 2012; IE, ME, UK, NO, 2018.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-2-2-1.xlsx

1 R&D investments as percentage of GDP

Figure 2.2-2: Business R&D investment in million euros, 2019 or latest year available, and Business R&D intensity annual growth 2010-2019 by type of region



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Eurostat (online data code: rd_e_gerdreg).

Note: No data for BE and NL; FR, 2013; UK, ME, 2018; AT, BG, DK, DE, EL, ES, HR, IT, HU, PL, PT, SI, RO, FI, SE, IS, NO, MK, 2019; CZ, EE, LV, CY, LU, MT, SK, RS, 2020.On the map, no data for FR, NL, BE, and per-capita GDP as the criteria adopted by regional Cohesion Policy in the 2014-2020 EU programming period has been used to classify regions in most developed (more than 90% of EU28 average per-capita GDP), transitioning (between 70% and 90%) and less developed regions (less than 70%).

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Business R&D expenditures are key in boosting the competitiveness of regions, promoting local job creation and reducing the EU's innovation gap (European Commission, 2014, 2017a and 2020). **Business R&D expenditures are also geographically concentrated, although they are sizeable in some transition regions**[3]. The latest data suggest a persisting concentration of business R&D expenditure in more-developed central locations (Figure 2.2-2).

An example is Baden-Württemberg, which has about 2 % of the EU population but boasts 9 % of the EU's business R&D. In many regions of eastern and southern Europe, R&D expenditures have also increased, linked to a structural shift to more knowledge intensive activities and expected returns on R&D investment, but also linked to an increase in public R&D boosted by EU funds. Furthermore, the ultimate objective is to accompany the transition of those regions and workers most affected by globalisation and industrial developments and to facilitate the transition to a low-carbon and circular economy (JRC, 2018). Over the past decade, less-developed regions have shown a higher annual growth in terms of business R&D intensity, in particular in Cyprus, Poland, Bulgaria and Greece, than in transition and more-developed regions.

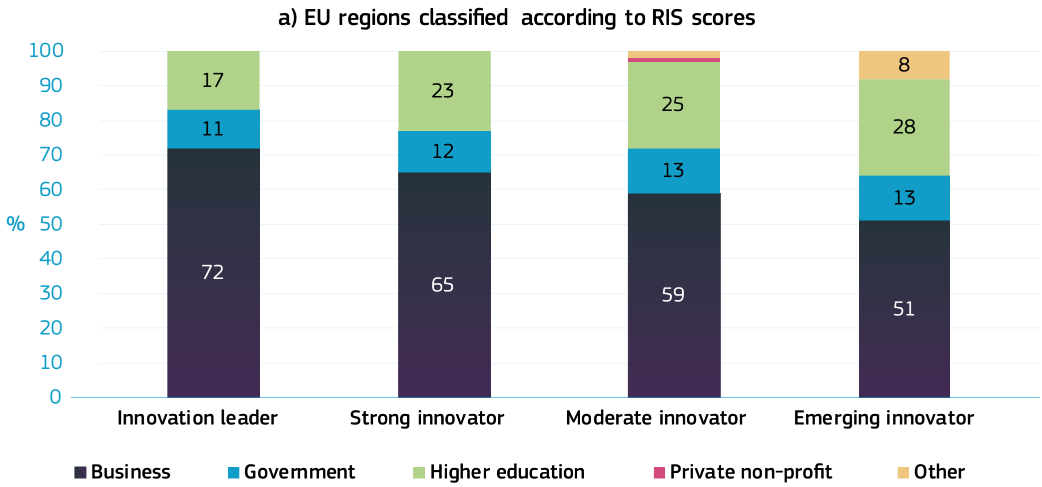
The regional impact of the COVID-19 pandemic on R&D investments has been driven by sectoral specialisation of regions. Throughout the crisis, many of the top R&D-investing companies in Europe active in, e.g., the information and communication and the health sectors have actually increased their R&D spending. Others, such as the automotive and the aerospace and defence sectors, have reduced it (JRC, 2021). As a result, we might expect R&D investments in regions to be affected by the crisis according to local specialisation in their industrial landscape.

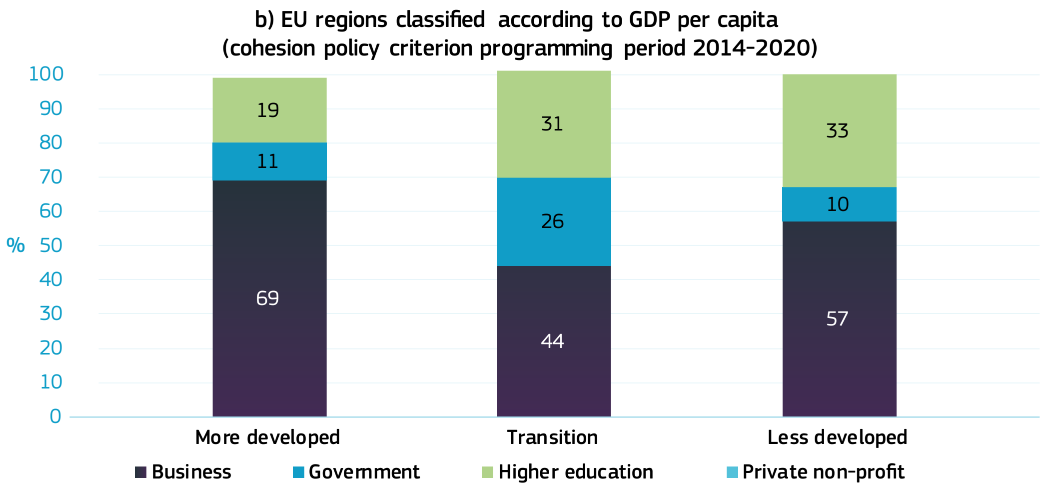
Regions with lower innovation capacity tend to rely relatively more on government and higher education sectors for R&D investments, whereas strong/leading innovators benefit more from business-enterprise R&D investments. Interestingly, it seems that innovation leaders are also characterised by the highest share of R&D investment from the government, but with less from the higher education sector (Figure 2.2-3). When classifying regions according to their GDP per capita, it seems that regions in transition (i.e. those between 70 % and 90 % of the EU average) have relatively low business R&D investment: only 44 %, compared to 69 % for more-developed regions and 57 % for less-developed regions. The development of R&D activities in transition regions relies relatively more on the government sector than it does in other regions as the share of R&D investments made by the government in transition regions is close to 26 %, compared to 10 % in less-developed regions and 11 % in more-developed regions.

CHAPTER 2.2

3 GDP per capita as the criteria adopted by regional Cohesion Policy in the 2014-2020 EU programming period has been used to classify regions as more-developed (more than 90 % of EU-28 average GDP per capita), transitioning (between 70 % and 90 %) and less-developed regions (less than 70 %).

Figure 2.2-3: Share of R&D investment per sector across EU regions classified according to RIS scores, 2019 and per GDP per capita (cohesion policy criterion programming period 2014-2020)





Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Eurostat and the Regional Innovation Scoreboard.

Note: No data for BE, FR and NL. GDP per capita as the criteria adopted by regional Cohesion Policy in the 2014-2020 EU programming period has been used to classify regions as more-developed (GDP per capita more than 90 % of EU-28 average), transitioning (between 70 % and 90 %) and less-developed regions (less than 70 %).

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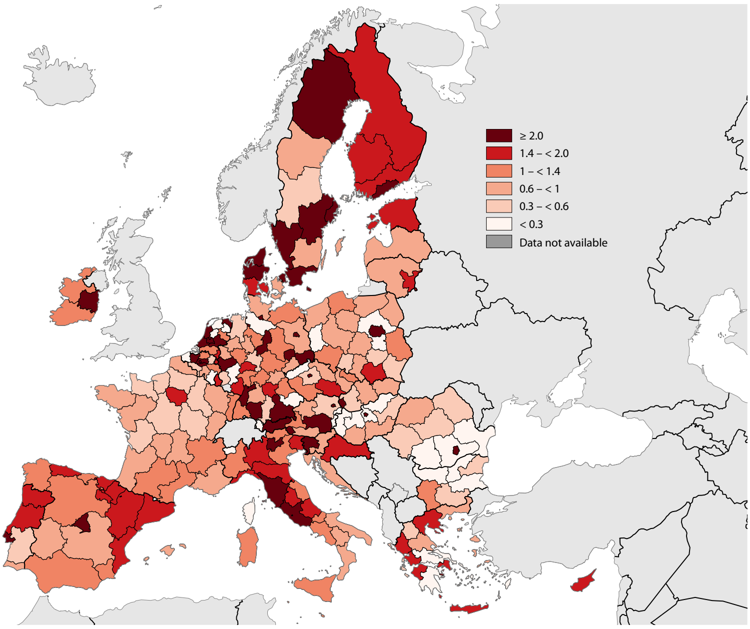
Scientific production measured by publications shows a relatively dispersed pattern across EU regions, with signs of convergence across regions. There are important regional differences in scientific publications per capita in the EU, although there is not as clear a divide as, for example, in overall innovation capacity (Figure 2.2-4). Moreover, many lagging regions, mostly in eastern and southern Europe, showed an improvement in scientific-output performance over 2010-2020. In contrast, the European regions that have the highest rate of scientific publications per capita did not record increases and in some cases, their relative contribution to the EU total number of scientific publications declined over the decade. Besides, the dispersion between European regions increased sharply during 2020, possibly due to the impact of the COVID-19 crisis on scientific production (see Chapter 1 – COVID-19, recovery and resilience).

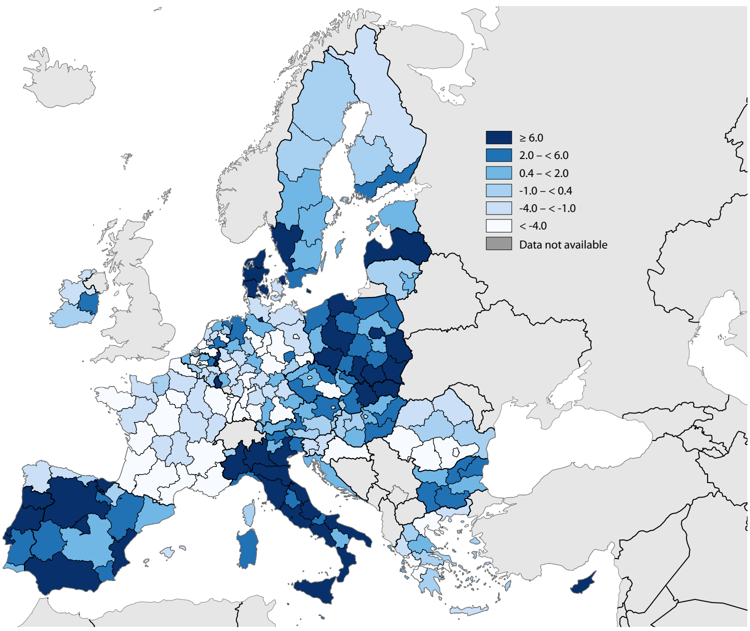
However, the production of high-quality publications continues to be highly concentrated in a relatively few regions. Hence, the 10% top cited publications are mostly produced in western Europe, with a dominance of Dutch and Nordic regions (Figure 2.2-5). Central and eastern European regions still show lower performance. If the positive trend in quantity of scientific publications translates into higher quality, we could experience some catching up in the future. However, this catching-up process tends to take longer and is conditional upon overall improvement in framework conditions for scientific production.

Figure 2.2-4: Scientific publications per 1000 inhabitants, 2020 and evolution of the contribution to EU total publications between 2010 and 2020

a) Scientific publications per 1000 inhabitants, 2020



b) Evolution of the contribution[1] to EU total publications between 2010 and 2020



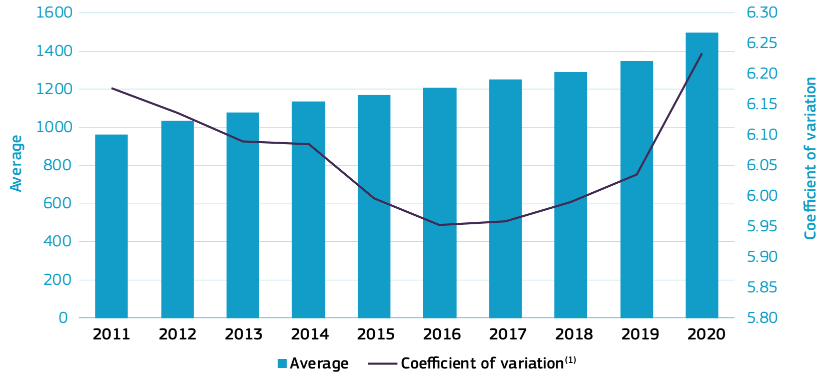
Science, Research and Innovation Performance of the EU 2022

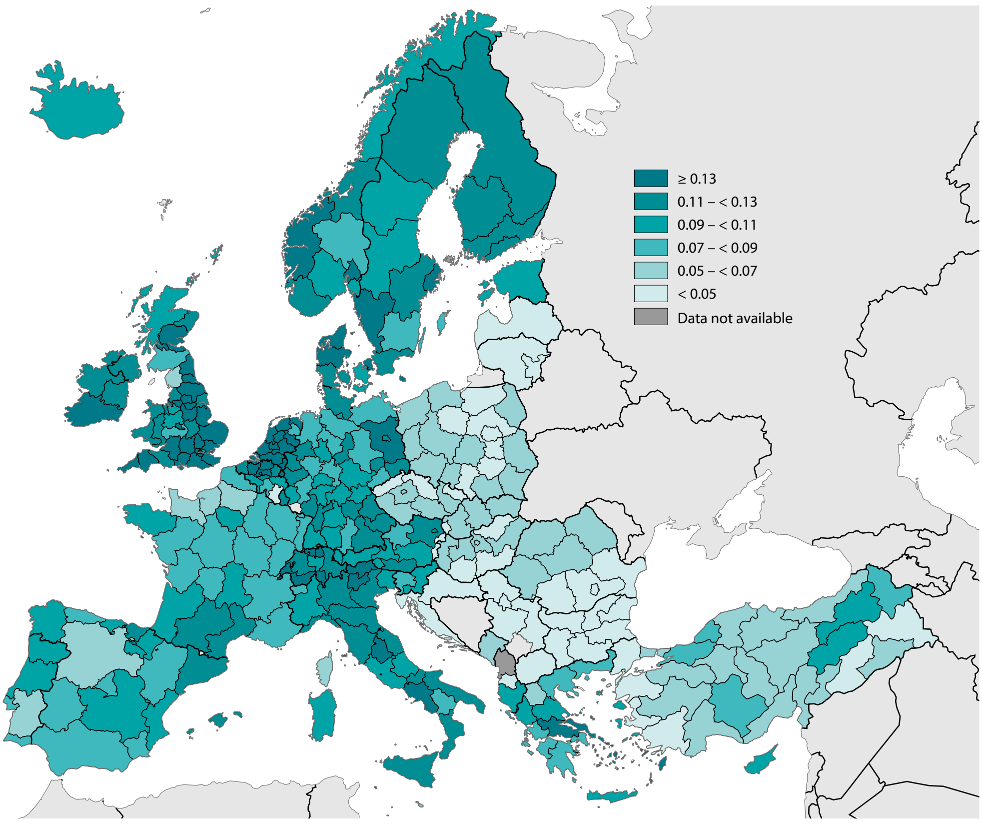
Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Science-Metrix using Scopus Database.

Note: [1]The contribution of each region to the EU total has been calculated for both 2010 and 2020 and regions have been allocated in 6 different classes according to the percentage increase of this share between both years. Fractional counting used.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-2-2-4.xlsx

Figure 2.2-5: Percentage of highly cited publications (top 10%) in 2018 per NUTS2 level (map) and evolution of regional disparities in publications per million inhabitants (graph)





Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Science-Metrix using Scopus database.

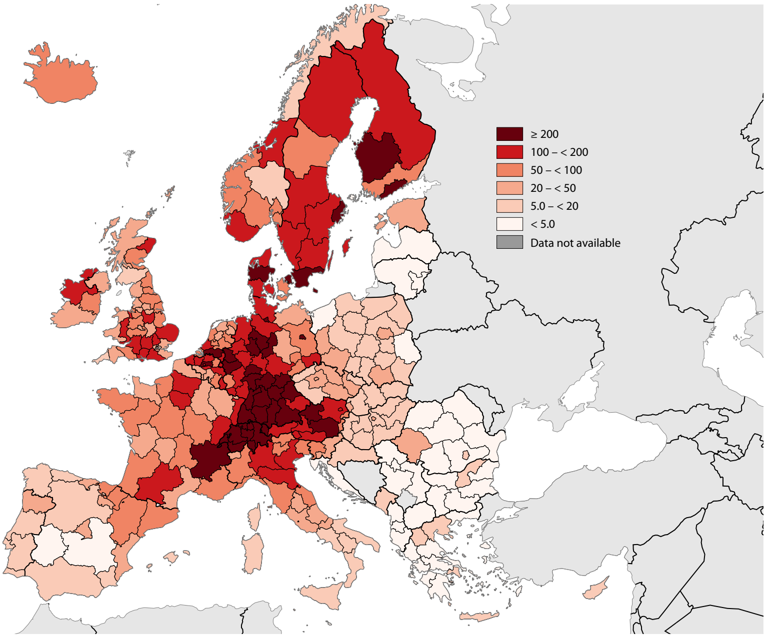
Note: (1)The coefficient of variation (CV) is the ratio of the standard deviation to the mean, which shows the extent of variability of data in a sample in relation to the average value. The higher the coefficient of variation, the greater the level of dispersion around the mean.

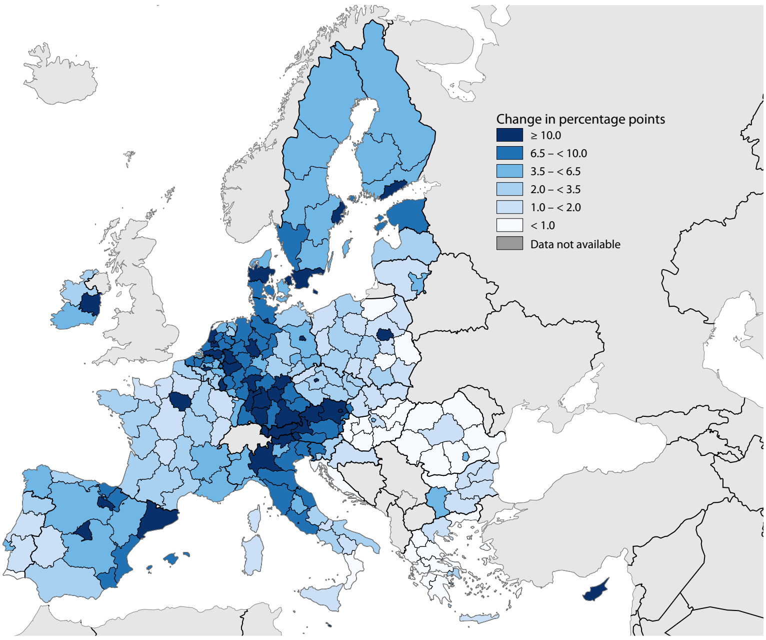
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-2-2-5.xlsx

The regional pattern of technological production is driven by the existing innovation divide. The divide between regions located in western and northern Europe and those in central and eastern Europe, as well as with some southern countries, continues to be pronounced. The technological output as measured by patents is still concentrated in regions with a high share of manufacturing and with headquarters of large companies, such as southern Germany, Austria, Denmark and the Rhone-Alpes region in France or some capital city regions. However, a look at **trends across European regions reveals that some regions in eastern and southern Europe have increased their contribution to EU total patent applications over the past decade** (Figure 2.2-6), in terms of European Patent Office (EPO) applications. Some of the least innovative regions, in Portugal and Greece, have increased their contribution to EU total patent applications over 2010-2018. However, the regions that experienced the highest increases in their contribution to EU total patents are in Austria, Belgium and Germany, which are already among the top innovative regions.

Overall, the pattern for **design and trademark applications is similar to that for patent applications**. However, the emergence of specialisation in less technologically intensive fields covered by designs and trademarks could point to growth in service innovation or design-based innovation in lagging regions. Better performance in designs can be found, for example, in the Polish regions of Małopolskie (PL21) and Wielkopolskie (PL41), while trademarks play a prominent role in Andalucia (ES61) and in many Bulgarian regions (Figures 2.2-7 and 2.2-8). Bulgaria already outperforms the EU average in design and trademark applications per unit of GDP.

Figure 2.2-6: Total patent applications to the EPO (fractional counting) in 2018 per million inhabitants at NUTS 2 level (red map) and evolution of the contribution of each region to EU total patents applications to the EPO between 2010 and 2018 (blue map)





Science, Research and Innovation Performance of the EU 2022

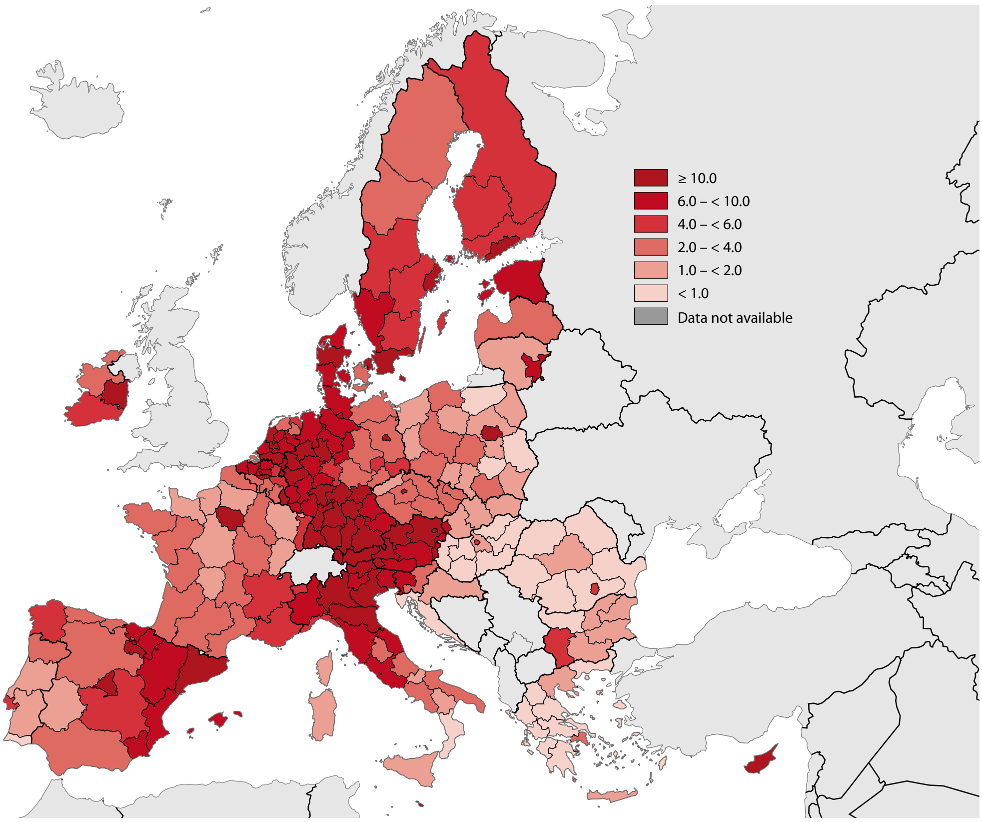
Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Science-Metrix using EPO REGPAT database.

Note: [1]The contribution of each region to the EU total has been calculated for both 2010 and 2018 and regions have been allocated in 6 different classes according to the percentage increase of this share between both years.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-2-2-6.xlsx

Many less-developed regions are too far away from the technological frontier and do not have the necessary capabilities, including human capital, to make effective use of additional R&D investments (Aghion and Griffith, 2008). These types of area, which are often economically lagging-behind, are regarded as less able to generate, import and absorb knowledge for innovations (Rodríguez-Pose, 2001). For example, in many regions in southern countries, such as Greece and Spain, around 20% of the labour force are employed in science and technology, with the exception of the capital regions (Figure 2.2-9). In stark contrast, this share is more than 40% in some northern European regions in Finland and

Figure 2.2-7: Cumulated volume of trademark applications (fractional counting) at NUTS2 level, 2003-2020

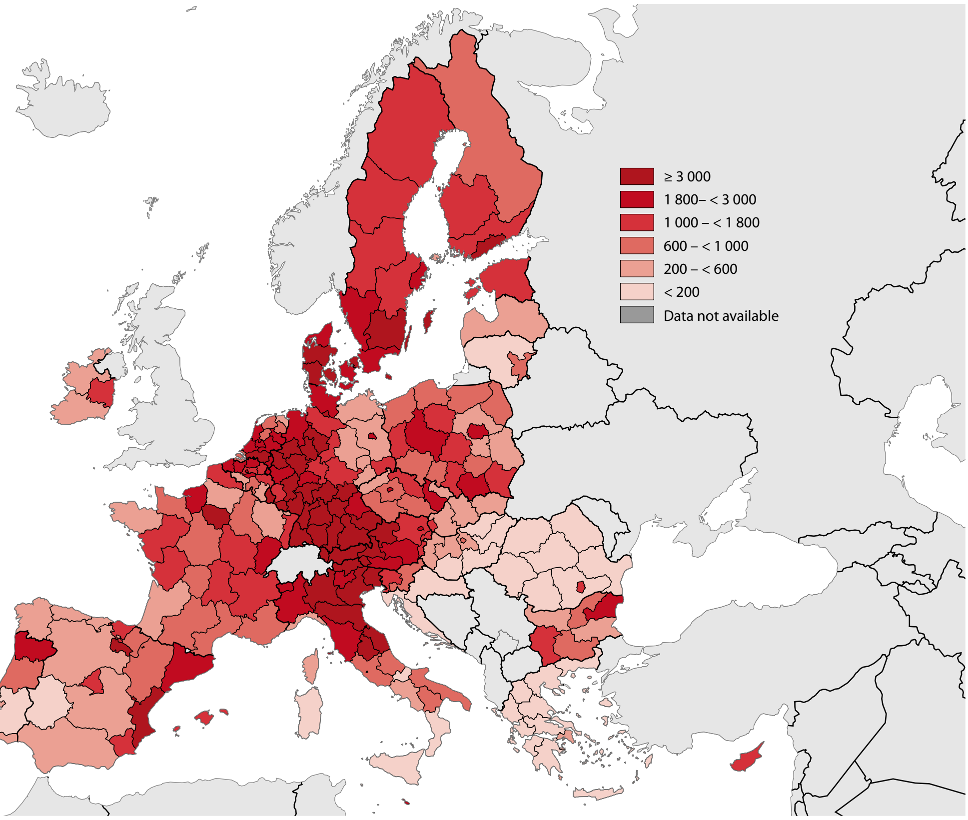


Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Science-Metrix using EUIPO database.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-2-2-7.xlsx

Figure 2.2-8: **Cumulated volume of design applications (fractional counting) at NUTS2 level over 2003-2020**



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Science-Metrix using EUIPO database.

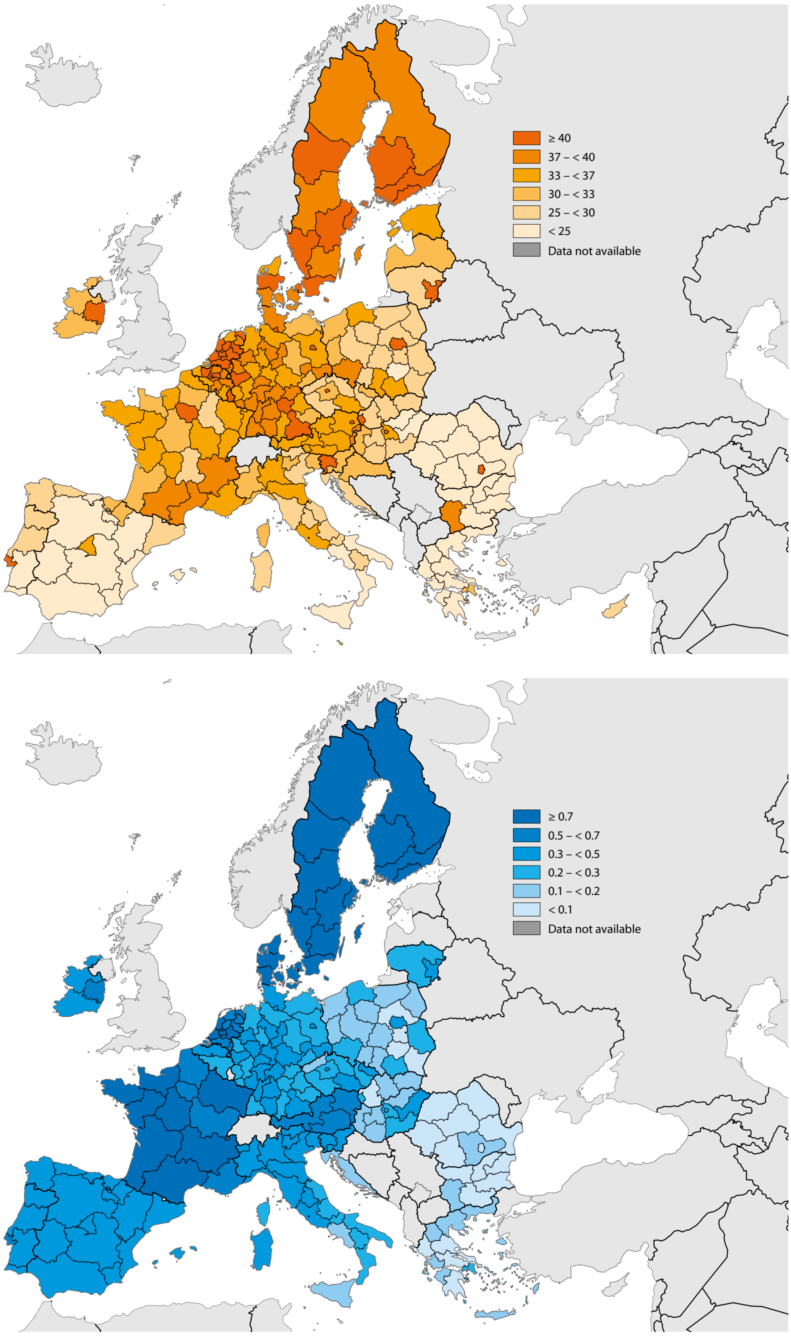
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-2-2-8.xlsx

Sweden or in the Netherlands, which have specialised in science and technology. It also appears that leading regions in terms of human capital devoted to science and technology have strengthened their position, such as regions in France, Sweden and Finland. On the other hand, the catching-up process has not been very strong in some countries, such as Greece or Spain, although other regions in Portugal, Poland and Austria have witnessed an increase of 11-20% since 2020.

The regional innovation divide

Agglomeration externalities are a key driver of geographical concentration of innovation. For example, spatial proximity allows firms to share specialised suppliers or to facilitate recruitment amongst a shared labour pool (Klepper, 2010; Ponds et al., 2010). Individuals and firms also benefit from localised knowledge spillovers as proximity facilitates the diffusion and adoption of innovation (Audretsch, 2003; Sonn and Storper, 2008). Better social interaction and networking opportunities in more densely populated regions facilitate the exchange and diffusion of new knowledge

Figure 2.2-9: Percentage of people employed in Science and Technology in 2020 over the total labour force across regions (orange map) and share of population engaged in Lifelong learning in 2021 at NUTS 2 level (blue map)



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation 2021 – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Eurostat and Regional Innovation Scoreboard.

Note: Lifelong learning is defined as the share of population aged 25-64 enrolled in education or training aimed at improving knowledge, skills and competences.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-2-2-9.xlsx

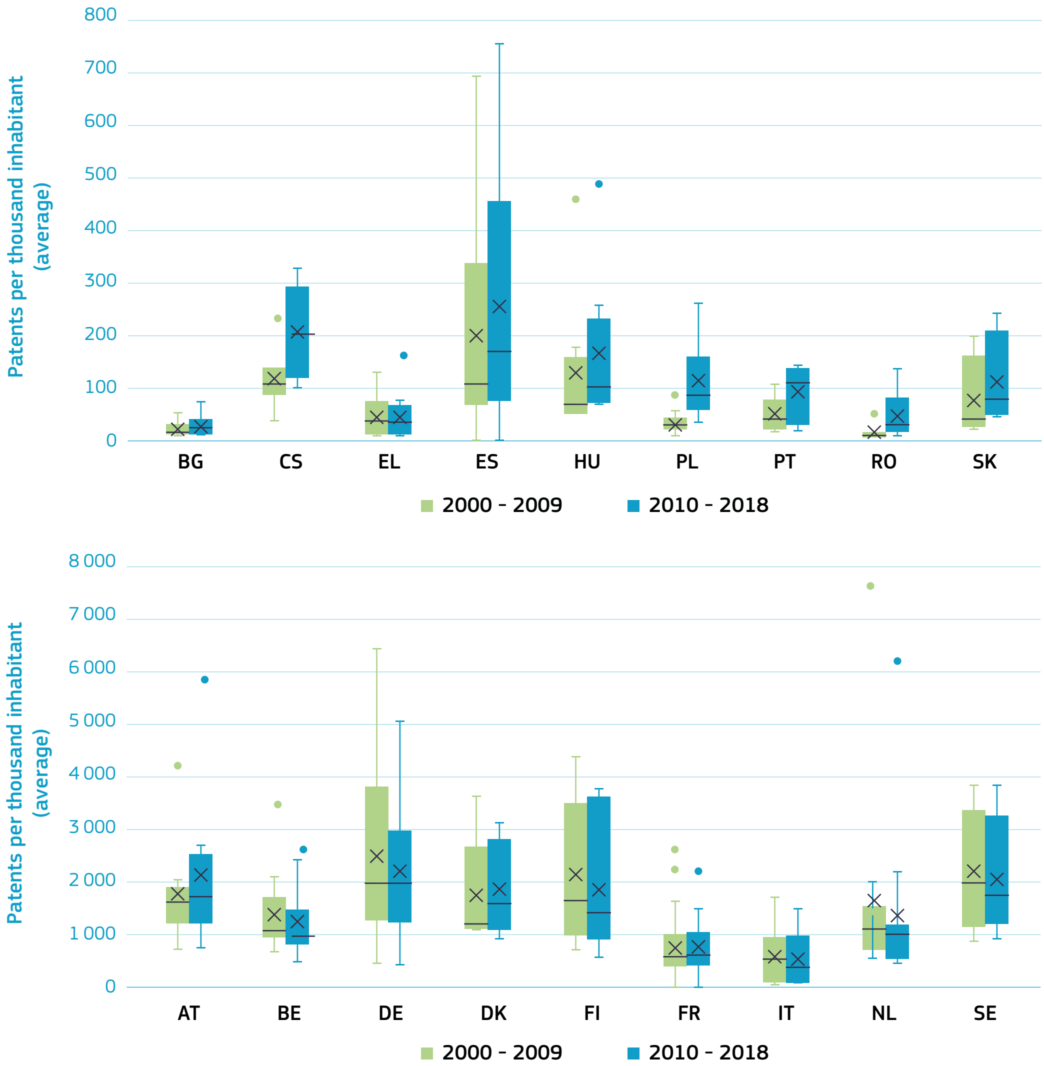
(Fujita et al., 2001). Isaksen et al. (2016) describe 'thick innovation ecosystems', found in metropolitan and technologically advanced regions, that host a variety of industries and knowledge- and innovation-supporting organisations. Indeed, Figure 2.2-10 documents that **innovative activities are increasingly concentrated in metropolitan regions**[4]. Some countries have much higher regional concentration of innovation and feature a large difference in patent applications filed between their metropolitan and non-metropolitan regions, e.g. Finland, Sweden, Germany, Denmark or France. In contrast, countries such as the Netherlands, Austria, Czechia, Italy, Latvia, Slovenia and Lithuania showed a smaller gap between metropolitan and non-metropolitan regions over 2000-2018.

Rural and urban areas differ in the intensity of innovation as well as in the type of innovation. As illustrated in Table 2.2-1, urban regions are much more active in patenting and publication activities than rural or intermediate regions. In Europe, metropolitan regions gathered 74 % of patent applications in 2018, 84 % of scientific publications in 2020, and 87 % of highly cited publications in 2020. When it comes to the types of innovation, it appears that high-density areas are characterised by a higher degree of unconventionality in innovation, meaning that **research activities and product innovations tend to be concentrated in higher-rank cities** or more agglomerated settings, **while process innovations and less technology-intensive activities tend to be more distributed in space** (Duranton and Puga, 2001; Lee and Rodríguez-Pose, 2013; Berkes and Gaetani, 2020). Besides, while rural regions more rarely produce learning related to R&D activities ('learning by searching') they **have a fundamental role in the other dimensions of learning** (by doing, by using, and – in particular – by interacting).

CHAPTER 2.2

4 Except in Bulgaria, where non-metropolitan regions tend to concentrate innovative activities.

Figure 2.2-10: Difference between metropolitan and non-metropolitan regions in average patent applications to EPO (fractional counting) per 1 000 inhabitants across EU, 2000-2018.



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Science-Metrix using EPO REGPAT database.

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Table 2.2-1: Urban-rural innovation divide in Europe

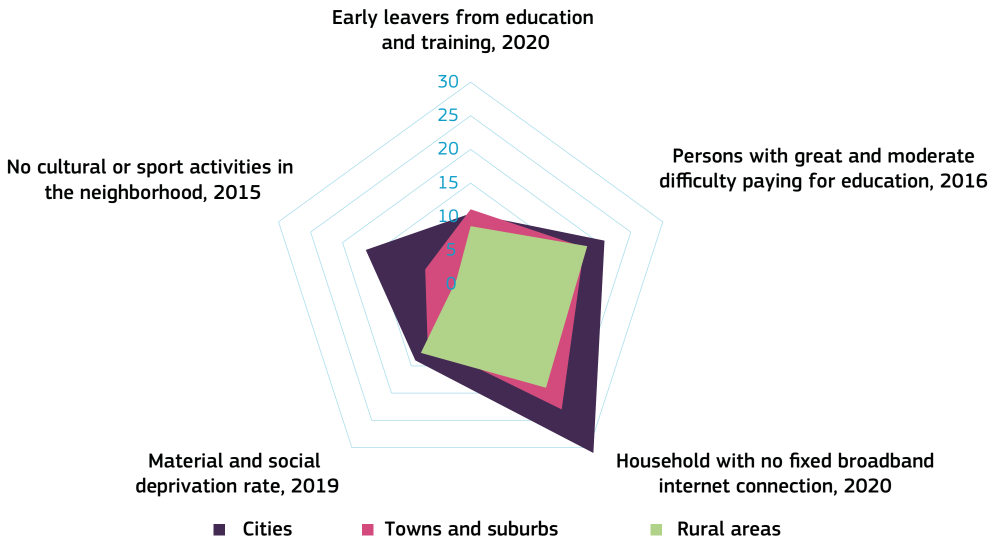
Type of regions	Predominantly urban regions	Intermediate regions, close to a city	Intermediate regions, remote	Predominantly rural regions, close to a city	Predominantly rural regions, remote
Number of regions in Europe	240	464	48	265	150
Publications per million inhabitants 2020 (frac. counts), % change 2014-2020	2 078.9 +6.46 %	1 145.2 +9.3 %	400.5 +19.2 %	397.7 +14.4 %	302.9 +44.5 %
Share of publications 2000-2020	63.7 %	30.5 %	0.6 %	4.2 %	1.0 %
Average of highly cited publications (top 10 %) over total publications 2000-2020	0.09 %	0.07 %	0.06 %	0.05 %	0.06 %
Average of highly cited publications (top 1 %) over total publications 2000-2020	0.01 %	0.01 %	0.01 %	0.00 %	0.01 %
Patents per million inhabitants 2018, % change 2014-2018	132.4 -14.6 %	104 -14.5 %	31.3 -29.8 %	65.8 -4.7 %	30.7 -15.2 %
Share of patents 2000-2018	52.8 %	36.1 %	0.8 %	8.6 %	1.7 %
Share of patents cited at least one time in total patents 2000-2018	17.4 %	19.5 %	14.8 %	20.0 %	21.6 %

Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Eurostat and Science-Metrix using EPO REGPAT and Scopus databases.

Access to education, science and infrastructure is unequal across territories (Figure 2.2-11), which may stoke the cultural divide between urban and rural settings and calls for increased infrastructure and facilities across Europe. Besides, populations in towns, suburbs and rural areas are more subject to material and social deprivation than populations of cities. It leads to a 'geography of discontent' (McCann, 2019), which is becoming apparent in many European countries and beyond as communities and localities display a sense of despair and being left behind, often manifested in anti-system voting. Urban-rural divergence is still growing in countries such as France, Sweden and Austria, with powerful political movements emerging from both formal and informal contexts, and rural areas remaining distant, both physically and technologically, from urban centres (Cowie et al., 2020). Rural individuals are underrepresented in science at all levels, and their absence from these processes skews the priorities and ethical considerations of science (O'Neal and Perkins, 2021). Furthermore, populations living in periphery and rural areas face difficulty in paying for education and training (Figure 2.2-11) as going to higher learning institutions often also means moving into urban centres, where housing prices are high. It also hinders labour mobility as people who lose their jobs because industries have either been displaced or closed may not be able to attend training and support facilities, often localised in urban centres. Rural and peripheral areas have a much higher share of their population with no fixed broadband internet connection. In turn, this can result in the loss of important perspectives that lead to innovations, and it propagates large-scale societal problems such as science scepticism, susceptibility to misinformation and lack of support for science funding.

Figure 2.2-11: Territorial disparities in access to education and connectivity in the EU, 2020 or latest year available



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Eurostat.
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-2-2-11.xlsx

The convergence process: challenged over recent years

A process of convergence in research outputs (patents and publications) that happened across the EU in the beginning of the 2000s due to high annual growth of the least performant regions and low annual growth for the most performant regions. This process **reduced over time and finally stopped from the middle of the 2010s**. Table 2.2-2 demonstrates that the least performant regions in terms of patents per million inhabitants and number of patents had been catching up over 2001-2005 (at a very high rate) then 2009-2013 (at a slower pace), but that this convergence stopped over 2013-2018. In contrast, the most performant regions had a lower growth rate in the beginning of the 2000s but ended up with a higher annual growth rate than the least performant regions over 2013-2018. **For scientific publications, it appears that the pronounced convergence process in the beginning of the 2000s was still valid over the 2016-2020 period, but at a much slower pace than previously**. These results are similar to regional performance as mapped by the Regional Innovation Scoreboards, which also demonstrated that over 2016-2021 the share of emerging innovators (the least innovative class) has increased in the less-developed regions. Less-developed regions indeed face more difficulties in translating research results into innovation, and the returns on additional R&D investment in terms of patenting tend to be lower than in other regions (Sterlacchini, 2008). Although there is convergence for scientific publications, many disadvantages prevail in less-developed regions of Europe and these are less capable of generating innovation from R&D inputs (Rodríguez-Pose and Ketterer, 2020).

Due to the high concentration of innovation, the vast majority of regions lag behind, even in the most innovative EU countries. In 2018, the majority of French (80 %), Belgian (70 %), Italian (85 %), Dutch (60-80 %) and Finnish (50-70 %) regions filed fewer patents per capita than the EU average per region (Table 2.2-3). Moreover, **the disparities have been on an increasing trend** and these regions experienced a severe drop in the number of patents filed per capita over 2010-2018. In the Netherlands in particular, while 60 % of regions had a patent per capita rate below the EU average in 2010, in 2018 more than 80 % of regions were below the EU average in terms of technological production per capita. Most of these regions were also characterised by declining patent productivity during the last decade, as was the case in the Netherlands, Finland and Ireland. In contrast, Sweden, Austria, Ireland and Finland experienced a decreasing rate of regional disparities within their borders in terms of technological production per capita.

Table 2.2-2: Annual growth 2001-2018/2020 for research outputs (patent applications and scientific publications – fractional counting) by groups of regions

	Annual growth			
Patents per million inhabitants	**2001-2005**	**2006-2010**	**2011-2014**	**2015-2018**
Most performant regions (1st tercile)	1.1	-0.6	0.3	-3.6
Middle performers (2nd tercile)	4.5	0.6	0.7	-4.7
Least performant regions (3rd tercile)	16.2	1.7	5.3	-11.8
Patents	2001-2005	2006-2010	2011-2014	2015-2018
Most performant regions (1st tercile)	2.4	0.06	-0.1	-2.8
Middle performers (2nd tercile)	5.5	1.6	1.3	-2.4
Least performant regions (3rd tercile)	16.7	1.6	4.1	-12.6
Publications per million inhabitants	2001-2005	2006-2010	2011-2015	2016-2020
Most performant regions (1st tercile)	4.1	2.9	1.4	0.9
Middle performers (2nd tercile)	6.0	4.3	2.6	1.7
Least performant regions (3rd tercile)	10.0	9.7	4.0	2.1
Publications	2001-2005	2006-2010	2011-2015	2016-2020
Most performant regions (1st tercile)	4.6	3.3	2.1	1.2
Middle performers (2nd tercile)	6.5	4.6	2.4	1.3
Least performant regions (3rd tercile)	11.2	9.2	4.1	2.6

Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Eurostat and Science-Metrix using EPO REGPAT and Scopus databases.

Table 2.2-3: Regions with total patent applications to the EPO per capita (fractional counting) below the EU average, 2010 and 2018

Patents per million inhabitants [1]						
	EU average 2010: 136.1 patents per million at regional level (NUTS3)			EU average 2018: 116.5 patents per million inhabitants at regional level (NUTS3)		
	No. and percentage of regions with patents per capita below the EU average	Average patents per capita for these regions	Average increase in patents per capita for these regions 2010-2018	No. and percentage of regions per capita below the EU average	Average patents per capita for these regions	Average increase in patents per capita for these regions 2010-2018
AT	15/35 (43 %)	84	+21 patents per capita	10/35 (29 %)	77	+8 patents per capita
BE	31/44 (70 %)	77	-3 patents per capita	30/44 (68 %)	61	-23 patents per capita
DE	122/401 (30 %)	78	-1 patents per capita	124/401 (30 %)	62	-44 patents per capita
DK	3/11 (27 %)	76	+10 patents per capita	4/11 (36 %)	79	-49 patents per capita
FI	10/19 (53 %)	59	-9 patents per capita	14/19 (74 %)	57	-33 patents per capita
FR	80/100 (80 %)	58	-8 patents per capita	79/100 (79 %)	44	-17 patents per capita
IE	8/8 (100 %)	70	-10 patents per capita	7/8 (88 %)	43	-18 patents per capita
IT	92/110 (84 %)	42	-6 patents per capita	94/110 (85 %)	36	-10 patents per capita
NL	24/40 (60 %)	81	-18 patents per capita	33/40 (83 %)	66	-39 patents per capita
SE	7/21 (100 %)	89	-27 patents per capita	11/21 (52 %)	59	-64 patents per capita

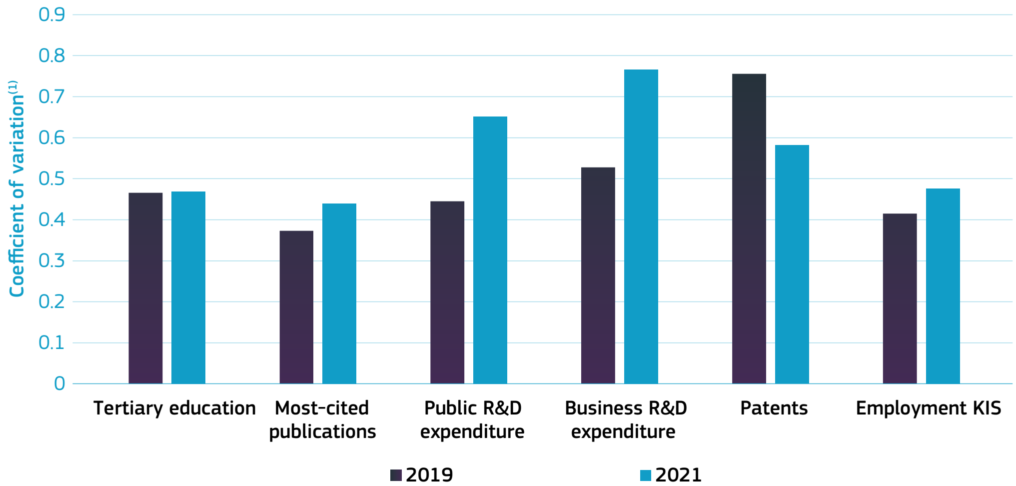
Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Science-Metrix using EPO REGPAT database.

Note: [1] Only countries where at least one region has a number of patents per capita above EU average are represented in this table.

Since the onset of the COVID-19 pandemic, it appears that the dispersion across EU regions has increased for several R&I indicators other than technological production, including R&D expenditures, employment in knowledge intensive sectors and most cited publications (Figure 2.2-12). This reflects that some regions are failing to catch up with the best-performing regions, which continue to improve their innovative capacity and to produce scientific knowledge. It may accentuate the dispersion observed since 2017 and put a definitive halt to the convergence patterns, not only in terms of research outputs, such as patents, but also in terms of R&D investments.

Figure 2.2-12: Regional disparities in key R&I components in 2019 and 2021 according to Regional Innovation Scoreboard

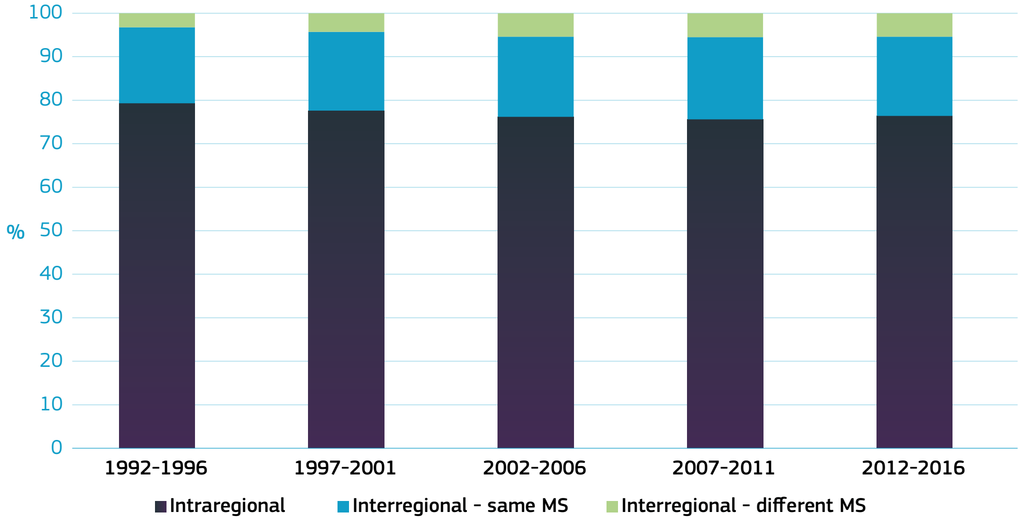


Source: DG Regional and Urban Policy, based on Regional Innovation Scoreboard 2021.
Note: (1)The coefficient of variation (CV) is the ratio of the standard deviation to the mean. which shows the extent of variability of data in a sample in relation to the average value. The higher the coefficient of variation. the greater the level of dispersion around the mean.
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-2-2-12.xlsx

Collaboration on R&I activities at regional level

Interregional co-patenting remains very limited in the EU, even if it has slightly increased from 1992 to 2016. Over 75% of collaborations on patents (co-patenting) take place within the same region, somewhat less than 20% are interregional with stakeholders in other regions of the same country and only 3-5% are interregional across national borders (Figure 2.2-13). Still, there are some improvements in terms of interregional collaboration beyond national borders as the share increased from 3.2% over 1992-1996 to 5.4% over 2012-2016.

Figure 2.2-13: Inter- and intra-regional collaboration in patenting (co-patenting) in Europe over the period 1992-2016



Science, Research and Innovation Performance of the EU 2022

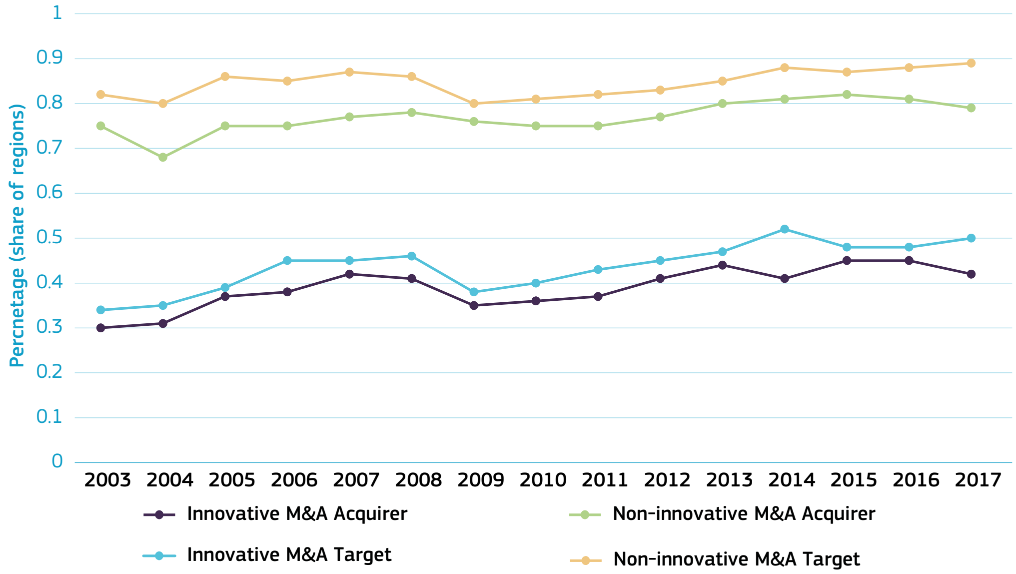
Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Balland and Boschma (2019).

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-2-2-13.xlsx

The importance of proximity goes beyond production of research and innovations as it seems that knowledge diffusion also remains mostly national. For example, the EIB (2021) used the cross-country citation index, which measures how often countries refer to one another in relative terms, to demonstrate **that most green knowledge stays within national borders or regions.** For both technological innovation and diffusion of knowledge, collaboration and circulation across regions and Member States is as critical to tackling global societal challenges as proximity can be. It ensures that inventions and knowledge benefit from work already done by others. Policy implications include strengthening the ties between regions across national borders, including through R&I policies at European level.

Innovative cross-regional merger and acquisitions (M&A) when the target company had filed patent applications prior to the deal **predominantly involve companies located in more-developed regions** (Figure 2.2-14). Integrating business units through M&A is usually to access new markets (new products or new locations), increase market power, efficiency or financial strength, take advantage of opportunities for diversification or acquire valuable assets such as technology or talented teams of workers (Andrade et al., 2001; Carpenter and Sanders, 2007; Gopinath, 2003). M&A that involve different locations are an important tool to promote mutual learning, collaborative knowledge-creation and diffusion across space.

Figure 2.2-14: Yearly share of regions involved in acquisitions[1] by deal type and company location, 2003-2017



Science, Research and Innovation Performance of the EU 2022

Source: Aquaro, Damioli and Lengyel (2020).

Note: [1]Acquisition is considered as innovative when the target company made one or more patent applications in the 20 years prior to deal completion.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-2-2-14.xlsx

Companies located in less-developed and in transition regions show very low or negligible proportions of involvement in M&A deals. Table 2.2-4 illustrates that, in the case of innovative deals, 91.9% of acquirers and 88.3% of targets were located in more-developed regions 2003-2017. In comparison, when it comes to non-innovative deals, these shares were higher. About 81.9% of acquirers and 88.4% of targets were located in more-developed regions. **In total, more-developed regions were home to both acquirers and targets for 84.1% of innovative acquisitions** and for 77.6% of non-innovative ones (Aquaro et al., 2020). All deals involving companies in less-developed and transitional regions did not exceed 7% of total deals.

Table 2.2-4: Number of M&A deals, both innovative and non-innovative, by category of European region, 2003-2017

Targets / Acquirers	Innovative M&A deals: Less developed	Transition	More developed	All	Targets / Acquirers	Non innovative M&A deals: Less developed	Transition	More developed	All
Less developed	2.9	0.3	1.6	4.9	Less developed	6.1	0.3	1.9	8.3
Transition	0.4	0.3	2.6	3.2	Transition	0.6	0.3	2.4	3.3
More developed	3.3	4.5	84.1	91.9	More developed	6.8	4	77.6	88.4
All	6.6	5.1	88.3		All	13.5	4.6	81.9	

Science, Research and Innovation Performance of the EU 2022

Source: Aquaro, Damioli and Lengyel (2020).

Note: An acquisition is considered as innovative when the target company made one or more patent applications in the 20 years prior to deal completion. GDP per capita as the criteria adopted by regional Cohesion Policy in the 2014-2020 EU programming period has been used to classify regions as more developed (more than 90 % of EU-28 average GDP per capita), transitioning (between 70 % and 90 %) and less-developed regions (less than 70 %).

2. Regional specialisation in R&I across different thematic areas

R&I in specific thematic activities is often concentrated in a relatively small number of regions. As regions gain reputation as hotspots for particular activities, they attract more talent working in these specific domains, resulting in local specialisation. This is particularly the case for more central regions. It appears that local concentration is more important for technological innovation than for scientific production. For technological production, there is indeed a need to reach a critical mass that might act as a catalyst for interaction between the different agents of the regional innovation system (Buesa et al., 2010).

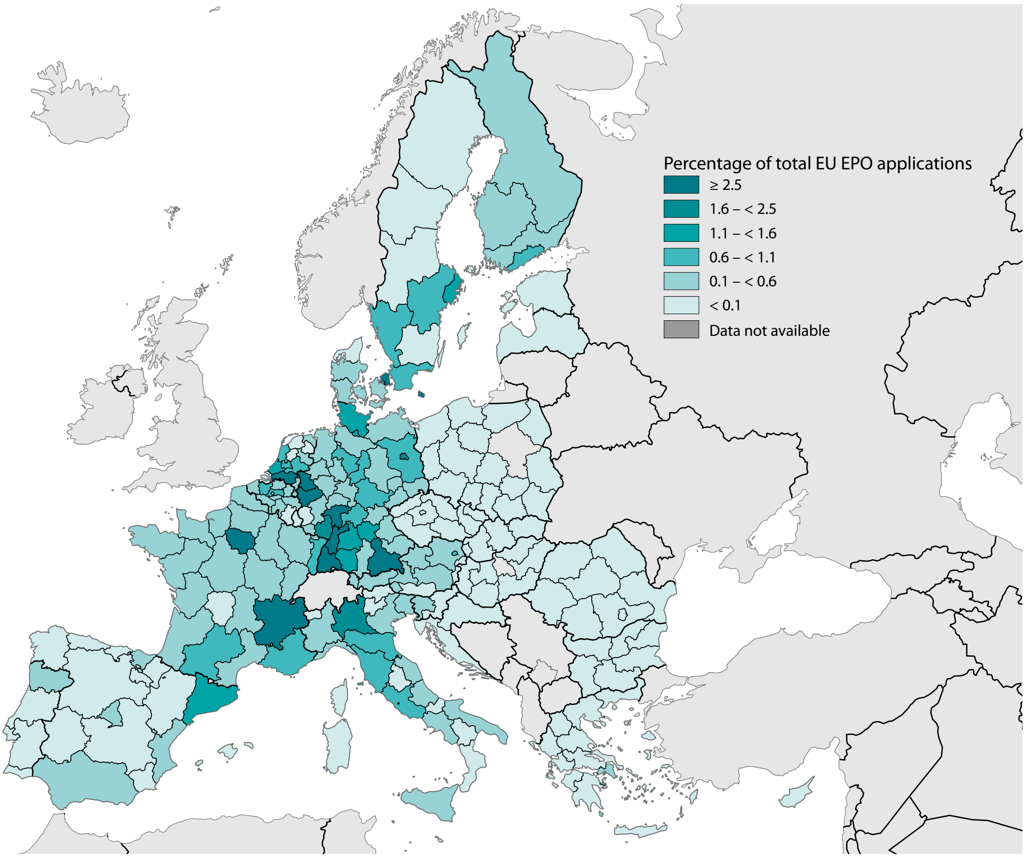
Health

There is a high degree of local specialisation in health when it comes to technological innovation (Figure 2.2-15). The top ten regions in Europe filed about 40 % of the total patent applications between 2003 and 2018 (Table 2.2-5). The high degree of regional specialisation in health can partly be explained by the localisation of top pharmaceutical industrial clusters and ecosystems, such as the Biotech-Cluster Rhine-Neckar, with more than 100 members, including small and large companies. It can also be explained by the localisation of large research centres, such as the Karlsruhe Institute of Technology or the BioM-Munich Biotech Cluster located in Oberbayern (DE), with more than 255 members, including 200 SMEs and 50-70 start-ups, or Medicon Valley Alliance in Hovestaden (DK), also with more than 250 members, including 230 SMEs[5].

Top pharmaceutical companies are part of these clusters or are located in the top regions: Bayer, Janssen in Köln (DE) and Merck in Darmstadt (DE). Unlike other industries, pharmaceutical patents relate to products with particularly long development cycles. For example, a new drug requires on average 10-15 years of development, from the early stages of conception to the final approval by health authorities (Lansdowne, 2020). Besides, developing R&I in health requires significant investment, particularly in terms of infrastructure and research equipment. This can explain to some extent the local specialisation in technological production as not too many companies can afford to make such long-term investments in R&D.

5 Reference on industrial clusters: European Cluster Collaboration Platform

Figure 2.2-15: Contribution of each EU region to the total number of patent applications to EPO (fractional counting) in Health over the period 2003-2018



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, adapted from DG Regional and Urban Policy study The importance of scientific domains for technological diversification in European regions (Balland and Boschma, 2021).

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-2-2-15.xlsx

Table 2.2-5: Contribution of the top ten EU regions to the total number of patent applications to EPO (fractional counting) in Health over the period 2003-2018.

TECH LEADERS[(1)]	% patents	No. patents	Patents per 1 000 inhbts.	% population 2018	SCIENCE LEADERS [(2)]	% publications	No. publications	Publications per 1 000 inhbts.	% population 2018
Île de France (FR)	8.3	22 060	22.1	2.7	Île de France (FR)	5.2	266 743	22.1	2.7
Darmstadt (DE)	4.9	13 047	13.2	0.9	Lombardia (IT)	2.8	143 374	14.3	2.2
Oberbayern (DE)	4.8	12 601	23.9	1.0	Comunidad de Madrid (ES)	2.4	123 004	19.3	1.5
Hovedstaden (DK)	3.7	9 691	51.8	0.4	Cataluña (ES)	2.3	117 009	15.8	1.7
Noord-Brabant (NL)	3.6	9 431	8.0	0.6	Lazio (IT)	2.3	116 318	19.7	1.3
Düsseldorf (DE)	3.3	8 821	11.7	1.2	Oberbayern (DE)	2.1	107 915	23.9	1.0
Karlsruhe (DE)	3.1	8 151	30.7	0.6	Noord-Holland (NL)	2.1	107 664	39.0	0.6
Köln (DE)	2.7	7 167	19.4	1.0	Zuid-Holland (NL)	2.0	102 418	28.4	0.8
Rhône-Alpes (FR)	2.6	6 781	12.5	1.5	Berlin (DE)	2.0	101 218	29.2	0.8
Freiburg (DE)	2.5	6 674	17.9	0.5	Stockholm (SE)	1.8	94 430	43.0	0.5
Average all EU regions	0.43	1.15	0.52	0.42	Average all EU regions	0.43	22.3	10.67	0.42
Contribution top ten	39.4 %	104 424	----	10.4	Contribution top ten	25.0	1 280 093	---	13.3

Science, Research and Innovation Performance of the EU 2022

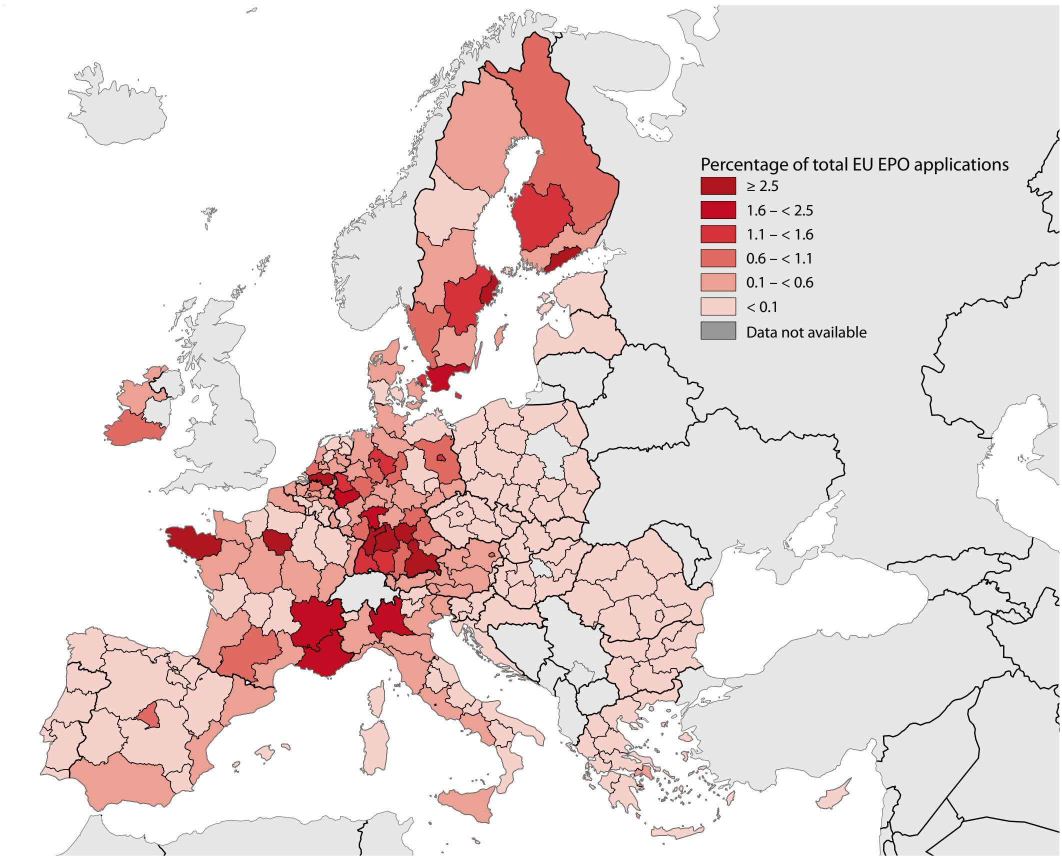
Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, adapted from DG Regional and Urban Policy study *The importance of scientific domains for technological diversification in European regions* (Balland and Boschma, 2021).

Note: [(1)]Tech Leaders: top ten regions in number of patents. [(2)]Science leaders: top ten regions in number of publications 2003-2018.

Information and communication

Information and communications innovations are highly concentrated, with the top ten regions filing more than 45 % of patents in the EU (Figures 2.2-16 and Table 2.2-6). The distribution of patents is consistent with the localisation of the largest industrial clusters in ICT and some of the most innovative companies in the world. Among such clusters and companies are the Baden Württemberg Connected e.V. cluster in Stuttgart (DE), the BICCnet Bavarian Information and Communication Technology Cluster in Oberbayern (DE), with close to 600 members, including 230 SMEs and Siemens, the CyberForum e.V.

Figure 2.2-16: Contribution of each EU region to the total patent applications to EPO (fractional counting) in the ICT sectors over the period 2003-2018



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, adapted from DG Regional and Urban Policy study *The importance of scientific domains for technological diversification in European regions* (Balland and Boschma, 2021).

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-2-2-16.xlsx

Table 2.2-6: Contribution of the top ten EU regions to the total patent applications to EPO (fractional counting) in the ICT sectors over the period 2003-2018

TECH LEADERS (1)	% patents	No. patents	Patents per 1 000 inhbts.	% population	SCIENCE LEADERS (2)	% publications	No. publications	Publications per 1 000 inhbts.	% population
Île de France (FR)	8.8	19 940	1.7	2.7	Île de France (FR)	5.3	57 381	4.7	2.7
Oberbayern (DE)	8.3	18 848	4.2	1.0	Cataluña (ES)	2.4	25 434	3.4	1.7
Noord-Brabant (NL)	5.5	12 505	5.0	0.6	Comunidad de Madrid (ES)	2.3	24 606	3.9	1.4
Stockholm (SE)	4.3	9 853	4.5	0.5	Rhône-Alpes (FR)	2.1	22 941	3.5	1.5
Stuttgart (DE)	4.0	9 177	2.3	0.9	Oberbayern (DE)	2.1	22 914	5.1	1.0
Mittelfranken (DE)	4.0	8 966	5.2	0.4	Lombardia (IT)	1.7	18 200	1.8	2.3
Helsinki-Uusimaa (FI)	3.1	7 059	4.4	0.4	Lazio (IT)	1.6	17 336	2.9	1.3
Bretagne (FR)	2.7	6 060	1.8	0.7	Berlin (DE)	1.6	17 046	4.9	0.8
Karlsruhe (DE)	2.6	5 816	2.1	0.6	Wien (AT)	1.6	16 966	9.4	0.4
Rhône-Alpes (FR)	2.3	5 229	0.8	1.5	Southeast Ireland (IE)	1.6	16 813	4.4	0.9
Average all EU regions	0.44	985.9	0.43	0.42	Average all EU regions	0.43	4704	0.42	0.43
Contribution of top ten	45.6	103 453	-------	9.3	Contribution of top ten	22.2	239 637	---	14.0

Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, adapted from DG Regional and Urban Policy study The importance of scientific domains for technological diversification in European regions (Balland and Boschma, 2021).

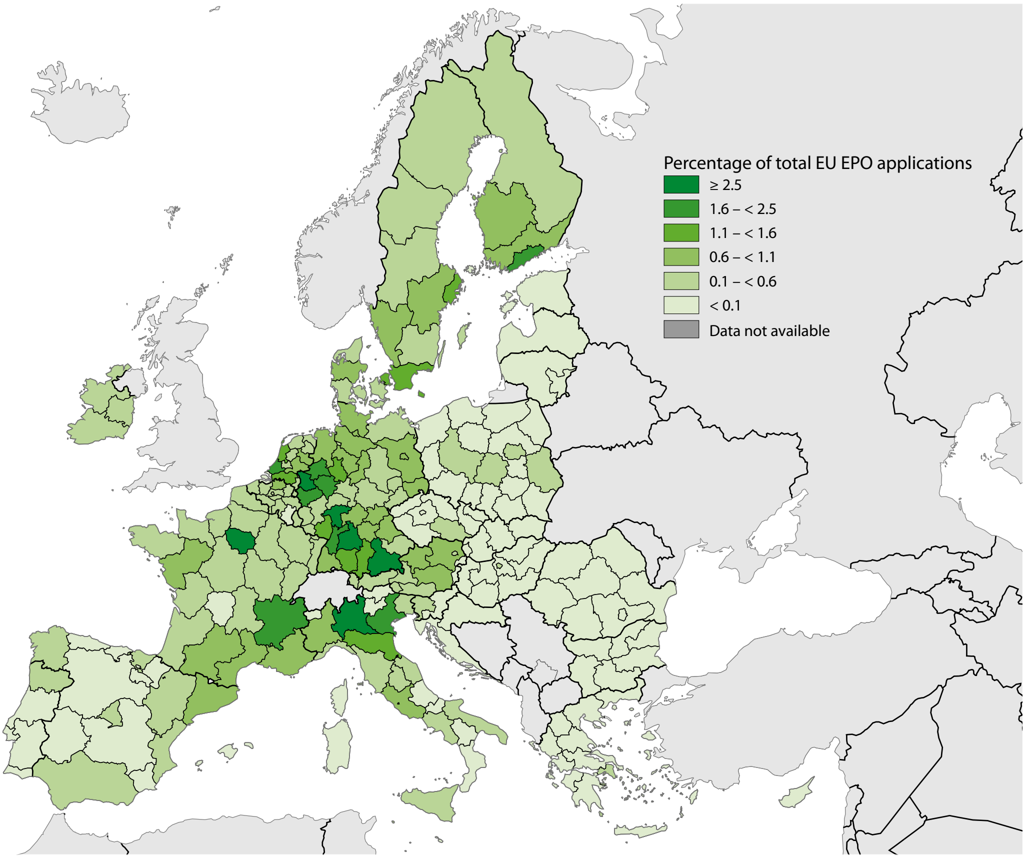
Note: (1)Tech Leaders: top ten regions in number of patents. (2)Science leaders: top ten regions in number of publications 2003-2018.

cluster, with more than 1 100 members, including 1 050 SMEs, in Karlsruhe (DE), Philips in Noord-Brabant (NL), Bosch in Stuttgart (DE), Nokia in Helsinki-Uusimaa (FI), the Cap Digital cluster, with more than 1 000 members, and the Systematic Paris-Region cluster, both in Ile-de-France (FR), and the Digital League cluster in Rhône Alpes (FR) (BCG, 2021). Public research institutions have also played a role, even if it is characterised by a lower propensity to file patents (Buesa et al., 2010). For example, Mittelfranken (DE) hosts the University of Erlangen-Nuremberg, ranked as the second most innovative university in Europe in 2019 (Reuters, 2019), while Rhone-Alpes (FR) and Bretagne (FR) both host large research labs of the France's National Centre for Scientific Research, one of the most innovative players in France (INPI, 2020).

Climate change, environment, resource efficiency and raw materials

Patenting in climate change. environment. resource efficiency and raw materials tends to be less concentrated across the different EU regions: the top ten regions filed about 30% of total patents applications (Figures 2.2-17 and Table 2.2-7). Among the top firms in the domain of energy and materials is Royal Dutch Shell in Zuid-Holland (NL), while among top innovative universities are the Technical University of Munich in Oberbayern (DE) and the Technical University of Denmark in Hovestaden (DK) (Reuters, 2019). Patenting in this area is, in absolute numbers, much less important than in the other domains. Due to a high rate of knowledge spillovers for green innovations and the existence of path dependence, green technological innovations may require more public support than other types of technological development (Roed Nielsen et al., 2016) (see Chapter 3 – R&I for sustainability).

Figure 2.2-17: Contribution of each EU region to the total number of patent applications to EPO (fractional counting) in climate change, environment, resource efficiency and raw materials over the period 2000-2018.



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, adapted from DG Regional and Urban Policy study *The importance of scientific domains for technological diversification in European regions* (Balland and Boschma, 2021).

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-2-2-17.xlsx

Table 2.2-7: Contribution of the top ten EU regions to the total number of patent applications to EPO (fractional counting) in climate change, environment, resource efficiency and raw materials over the period 2000-2018.

TECH LEADERS (1)	% publications	No. publications	Publications per m. inhbts.	% population	SCIENCE LEADERS (2)	% patents	No. patents	Patents per m. inhbts.	% population
Île de France (FR)	3.3	28 923	2 353	2.7	Île de France (FR)	5.2	465	38.1	2.7
Cataluña (ES)	2.4	20 713	2 707	1.7	Düsseldorf (DE)	3.2	286	55.0	1.2
Andalucía (ES)	2.1	18 471	2 179	1.9	Stuttgart (DE)	3.1	277	67.2	0.9
Comunidad de Madrid (ES)	2.1	18 032	2 673	1.5	Oberbayern (DE)	2.8	254	54.6	1.1
Lombardia (IT)	2.0	16 921	1 687	2.2	Lombardia (IT)	2.8	250	24.9	2.2
Lazio (IT)	2.0	16 918	2 939	1.3	Darmstadt (DE)	2.5	224	56.2	0.9
Oberbayern (DE)	1.6	13 581	2 883	1.1	Rhône-Alpes (FR)	2.3	210	31.7	1.5
Hovedstaden (DE)	1.5	13 186	7 143	0.4	Arnsberg (DE)	2.2	199	55.5	0.8
Zuid-Holland (NL)	1.5	13 164	3 516	0.8	Köln (DE)	2.2	195	43.7	1.0
Helsinki-Uusimaa (FI)	1.5	12 936	7 656	0.4	Karlsruhe (DE)	2.2	195	69.6	0.6
Average all EU regions	0.4	6 837	1 844	0.4	Average all EU regions	0.4	37.4	18.5	0.4
Contribution of top ten	20	172 844	---	14	Contribution of top ten	29	499		13

Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, adapted from DG Regional and Urban Policy study The importance of scientific domains for technological diversification in European regions (Balland and Boschma, 2021).

Note: [1]Tech Leaders: top ten regions in number of patents. [2]Science leaders: top ten regions in number of publications 2003-2018.

Table 2.2-8: Patent applications to EPO (fractional counting), 2000-2018. Percentage of total in the top ten regions per technologies

Regional specialisation	Nano-technologies	Micro- and nano-electronics	Advanced manufacturing technologies	Advanced materials	Photonics	Industrial bio-technology
Auvergne-Rhône-Alpes (FR)	13.30	11.20	6.17	4.61	3.64	3.78
Baden-Württemberg (DE)	11.56	9.66	8.52	6.00	11.65	6.00
Zuid-Nederland (NL)	7.38	10.37	6.79	3.81	13.51	
Ile-De-France (FR)	6.19	4.54	5.58	4.85	7.26	6.56
Bayern (DE)	6.06	18.42	10.79	7.41	11.22	8.15
Nordrhein-Westfalen (DE)	4.82	4.10	9.11	12.62	7.38	8.60
Vlaams Gewest (BE)	3.75	4.64	2.92		2.12	4.08
Hessen (DE)		3.26	3.42	5.34	2.83	4.00
West-Nederland (NL)	3.12		2.66			5.34
Nord-Ovest (IT)	3.04			3.37	3.67	
Södra Sverige (SE)	2.42					
Sachsen (DE)		3.47				
Südösterreich (AT)		2.77				
Östra Sverige (SE)			3.05			
Rheinland-Pfalz (DE)				5.15		
Westösterreich (AT)					3.56	
Berlin (DE)						3.51
Danmark (DK)						4.48
Région Wallonne (BE)				3.83		
Contribution of top 10 regions to EU total	61.6%	72.4%	57.1%	59.0%	67.0%	54.5%

Science, Research and Innovation Performance of the EU 2022
Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Science-Metrix using EPO REGPAT database.

When it comes to patenting activity related to strategic areas and key technologies, European capital regions are not in the lead; there is also a high degree of concentration. Local specialisation is very high, with the top ten EU regions filing 55-72 % of patent applications related to nanotechnologies, micro- and nano-electronics, advanced manufacturing and materials, photonics and biotechnology (Table 2.2-8).

The high degree of regional concentration in technological development in some areas, such as health and ICT, demonstrates the importance of technology transfer across Europe and beyond. Regions capable of keeping pace with technological progress tend to be more resilient in times of structural change and better equipped to face new challenges and to compete globally. To profit from new opportunities, notably as regards digital technologies, firms need to have a sufficient level of absorptive capacity. This capacity is fundamental to making productive use of globally distributed knowledge networks (Asheim et al., 2019). Resilience at regional level will partly depend on the development of innovation systems and intermediaries that can encourage diffusion and absorption of productivity enhancing technologies, as well as the ability to build on national and regional capabilities to generate new knowledge.

Read more in Chapter 14 – Innovation policy for a complex world

(Pierre-Alexandre Balland, Utrecht University)

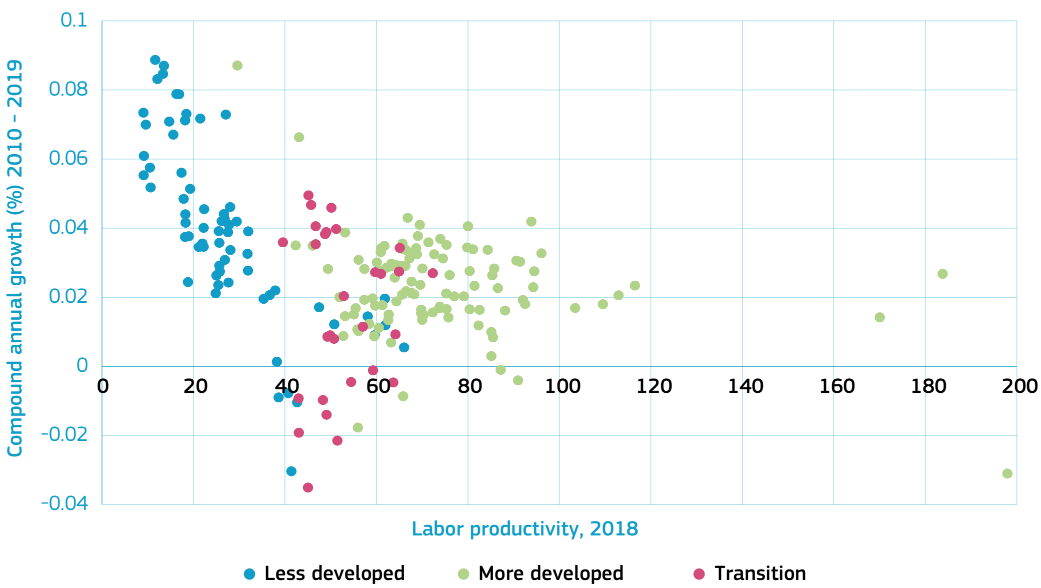
This chapter examines theoretically and empirically the spatial concentration of innovation in EU regional ecosystems. It proposes a detailed geography of patents in several strategic areas and key technologies such as artificial intelligence, blockchain, quantum computing, batteries, hydrogen, mRNA, and oncology diagnostics and treatments, and looks at the complementarities across EU regions.

The chapter focuses on the importance of leveraging regional ecosystems with human and artificial intelligence and shows how this approach can be used to assess potential new opportunities for collaboration across EU regions and to optimise knowledge sharing to increase EU competitiveness in strategic areas and some key technologies.

3. The impact of regional R&I disparities on productivity and growth

Regional disparities play a part in the European productivity story. In addition to the general drivers of the secular slowdown in productivity growth (see Chapter 4.1 – Productivity), regional divergencies are particularly pronounced in many Member States, driven inter alia by growing gaps between capital and other metropolitan and non-metropolitan regions. Overall, there seems to be some degree of convergence in productivity performance as witnessed by the negative relationship between productivity levels and productivity growth (Figure 2.2-18). It is driven mainly by regions in less-developed EU countries, especially in central and eastern Europe, which recorded relatively high productivity growth, albeit from low starting levels. However, **many European regions seem to face the middle-income trap and struggle to make the transition from middle-income to high-income status** (Borunsky et al., 2020). There is thus little correlation between productivity levels and growth in these transition regions. They often experience a problematic combination of moderate productivity levels and low productivity growth. A similar situation can even be observed in some more-developed regions. **Many regions in more-developed countries with average productivity levels, such as regions in the south of Europe or regions with industrial transition issues, are no longer catching up**. These trends hint at the risk of some kind of middle-income trap, jeopardising the convergence process.

Figure 2.2-18: Labour productivity[1], 2018 and compound annual growth, 2010-2018 by regional development



Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Eurostat.
Note: [1]GDP per worker in current PPS. FR and PL NUTS2 regions not included.
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-2-2-18.xlsx

EU regions with good R&I performance also have high productivity. Indicators of R&I performance show strong performance in regions that have the highest productivity levels (Table 2.2-9). This positive link also holds for regions ranking high in productivity growth. However, the very top regions (80-100% quintile) in terms of productivity growth present slightly lower R&I indicators. This can be explained by the presence of many CEE regions, in particular Bulgarian and Romanian regions. All CEE Member States show levels of labour productivity that remain below the EU average. On the other hand, these regions show a tendency for stronger growth rates in countries that started from lower levels, such as Romania or Bulgaria, reflecting the convergence process (Correia et al., 2018). And **while there is**

Table 2.2-9: R&I indicators by regional quintiles[1] for productivity

		Labour productivity 2019					Productivity growth 2010-2019				
		0-20%	20-40%	40-60%	60-80%	80-100%	0-20%	20-40%	40-60%	60-80%	80-100%
R&D per capita 2019	Average	92.8	229.5	482.4	925.7	1 480.6	304.9	911.7	843.8	507.6	175.1
	Median	82.1	204.6	456.8	702.0	1 326.0	204.6	655.4	736	273.2	98.0
Business R&D per capita 2019	Average	56.7	120.0	264.5	637.8	998.1	156.3	620.4	585.2	342.3	109.2
	Median	41.3	100.5	227.2	561.8	697.6	80.7	373.7	566.4	183.5	35.4
Patents per m. inhbts. 2018	Average	8.8	19.9	73.3	134.6	210.9	30.7	119.3	170.1	84.9	42.6
	Median	6.3	13.4	47.9	100.6	178	15.7	99.4	140.4	31.8	30.9
Publications per 1 000 inhbts. 2020	Average	0.6	1.1	1.0	1.2	2.1	1.4	1.4	1.4	1.1	0.8
	Median	0.6	1.1	0.9	1.2	2.2	1.3	1.2	1.1	0.8	0.7
Highly cited publications (top 10%) per m. inhbts. 2020	Average	0.2	0.8	1.1	1.5	3.0	1.4	1.8	1.8	1.0	0.7
	Median	0.2	0.7	1.0	1.4	2.7	1.0	1.2	1.4	0.5	0.5

Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Eurostat and Science-Metrix using EPO and Scopus database.

Note: [1]Regional quintiles for productivity are based on GDP PPS per worker. The green gradient is applied by blocs so that the colouring only considers single indicator row for calculating the gradients thresholds.

substantial heterogeneity in the evolution of innovation performance across CEE regions, many remain modest innovators. One of the crucial reasons for their low innovation performances are the low levels of investment in intangible assets, such as R&D. As in the rest of the EU, CEE countries are not making sufficient strides to improve their R&D investment and continue to lag significantly behind in R&D intensity. However, the rapid economic growth and fast convergence process seem to keep productivity growth above the EU average (Borunsky et al., 2020). In such cases, much of the growth has been fuelled by a combination of factors, such as the rapid expansion of global supply chains and foreign direct investment, with a smaller role for innovation-driven productivity growth.

Regions that are catching up from low levels of productivity seem to profit from knowledge diffusion via international companies and capital deepening. In many less-developed regions, notably in Romania, Bulgaria and Poland, the high levels of productivity growth have not been underpinned by good performance of the corresponding R&I systems (Table 2.2-9). Prior to the crisis, CEE countries captured capital inflows, with foreign direct investment being the most important component. After the financial crisis, capital inflows to the regions slowed down and lower efficiency gains associated with them led to declines in productivity growth (Correia et al., 2018). At the same time, regional economies of southern European, notably Italy and Greece, experienced lower productivity growth, a trend that exacerbated after the economic crisis, halting the convergence process. **The fast pace of innovation dynamics poses new challenges to the production systems of many less-developed regions, which are often not sufficiently oriented towards knowledge intensive sectors, as mirrored in the lower performance of their regional R&I systems**. Many transition regions characterised by low R&I performance have also not done well in productivity growth. This implies that regions, in particular less-developed ones, should shift to a knowledge based and innovation-driven growth model to continue to catch up. This would help to avoid the middle-income trap that has affected the development of many transition regions in the recent past.

Box 2.2-1: The EU added value of support to location-based innovation

Transnational collaboration is deeply enshrined in the EU legal bases and can even be defined as the *raison d'être* of European R&I policy and programmes. However, are there arguments for substantial 'European added value' that supports activities largely taking place in one location?

The treaties on the functioning of the European Union[6] make several references to facilitating free movement of knowledge and the promotion of collaborative activities, notably in Article 180.

In pursuing these objectives, the Union shall carry out the following activities, complementing the activities carried out in the Member States:

(a) implementation of research, technological development and demonstration programmes, by promoting cooperation with and between undertakings, research centres and universities;[...]

Yet for the European research area to be achieved[7], the Union shall '[promote] all the research activities deemed necessary by virtue of other Chapters of the Treaties.' The European Green Deal as the EU's growth strategy embraces the green and digital transitions and guides environmental, agricultural, marine and industrial policy. All these domains recognise the role of local networks for innovation, including technical demonstration as well as social and governance innovation (e.g. in local innovation test beds). Different socio-economic, cultural and administrative environments lead to different innovative solutions to the same challenge. Analysing diverse environments in terms of what works where is an essential part of joint learning and contributes to 'dissemination and optimisation of results' (Article 180(c)).

The high value assigned to transnational cooperation is reflected in the Horizon Europe framework programme as it states that 'except in duly justified cases where the work programme otherwise provides, legal entities forming a consortium shall be eligible for participation...'[8]. It also defines certain action types for which support of single entities is justified, namely:

- ERC grants based on consideration of European excellence;
- the EIC, for which the argument was accepted in the negotiation of Horizon 2020.

If the green transition and achieving climate neutrality by 2050 is seen as an all-encompassing innovation project requiring joint learning, the experiences from local actors' networks, the multi-actor-approach, can be considered as a contribution to a European added value, even if a single project has no transnational nature. The (obligatory) contribution to the joint learning efforts would provide for this.

Acknowledging this argument could tremendously ease the creation of synergies between the framework programme for R&I and other EU programmes under indirect management, such as cohesion funds or the European Maritime, Fisheries and Aquaculture Fund, in particular in the context of European Missions. The framework programme would mobilise local innovation networks through competitive EU-level calls to create a portfolio of funded projects under diverse environments (i.e. excellence in terms of best in different classes versus excellence in terms of best in Europe). It would also provide a joint learning environment that includes horizontal scientific analysis. Excellent projects not fundable due to budget limitations would be awarded a seal of excellence and could easily be taken up by national and regional support schemes as the projects would not be based on transnational partnerships.

6 Article XIX 'Research and technological development and space', Articles 179 and 180

7 Article 179(1)

8 Article 22(2) of the Horizon Europe Framework Programme

4. Conclusions: a fragmented regional R&I ecosystem

This chapter proposes a state of play and dynamics of regional R&I in the EU. It demonstrates that R&I inputs and outputs are concentrated in more-developed regions, although the contribution to the EU total of the least-performing regions has increased slightly in the last decade in terms of research inputs (R&D investments, notably). **Besides, patenting activity in health, ICT and climate mitigation technologies is highly concentrated** in a few EU regions. European R&I policies could target **different types of innovation according to territorial specificities in terms of peripherality and economic structure to achieve a better match between competitiveness and inclusiveness goals**. European policies must put greater emphasis on promoting innovation combined with more focus on the local context to trigger economic dynamism in less-developed regions.

Recent developments have halted the convergence process across EU regions in terms of technological production as the least-innovative regions had a decreasing rate of patent applications over 2013-2018. Moreover, regions with lower or moderate innovation capacity still rely more on the public sector for R&D investments than those with strong innovation capacity. **Many European regions seem to face the middle-income trap and struggle to transition from middle-income to high-income status**. For less-developed regions, which tended to have stronger growth rates in countries that started from lower levels, **much of the growth has been fuelled by a combination of factors** such as the rapid expansion of global supply chains and foreign direct investment. **There has been a smaller role for innovation-driven productivity growth**. This tendency to higher dispersion across regions is well-documented and applies to many other characteristics (e.g. economic growth, wage developments), pointing at a rise in regional inequality in Europe (Rodríguez-Pose et al., 2018). This is not a uniquely European problem, but one common to many countries, both developed and developing (Ganong and Shoag, 2015).

The green and digital transitions pose different challenges to innovation policy than growth orientation alone. Integration into global value chains and (foreign) direct investment in sectors of recognised competences have been drivers for growth in many regions and were often the focus of R&I policies. **The green transitions of societies will be realised through location-based innovation, i.e. deeper interaction in local stakeholder networks enabled by digital technologies**. Societal transformation will redefine the role of local knowledge generation versus experimentation with the recombination of existing approaches and technologies. R&I activities are increasing, even in less-developed regions, as shown by the increasing number of publications. This is a strength and an encouraging signal in this respect.

Effective public support for innovation must **further identify and understand both specificities and local obstacles in the single market that could block the potential** of regional innovation to increase the competitiveness of the EU, address the innovation divide and leave no one behind. Europe's full economic potential will not be achieved without tackling the fragmentation of the European innovation ecosystem and enhancing the synergies and **coordination at all levels**. These include **R&I policies and Cohesion Policy**, together with education and training implemented through a broad range of instruments. A place-based approach to promoting innovation, especially the diffusion and commercialisation of existing innovation in lagging regions, is critical. This approach could be supported in line with the specificities of each region, and regions' current or possible comparative advantages as mapped in smart specialisation strategies.

References

Aghion, P., Grifith, R., (2008), *Competition and Growth: Reconciling Theory and Evidence*, MIT Press, 25 Jan 2008 , Business & Economics.

Audretsch, D.B., (2003), *Managing knowledge spillovers: the role of geographic proximity*, O. Sorenson. J.A. Baum (eds.), Geography and Strategy., Emerald Group Publishing Limited, pp. 23-48.

Asheim, B.T., Isaksen, A., Trippl, M. (2019), *Advanced Introduction to Regional Innovation Systems*, Cheltenham: Edward Elgar.

Aquaro, M.. Damioli, G., Lengyel, B., (2020), *Innovative Mergers & Acquisitions and the integration of European regions*, Joint Research Centre, Publications Office of the European Union. Luxembourg.

Balland, P.-A.. Boschma, R., (2019), *Exploring the impact of inter-regional linkages on regional diversification in Europe in the context of smart specialization*. Directorate General for Regional and Urban policy Report.

Berkes, E., Gaetani, R., (2020), *The Geography of Inconventional Innovation,* Economic Journal.

Boston Consulting Group (2021), *Overcoming the Innovation Readiness Gap*. Avril 2021.

Buesa, M. (2010), 'The determinants of regional innovation in Europe: A combined factorial and regression knowledge production function approach', Research Policy, 39(6), pp. 722-735.

Carpenter, M. A., and Sanders, W. G. (2007). Strategic management: A dynamic perspective. Upper Saddle River, NJ: Pearson Prentice Hall.

Cowie, P., Townsend, L., Salemink, K. (2020), 'Smart rural futures: Will rural areas be left behind in the 4th industrial revolution?', *Journal of Rural Studies*, 79, pp. 169-176.

Doehne, M., Rost, K. (2021), 'Long waves in the geography of innovation: The rise and decline of regional clusters of creativity over time', *Research Policy*, Volume50. Issue 9. November 2021. 104298.

Duranton, G., Puga, D., (2001), 'Nursery cities: Urban diversity. process innovation. and the life cycle of products', *American Economic Review*, 91(5), pp.1454–1477.

European Commission (2014), For a European Industrial Renaissance. Commission Communication. COM(2014) 14 final.

European Commission (2017a), Investing in a smart. innovative and sustainable Industry. a renewed EU Industrial Policy Strategy. Commission Communication. COM(2017) 479 final.

European Commission (2017b), Competitiveness in low-income and low-growth regions - The lagging regions report. Brussels. 10.4.2017 SWD(2017) 132 final.

European Commission and European Investment Bank (2018), Correia A.. Bilbao-Osorio B.. Kollar M.. Gereben A.. Weiss C. (2018). EIB Innovation investment in Central. Eastern and South-Eastern Europe: Building future prosperity and setting the ground for sustainable upward convergence. EIB Regional study December 2018.

European Commission (2020), Science. Research and Innovation Performance of the EU 2020., DG Research and Innovation, Publications Office of the European Union, Luxembourg.

Borunsky. L., Deiss. R., Martino. R. (2020). *The geography of R&I and productivity: regional disparities and dynamics*. European Commission. Directorate-General for Research and Innovation. Publications Office. 2020. https://data.europa.eu/doi/10.2777/10591

European Investment Bank (2021), EIB *Investment Report 2020/2021: Building a smart and green Europe in the COVID-19 era*.

Fritsch, M., Wyrwich, M. (2021), 'Is innovation (increasingly) concentrated in large cities? An international comparison', *Research Policy*, 50(6).

Fujita, M., Krugman, P., Venables, A.J., (2001), *The Spatial Economy. Cities. Regions. and International Trade*. The MIT Press.

Ganong, P., Shoag, D., (2015), Why has regional income convergence in the US declined?, Cambridge: Harvard Kennedy School Working Paper.

Iammarino, S., Rodríguez-Pose, A., Storper M., (2018), *Regional Inequality in Europe: Evidence. Theory and Policy Implications.*

Isaksen, A., Trippl, M. (2016), *Path development in different regional innovation systems: A conceptual analysis*, In M. D. Parrilli, R. D. Fitjar, & A. Rodríguez-Pose (eds.), Innovation drivers and regional innovation systems.

European Commission(2018), For a transformative industry and innovation strategy. Joint Research Centre. IRITEC Briefs Series. Issue 5.

Grassano. N.. Hernández. H.. Guevara. H.. et al.. (2021). The 2021 EU industrial R&D investment scoreboard: executive summary, Joint Research Centre, European Commission, Publications Office. 2021.

Klepper, S. (2010), 'The origin and growth of industry clusters: the making of Silicon Valley and Detroit', *J. Urban Econ.*, 67, pp. 15-32.

Lansdowne, L.E., (2020), *Exploring the Drug Development Process. Technology Networks*, Published: March 13. 2020.

Lee, N., Rodríguez-Pose, A. (2013). 'Original Innovation. Learnt Innovation and Cities: Evidence from UK SMEs', *Urban Studies*, Urban Studies Journal Limited. 50(9), pp. 1742-1759.

McCann, P., (2019), 'Perceptions of regional inequality and the geography of discontent: insights from the UK', *Regional Studies*, 54 (2). pp. 256-267.

Muscio, A., Pozzali, A., (2013), 'The effects of cognitive distance in university-industry collaborations: some evidence from Italian universities', *The Journal of Technology Transfer*.

Roed Nielsen, K., Nielsen, K. S., Reisch, L. A., (2016), *Reality Test: Users, Innovation and Sustainability: European Policymakers' View on Sustainable User Innovation and Entrepreneurship,* Copenhagen Business School, CBS.

O'Neal, L., Perkins, A. (2021), 'Rural exclusion from science and academia', *Trends in Microbiology*, 29(11), pp. 953-956.

Ponds, R., Van Oort, F., Frenken, K., (2010), 'Innovation. spillovers and university-industry collaboration: an extended knowledge production function approach', *J. Econ. Geogr*, 10, pp. 231-255.

Reuters (2019), *Top 100: Europe's Most Innovative Universities 2019 announced*. RPB. APRIL 30.

Rodríguez-Pose, A., (2001), 'Is R&D investment in lagging areas of Europe worthwhile? Theory and empirical evidence', *Papers in Regional Science*, 80(3).

Rodríguez-Pose, A, Ketterer, T. (2020), 'Institutional change and the development of lagging regions in Europe', *Regional Studies*, 54(7), pp. 974-986

Sonn, J.W., Storper, M., (2008), 'The increasing importance of geographical proximity in knowledge production: an analysis of US patent citations. 1975–1997', *Environ. Plan. A*, 40.

Sterlacchini, A., (2008), 'R&D. higher education and regional growth: Uneven linkages among European regions', *Research Policy*, 37.

CHAPTER 3

R&I FOR SUSTAINABILITY

R&I FOR SUSTAINABILITY

KEY FIGURES

About
2/3
of energy start-ups are clean in the EU in 2020

4.4 m
jobs in the environmental economy sector the EU in 2018

-29 %
is the drop in secure, clean and efficient energy patenting activity in the EU between 2012-2017

Almost
13 %
of material resources used in the EU in 2020 came from recycled waste materials

1 out of 6
climate adaptation patented inventions has been transferred in at least one country between 2010 and 2015 least one country between 2010 and 2015

KEY QUESTIONS WE ARE ADDRESSING

- How does R&I support the achievement of a more sustainable and inclusive society?
- How should R&I policymaking be adopted to better support the deep transformation of our systems towards sustainability?

KEY MESSAGES

What did we learn?

- The scale of current research and innovation policy to achieve the green transition is insufficient for implementing the European Green Deal as the EU's new growth model.
- The EU is the global leader in patenting activity in the areas of climate action, environment and secure, clean and efficient energy.
- There was a general decline in clean and efficient energy patenting activity in the EU between the early 2010s and 2018. Since then, this decline has started reversing, but acceleration in patenting activity would be needed to make up for the lost years. This development is not unique to the EU but can also be seen in the US, Japan, and the UK.
- The EU is the global leader in scientific publications on topics related to sustainability, e.g. sustainable cities and communities, responsible consumption and production, industry, innovation and infrastructure, as well as the adaptation of food systems.
- The transfer rate between high, middle- and low-income countries for climate adaptation technologies is lower than for other technologies, even if adaptation is urgently needed in some developing countries.
- Net-zero-aligned investments can generate jobs as they can lead to activities that are both labour-intensive and fast in implementation.

What does it mean for policy?

- Given the complexity of transition and transformation processes (i.e. complex and interrelated socio-technical systems, goals and interests involved), the structures governing R&I policy processes could be designed to mobilise and support deep transformations across societal and economic systems.
- The five European Missions have the potential to deliver such changes and achieve the objectives of the European Green Deal.

- Emerging technologies, social and place-based innovations are highlighted as essential parts of the transformative change towards sustainable futures.
- The gap in profitability between clean and polluting technologies must be bridged by ensuring an internalisation of the environmental costs of non-green technologies while supporting market innovators seeking to scale-up.
- R&I policies could facilitate an acceleration in patenting activity on clean energy technologies, in particular in sectors with high potential, such as hydrogen and geothermal.
- The uptake of new and green technologies could be accompanied by a just transition approach, where the workers in the downscaling, polluting areas are supported in their transition into related fields of work through reskilling and financial incentives.
- At the European level, the industrial technology roadmaps for R&I under the New ERA for Research and Innovation policy outline the investment needs and conditions for some key products and processes to achieve sustainable transitions.
- Policy efforts need to boost technology transfer to the most vulnerable territories.
- EU R&I policies have a role to play in coordinating the main actors of the transition: industry, universities, and the nations and regions themselves (government and civil society), as they appropriate the transition and tailor it to their own strengths, challenges and opportunities.
- Foresight, experimentation, systems methodologies (e.g. system dynamics, life cycle assessment) and co-creation participatory exercises can bring novel ideas for policy-making and challenge dominant visions.
- EU R&I policies are critical in the policy mix to achieve the green transition and well complement net-zero policies.

Sustainability implies that we should thrive in a safe and just space between planetary boundaries and social boundaries[1] (Raworth, 2017). On the one hand, an environmental ceiling of planetary boundaries should not be crossed as this would mean unacceptable environmental degradation and potential tipping points for the Earth's systems. On the other hand, many dimensions of human deprivation lie below social foundations[2].

Moving into the space between these two boundaries is an aspiration that requires 'far greater equity in the use of natural resources, and far greater efficiency in transforming those resources to meet human needs' (Raworth, 2012). **Economic, social, and environmental sustainability are not separate**. They are interdependent and build upon one another.

1 Planetary boundaries' is a concept which refers to a series of sustainability limits beyond which lie tipping points for many earth systems that could result in the planet becoming inhospitable for humanity. In her book 'Doughnut Economics' (2017), Kate Raworth joined the idea of planetary boundaries with that of a social foundation to provide the 'safe operating space' for humanity.

2 Kate Raworth (2017) has summarised the social foundations in the Doughnut, which shows how the safe and just space for humanity lies between the social foundation of human well-being and the ecological ceiling of planetary pressure.

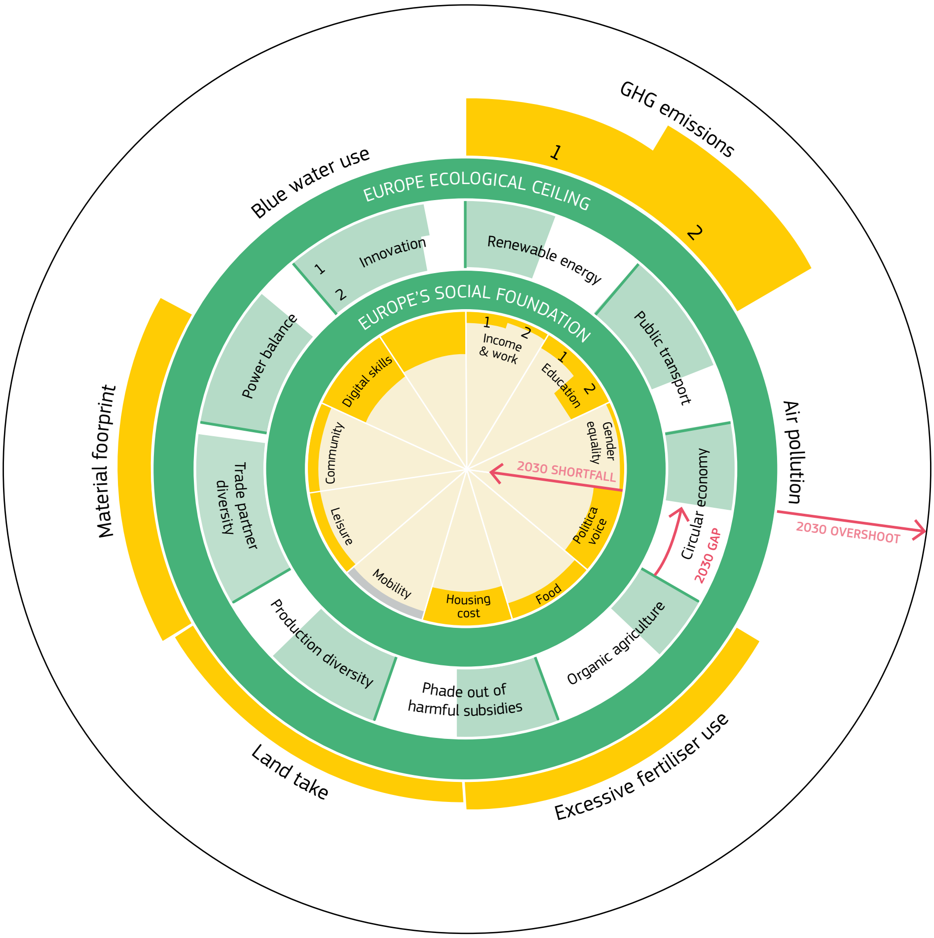
A fair and prosperous society, with a modern, resource-efficient and competitive economy thrives when there are **no net emissions of greenhouse gases and when economic growth is decoupled from resource use**. Thus, protecting, conserving and enhancing natural capital, and protecting the health and well-being of citizens from environment-related risks and impacts are key dimensions of economic sustainability (European Commission, 2019). Economic growth shall be seen as a means to achieving societal goals. These include environmental sustainability, reduced inequality, greater wellbeing and improved resilience (OECD, 2020) and it will require a shift in the economic paradigm (EEA, 2021).

Based on Jeffrey Sachs' thinking (2012 and 2015) and a long-lasting inclusive and participatory consultation process, the new 2030 Agenda for Sustainable Development adopted in September 2015 by all 193 member states of the United Nations (UN) 'embrace the so-called triple bottom line approach to human well-being' (Sachs, 2012, p. 2206). The complex interdependence and mutually reinforcing nature of the three dimensions of sustainable development – economic, social and environmental – is one of the hallmarks of the Sustainable Development Agenda, and paved the way for 17 Sustainable Development Goals (SDGs) and 169 targets to be '**integrated and indivisible, global in nature and universally applicable**' (UN, 2015, p. 13). A vast number of practitioners in R&I have engaged in implementing the approach of the Sustainable Development Goals and enabling deep, sustainable transformations in societal systems like energy, water, mobility, agriculture and health car. Through practice, they have collaborated with policy makers across governmental levels (local, regional, national and European) and strengthen the role of R&I policy in contributing to environmental preservation and climate mitigation while enabling social justice and human well-being, and economic development (European Environmental Agency (EEA), 2019; Fagerberg, 2018). The UN identifies four levers of change, governance, economy and finance, individual and collective action, and science and technology (UN, 2019).

In the previous edition, SRIP 2020, a key message was that **no country in the world seems to meet basic needs for its citizens at a globally sustainable level of resource use** (European Commission, 2020). Europe achieves the social thresholds for almost every indicator, but it does so by transgressing the safe levels for almost all biophysical boundaries. The only one that Europe does not exceed is water use. Besides, the situation is not likely to improve by 2030 as Figure 3.1 shows. At the other extreme, countries like Sri Lanka stand within the safe boundary for every single environmental indicator but only achieve an acceptable level for three of the social indicators. The situation in the United States is similar to the EU, with most social thresholds achieved and biophysical boundaries transgressed. In comparison, China presents more shortfalls regarding the social dimensions but less overshoot on the biophysical aspects.

The EU is fully committed to ensuring prosperity within planetary boundaries. The European Green Deal, a flagship of the von der Leyen Commission that aims to put the EU firmly on the path towards climate neutrality by 2050, is the EU's new growth model. Several packages have been adopted since then to ensure its achievement, in particular the Fit for 55 plan, which adapts existing climate and energy legislation to meet the new EU objective of a minimum 55 % reduction in greenhouse gas (GHG) emissions by 2030. The EU endorses a holistic and integrated approach, mainstreams the SDGs into EU policies and initiatives, with sustainable development as an essential guid-

Figure 3-1: EU 2030 portrait using Doughnut economics



Source: ZOE-Institute for future-fit economies Transformation Policy Report #4 — 11/2021
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-3-1.xlsx

ing principle for all of its policies. This calls for policy coherence as economic activity needs to be increasingly aligned with the four dimensions of competitive sustainability: environmental sustainability, productivity, fairness, and macroeconomic stability[3]. Hence, it requires an integrated multidimensional policymaking approach, which is directional and evidence-informed. The sustainability transformation is also an unprecedented governance challenge at all levels, from local to global.

Well-conceived and coherent policies should stimulate the three sustainability dimensions – environmental, social and economic – to reinforce each other. In order to achieve this, **EU R&I policy could be guided by principles such as co-creation, diffusion, uptake, transformation and the directionality of R&I and be compliant with the 'do no significant harm' (DNSH) principle**[4] enshrined in the European Green Deal objectives.

3 As defined in Articles 17 of Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020 on the establishment of a framework to facilitate sustainable investment, and amending Regulation (EU) 2019/2088.

4 Normalised with goalposts.

Box 3-1. The Transitions Performance Index

The Transitions Performance Index (TPI), a European Commission initiative by DG Research and Innovation, is a scoreboard that monitors, scores[5] and ranks countries on fair and prosperous sustainability. It provides a global ranking for 72 countries[6] in four transitions – economic, social, environmental and governance – over the 2011-2020 decade. These measurements are inspired by a model of prosperity that focuses on resilience, inclusiveness, sustainability and that supports the EU's 2022 Annual Sustainable Growth Survey. The TPI is based on 28 internationally comparable indicators, mostly hard data, and builds on the indicators for the UN's Sustainable Development Goals (SDG) and on the European Commission's current priorities. It offers an evidence-based tool for all who are striving towards fair and sustainable prosperity and intends to contribute to the Beyond GDP debate.[7] The TPI illustrates the specific contributions of each transition to the overall performance of a country, indicating strengths and weaknesses, room for progress, unbalances in their profile and possible trade-offs.

The second edition of the TPI was published in March 2022[8], and includes additional indicators on digital use and skills, and on material footprint compared to the previous report. The latter indicator aims to reflect environmental spillover effects and to better gauge the impact of consumption on the environment.

Figure 3-2: The Transitions Performance Index, 2021

TRANSITIONS PERFORMANCE INDEX

ECONOMIC TRANSITION	SOCIAL TRANSITION	ENVIRONMENTAL TRANSITION	GOVERNANCE TRANSITION
Education	Health	Emissions reduction	Fundamental rights
Wealth	Work and inclusion	Biodiversity	Security
Labour productivity and R&D intensity	Free or non-remunerated time	Material use	Transparency
Industrial base	Equality	Energy productivity	Sound public finances

Source: Authors' elaboration

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-3-2.xlsx

5 Normalised with goalposts.

6 A total of 72 countries are included in the TPI: all EU countries, associated countries, Organisation for Economic Co-operation and Development (OECD) member countries, countries with at least 40 million inhabitants and a GDP per capita higher than USD 2 000 (IMF current dollar estimates).

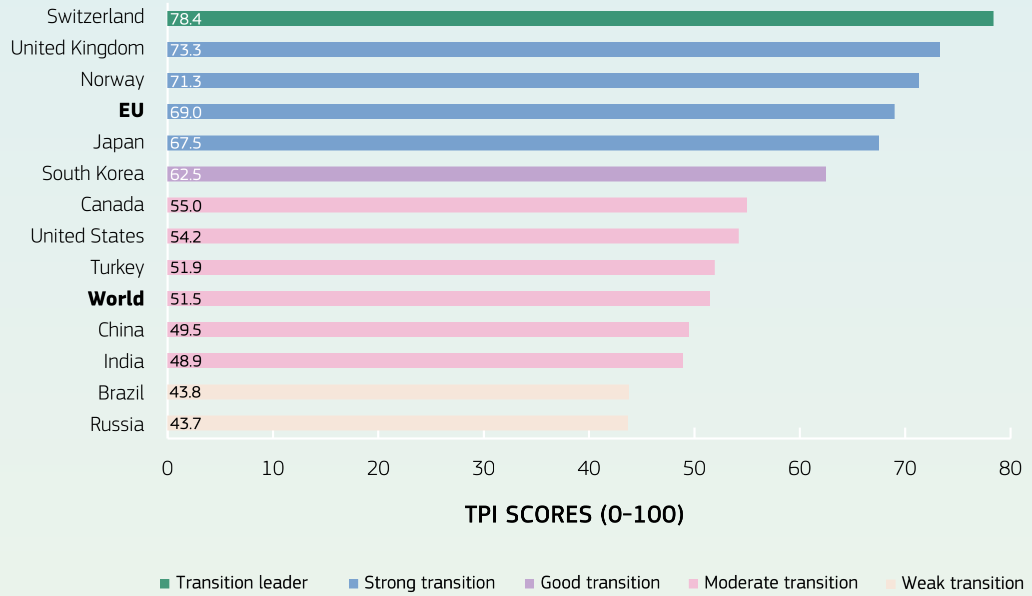
7 Background - Beyond GDP - European Commission (europa.eu)

8 https://op.europa.eu/fr/publication-detail/-/publication/50fff167-a34e-11ec-83e1-01aa75ed71a1/language-en/format-PDF/source-253126101

To respond to global challenges and benchmark countries beyond the EU, a global metric such as the TPI is needed. When looking at the EU's ten main trading partners, the EU[9] ranks fourth (Figure 3.3) and is in the strong transition group. The only main trading partner in the same transition group as the EU outside of Europe is Japan, while South Korea is not far behind in the good transition[10] group. The gap with Canada and the United States is substantial; both countries are in moderate transition, performing slightly better than Turkey, China and India. The world average represents an average moderate performance as well, whereas Brazil and Russia are in the weak transition group. In terms of progress, since 2011 China has progressed by 7.6%, the United States by 3.3% and the EU by 4.9%[11].

All EU countries belong to the groups of leaders, strong or good transition: none belongs to the moderate or weak transition groups (Figure 3.4). It is therefore a robust indication of the overall positive impact of EU orientations. Denmark (ranking first among EU countries) and Ireland are transition leaders. In terms of

Figure 3-3: European Union and main partners TPI scores 2021 and transition group



Source: European Commission, Tranistion Performance index 2021

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-3-3.xlsx

9 Population-weighted average of the 27 EU Member States

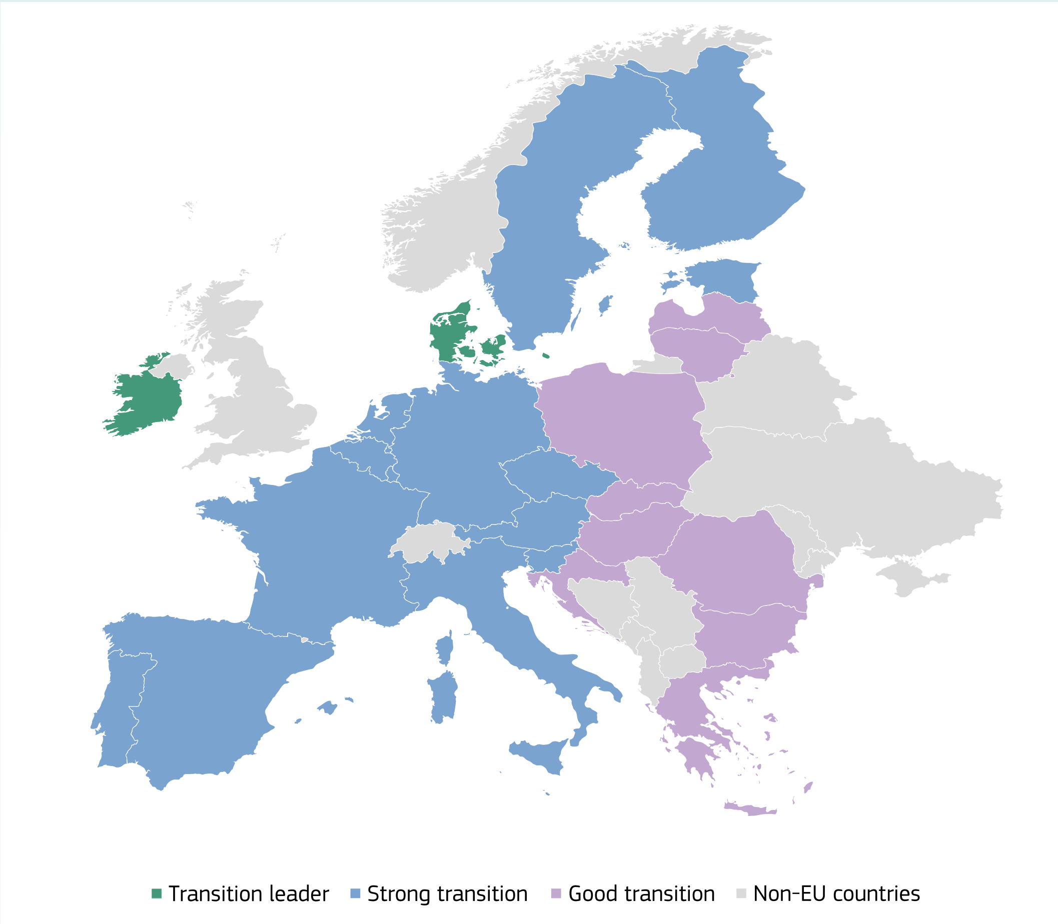
10 Five performance groups are defined with fixed score intervals.

11 For comparison the world TPI arithmetic average is 6.2%.

progress in the EU, all but one EU country have improved their performances since 2011, particularly Croatia, which showed an exceptional result of catching up (13.5%), and Greece and Estonia (above 10% progress). Cyprus, Finland and Sweden progressed less than 2%, whereas Hungary is the only EU Member State that stagnated over the last 10 years (-0.2%). These countries are at risk of losing ground in the transition process unless they renew collective efforts. When looking at the performance by pillar, EU Member States have not improved sufficiently in the economic and environmental transitions. Pursuing ambitious targets and related investments in these domains is an absolute necessity if the EU and Member States wish to achieve balanced and sustainable prosperity.

Several other key features emerge from the TPI results. Country disparities highlight that performance and progress are not predetermined by income group or geographical position; they do require, however, relevant policy efforts. Looking at the results by transitions, progress has been significant in the Economic (10.1%),

Figure 3-4: EU Member States Transitions Performance Index groups (2020)



Source: European Commission, Transition Performance Index 2021

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-3-4.xlsx

Environmental (6.0 %) and Social (4.7 %) transitions, whereas on average the 72 countries show a decline in governance (-2.6 %). Nevertheless, these results hide large disparities between countries that are analysed more thoroughly in the report. The large heterogeneity in economic performance shows opportunity for progress. Social transition is the most successful pillar with 26 leader performers. The decline in scores for governance transition at the global level is partly driven by the strong deterioration of public finances. The environmental transition has a different dynamic than the three other transitions, showing that most countries have not bended their curves for their green transition.

While the effect of the pandemic is not fully captured statistically in this year' edition, the pandemic has had a considerable impact on transition processes and challenges social cohesion and resilience, both of which are key enablers for a fair and sustainable transition.

1. R&I delivering on societal challenges

1.1 R&I is fundamental to preserving biodiversity and enabling the transition to a net-zero world

All the scenarios that limit warming to below 2° C heavily rely on research and technology progress and its uptake. In addition to demand management, phasing-out, change in the functioning of the economic system, it is estimated that **half of the global reductions in CO_2 emissions by 2050 will have to come from technologies that are currently at the demonstration or prototype phases** (IEA, 2021). Besides, numerous studies confirm the positive impacts of green innovation on environmental protection (for a complete literature review, see Takalo et al., 2021).

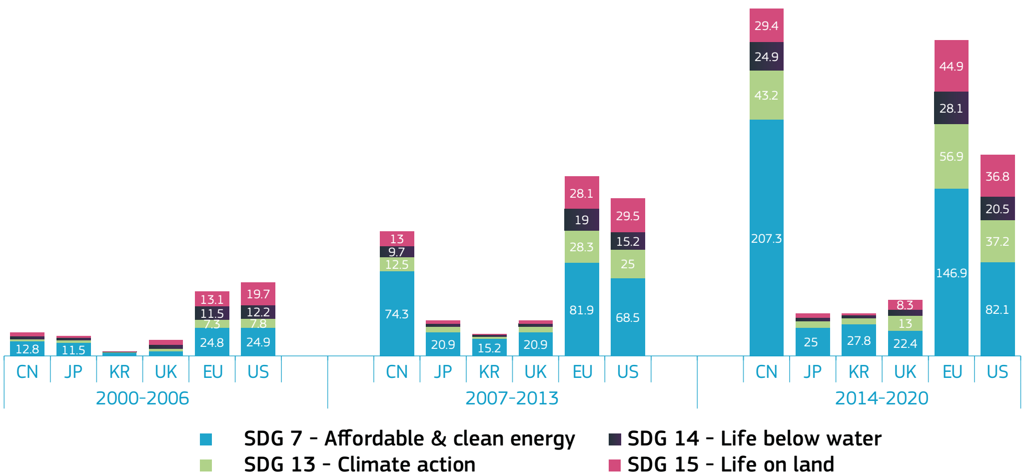
Strengthening the science base on the environment and nature is a key element to ensure the preservation of biodiversity and ecosystems. The EU has long been in the lead in terms of scientific publications dedicated to four environmentally related SDGs – climate change, clean energy, life on land and life below water – but has lately been surpassed by China. Figure 3.5 demonstrates that the volume and the share of publications dedicated to climate change, clean energy, life on land and life below water have increased worldwide over the past two decades, despite a slowdown in the pace of publications on clean energy in the EU and the United States beginning in the mid-2010s.

Over 2014-2020, China has substantially intensified publication in these areas and has also surpassed the EU in terms of quality for affordable energy and climate action (Table 3-1). **Scientific knowledge leads to continuing demand for strengthening strategies to preserve and restore ecosystems**, such as wastewater policies for sanitation, the definition of protected areas, which have proven to be essential for biodiversity conservation (Coetzee et al., 2014). For the life below water SDG, it is worth noting that the EU has established a significant toolbox containing nearly 600 policy tools (170 at the EU level and 417 at the national level) that together form a coherent framework to achieve this sustainable goal[12]. The **identification of protected areas across the EU relies on scientific criteria** to ensure that they have the highest potential for preserving biodiversity (wetlands for migratory waterfowl, sites gathering 1 % of the population of listed vulnerable species). **These protected areas also facilitate research on biodiversity, driving forward knowledge for refining preservation and protection policies.**

Environmental knowledge created but not yet brought to the market by incumbent companies or research organisations **shapes the creation and financing of green start-ups** (e.g. Audretsch and Keilbach, 2004). Environmental knowledge positively impacts new venture creation in green technologies as entrepreneurs and start-ups' new ideas for business are based on such knowledge (Colombelli and Quatraro, 2017; Cojoianu et al., 2020).

12 https://ec.europa.eu/oceans-and-fisheries/news/new-report-eus-performance-un-sustainable-development-goal-14-2021-05-11_en

Figure 3.5: Number of scientific publications[1] in climate action, life on land and below water and clean energy



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Science-Metrix using Scopus database.

Note: [1] The data labels are expressed in thousands of publications and the publications for each SDG are not mutually exclusive. Fractional counting used.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-3-5.xlsx

Table 3-1: Percentage of highly cited publications per SDG, per country/region, 2018

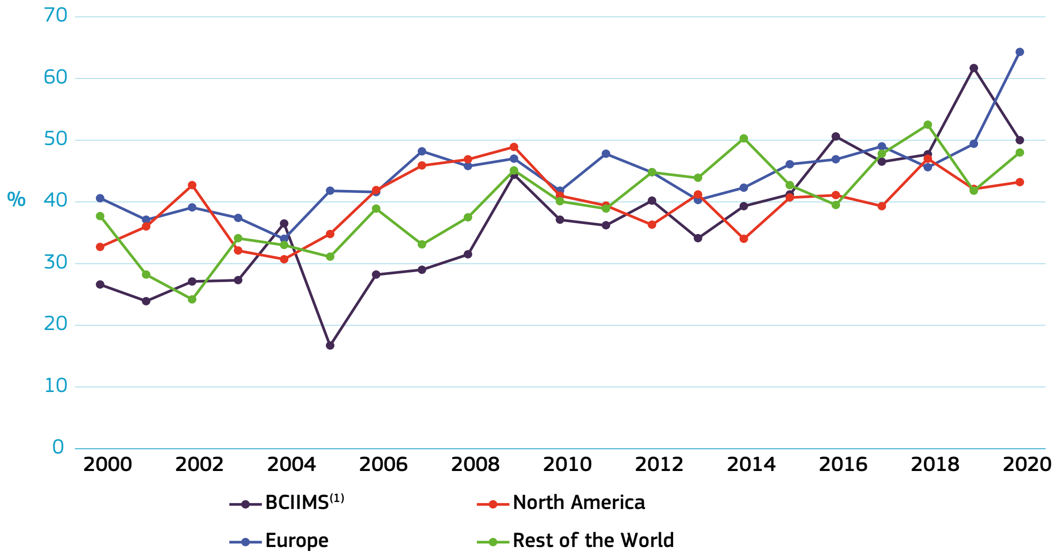
	CN	JP	KR	EU	UK	US
SDG 7 – Affordable and clean energy	**19.0**	9.1	11.6	13.6	19.9	19.5
SDG 13 – Climate action	**18.9**	10.8	10.2	16.5	20.9	19.9
SDG 14 – Life below water	**13.6**	8.2	9.3	16.3	21.2	16.0
SDG 15 – Life on land	**11.5**	7.0	6.1	12.7	17.9	11.3

Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Science-Metrix using Scopus database.

Note: The data labels are expressed in thousands of publications and the publications for each SDG are not mutually exclusive. Fractional counting used.

Figure 3.6: Evolution of the share of clean energy start-ups(2) in total energy start-ups by region, 2000-2020



Science, Research and Innovation Performance of the EU 2022

Source: International Energy Agency calculations based on company-level data obtained from Crunchbase (www.crunchbase.com).

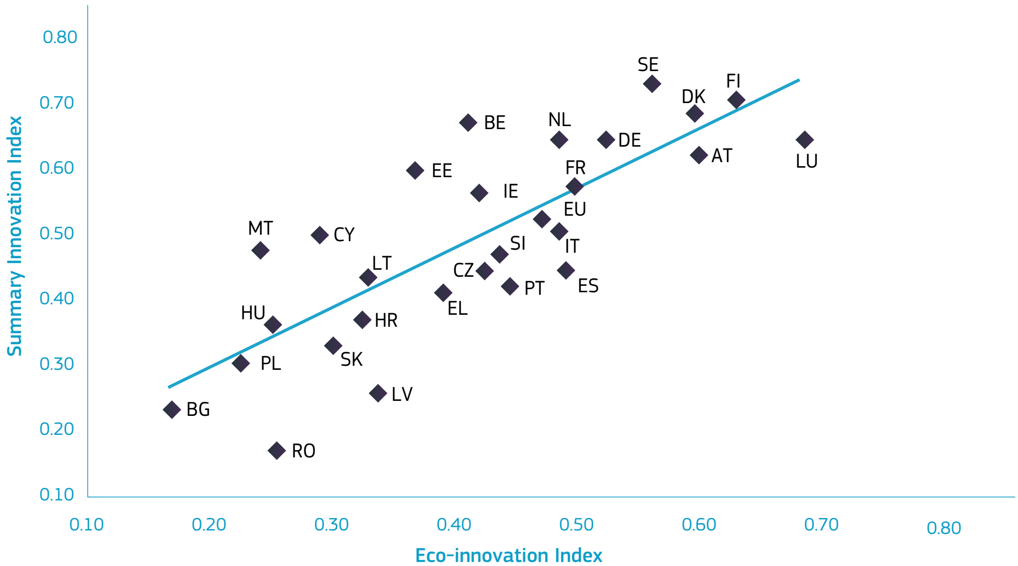
Note: BCIIMS – Brazil, China, India, Indonesia, Mexico, South-Africa. Start-ups are classified according to a taxonomy of over 700 labels, amongst which 26 tags have been identified as explicitly energy-related and tags characterised as 'clean' (e.g. renewables) by the nature of the tag itself, and those which separately list any energy tag in addition to a 'clean' tag in the descriptions of their business strategies.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-3-6.xlsx

Strengthening the science base on both the natural capital and green aspects of our economy has developed new market opportunities for process and product innovations. Such knowledge feeds the creation of clean start-ups. For example, over 2000-2020, the share of clean start-ups in the total number of energy start-ups has increased significantly in each region of the world, including in Europe, which had an increase from 41 % to 64 % in 2020 (Figure 3.6).

There is a strong positive correlation between the Eco-Innovation Index and the Summary Innovation Index (i.e. the composite index of the European Innovation Scoreboard). The summary Eco-innovation index is a composite indicator, which measures the performance of EU Member States on environmental innovations (Figure 3.7). Given that both indices aim at measuring innovation performance, are based on a similar methodology and have a number of common indicators, this relation is not surprising. According to the Eco-Innovation Index 2021, there are nine Eco-Innovation leaders in Europe: Luxembourg, Finland, Austria, Denmark, Sweden, Germany, France, Spain and the Netherlands. Three of them, Sweden, Finland and Denmark, are also Innovation Leaders. Given that the EIS' Summary Innovation Index and the Eco-Innovation index are highly correlated, eco-innovation should be central to the strategic planning of national economies.

Figure 3-7: Comparison of the Eco-Innovation Index 2021 and the European Innovation Scoreboard 2021 (normalised scores)



Source: EU Eco-Innovation Index 2021 Policy brief July 2021
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-3-7.xlsx

Technological progress is critical in mitigating the effects of climate change as the use of technology reduces the investment costs of emissions reduction policies. Thanks to technological development, the global production costs of wind and solar energy have significantly decreased in recent years, even though there are substantial differences in total installed cost across countries (Figure 3.8). This reduction makes clean energy a realistic alternative to fossil-fuel resources, and solar and wind are currently the cheapest forms of new power generation in a large number of countries (representing over 70 % of global GDP, which includes several European countries, cf. Stern and Valero, 2021). The integration of clean energy technologies currently plays an important role in climate change mitigation (Perera et al., 2017). In the past, since the deployment of clean energy projects was not cost effective, any drop in oil prices induced a shift from renewable investment back to fossil fuel energy (Ozdurak, 2021). However, **for some other clean resources, such as hydropower and geothermal, installed costs have not significantly decreased over the past decade** (Figure 3.8). Besides, the cost of these clean energy sources still exceeds the cost of fossil fuels. Hence, deeper decarbonisation will likely require significant innovation-driven cost reductions, in particular for

Figure 3-8: Evolution of global costs and production capacity of renewable energy, 2010-2019

Source : DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit based on IRENA and Eurostat.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-3-8.xlsx

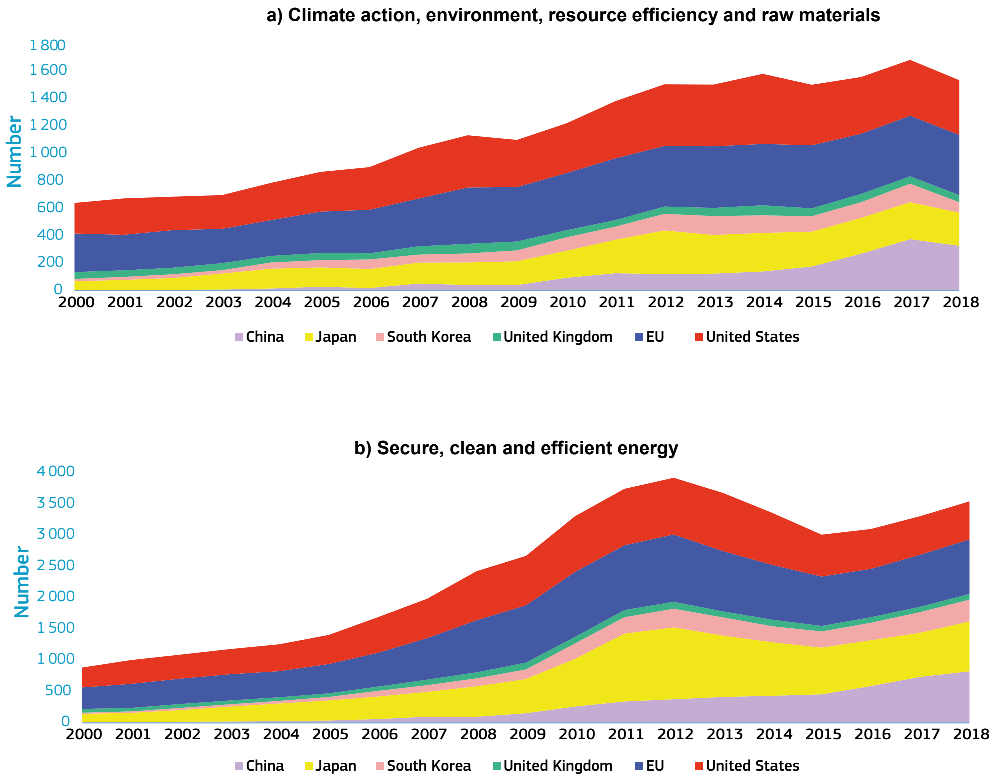
energy storage technologies, which can provide the power system with the flexibility required when intermittent renewables are present in the electricity generation mix (Giarola et al., 2021; Stock, 2021).

The EU is the global leader in patenting activity in the climate action, environment and secure, clean and efficient energy sectors. However, there has been a global decline in clean and efficient energy patenting since the early 2010s, though more recently this trend has reversed (Probst et al., 2021; IEA, 2019; Figure 3.9). During the 2010s, patenting in the areas of clean and efficient energy has indeed dropped drastically in Japan (-41 % over 2012-2017), the US (-36 % over 2013-2018), the EU (-29 % over 2012-2016), the UK (-24 % over 2011-2017) and South Korea (-15 % over 2012-2015). Conversely, China's patent applications in secure, clean and efficient energy have more than tripled from 2012 to 2018, even though the growth rate slowed down between 2013 and 2016. A detailed study of the IEA and EPO (2021) shows that, **after a rapid rise in the period to 2013, patenting activity in low-carbon energy technologies slumped as well between 2014 and 2016**. Market prices have provided insufficient incentives for the development of innovations that lower emissions, in particular following the significant fall in carbon prices set by the EU Emissions Trading System (ETS) after the start of the global financial crisis in 2008 and again around 2011 (EIB, 2020). Some of the decline could also be explained by the increasing maturity of climate change mitigation technologies in these markets, resulting in a lower propensity to patent. For example, many of the more recent developments that have brought down costs in the solar PV sector are likely to be related to improved know-how in exploiting the innovations from previous years (IEA, 2021).

An acceleration in patenting activity on clean energy technologies, in particular in sectors with high potential such as hydrogen and geothermal, is needed. However, while solar and wind technologies have reached a certain maturity, it is not the case for other technologies, such as energy storage or hydrogen applications for transport, as well as hydropower energy sources and bioenergy (including geothermal), for which total installed costs have not significantly been brought down (Figure 3.9). **Since 2017/2018, patenting activity in low-carbon technologies has been increasing again, but at a rate that remains below that witnessed before 2013. An acceleration in activity would be needed to make up for the lost years** (IEA, 2021). Patents in fossil energy have experienced a four-year decline starting in 2017, unprecedented since the second World War. This decline can mean a more definite shift to clean energy sources.

Should we have a limited but targeted focus on some key industries and technologies to achieve the transition? Figure 3.10 demonstrates that over 80 % of the GHG emissions by European industry comes from three sectors: electricity, gas, steam and air conditioning supply (34 %), manufacturing (31 %), and transportation and storage (18 %). Besides, **the manufacturing of only four categories of product**s – non-metallic products (in particular cement), metals (in particular steel and aluminium), chemicals and coke and refined petroleum –, **is responsible for about 27 % of all CO_2 emissions in Europe.** Large reductions in industrial GHG emissions would therefore seem possible by focusing on a limited set of product and process improvements (Risman et al., 2020). Furthermore, some scenarios to limit global warming foresee great efforts on a few key technologies, such as clean hydrogen, and innovative processes to achieve the transition to a net-zero world.

Figure 3-9: Evolution of number of patent applications[1] filed under PCT in climate action, environment, resource efficiency, raw materials and clean energy, 2000-2018



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Science-Metrix using EPO PATSTAT dababase.

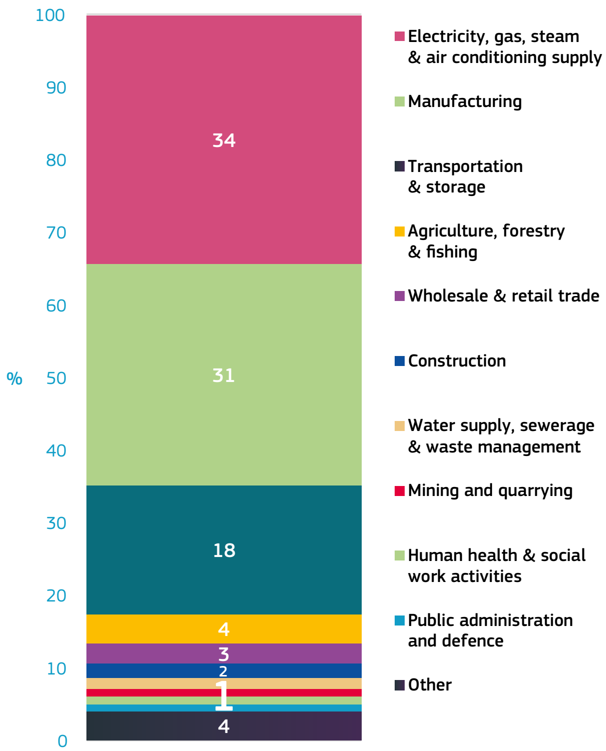
Note: [1]Fractional counting used.

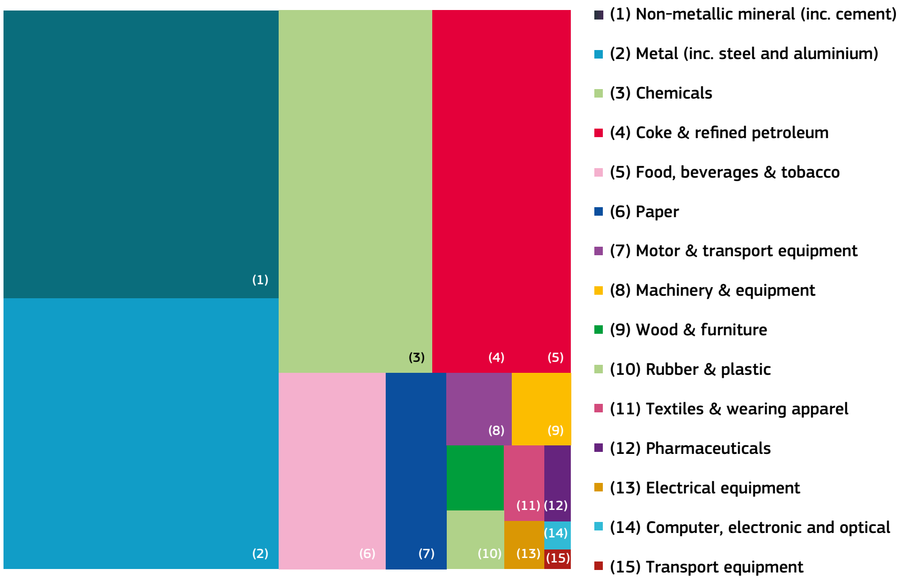
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-3-9.xlsx

The industrial technology roadmaps for R&I under New ERA for Research and Innovation', map the investments needs and the conditions for some key products and processes to achieve the sustainable transitions in the EU. The European industrial alliances in hydrogen, batteries, and raw materials, involving public authorities and industries, provide open platforms to establish the coordination of research, development and innovation investment plans for these key technologies (See Chapter 2.1 – Zoom out).

Figure 3-10: CO_2 emissions in the EU in some key sectors, 2019

a) CO_2 emissions per sector (% of total)





Science, Research and Innovation Performance of the EU 2022

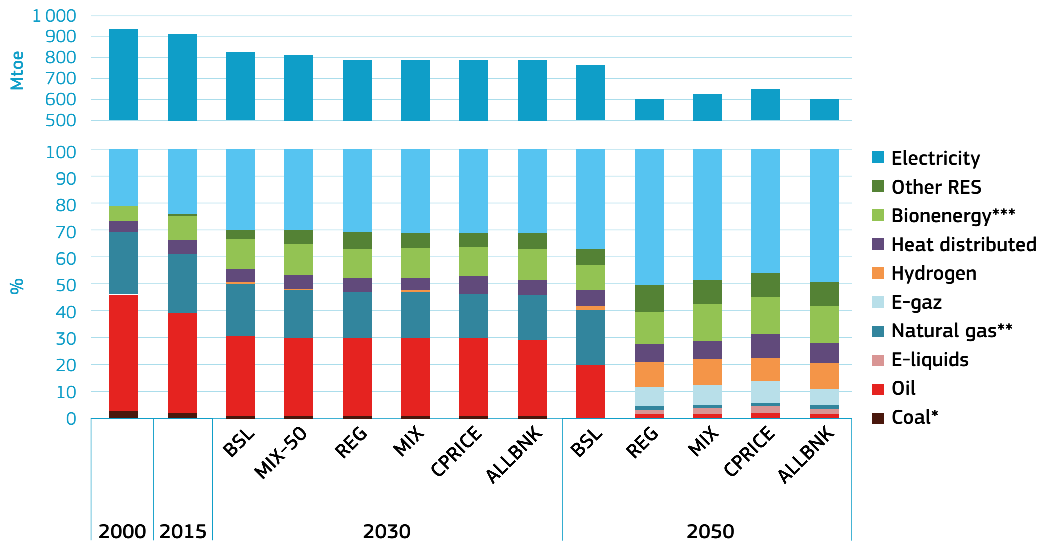
Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Eurostat (online data code: ENV_AC_AINAH_R2)

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-3-10.xlsx

The EU green transition and its pace rely heavily on geopolitical context. The EU Green Deal is expected to solve the EU's energy security problems related to the highly dependent relation between EU and its current main energy suppliers, notably Russia, but in the long run. Following the adoption of a new greenhouse gas emission target for 2030, the European Council concluded that EU member states were free 'to decide on their energy mix and to choose the most appropriate technologies to achieve collectively the 2030 climate target, including transitional technologies such as gas' . Estimations by the European Commission (2020) using different scenarios foresee that most of the change for oil and gas will happen between 2030 and 2050 and natural gas will contribute just a tenth of EU energy in 2050 (Leonard at al., 2021). However, it also shows that, between 2030 and 2050, gas, mainly imported, will be a transitional source (Figure 3.11). Some uses, like high-temperature heat in industrial processes, cannot indeed be easily replaced by green electricity. Only 40% of Europe's industrial use of gas is in low-temperature applications that can be readily electrified. Hydrogen for powering vehicles, generating electricity or providing long-term energy storage could support such a transition but not in the short term. Furthermore, between 2010 and 2014, 60% of imports of raw materials came from China.

Europe's demand for raw materials is forecast to double by 2050 (European Commission, 2020) and it has hardly any mining or processing activity for these primary minerals (see Chapter 2.1 – Zoom out). Substitution, the application of the circular economy principles with new business models for intensified use of products and components, along with the full use of secondary materials' resources are important knowledge intensive innovation pathways that may require more attention in the future to overcome these issues.

Figure 3-11: EU energy mix evolution – target: -55% lower emissions in 2030 compared to 1990 and climate neutrality in 2050



Source: European Commission (2020).

Note: All scenarios are considered: BSL, MIX-50, REG, MIX, CPRICE, ALLBNK.

Note: * includes peat, oil shale; ** includes manufactured gases; *** solid biomass, liquid biofuels, biogas, waste.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-3-11.xlsx

Box 3-2: Boosting R&I on strategic areas and technologies under the EU's R&I framework programme: examples of R&I projects funded by Horizon 2020

Semiconductor:

New-generation power semiconductors, made in Europe | Research and Innovation (europa.eu) An EU, industry, national and regional-funded research project has developed the next generation of energy-efficient power semiconductors using gallium nitride devices on innovative substrates.

Novel silicon lasers promise semiconductor revolution | Research and Innovation (europa.eu) An EU-funded project is enabling efficient intra-chip and chip-to-chip communication via a new type of silicon capable of emitting light. It is demonstrating a technological breakthrough that could revolutionise the electronics industry and make devices faster and much more energy efficient.

Batteries:

Boosting battery power for electric vehicles | Research and Innovation (europa.eu) EU-funded researchers are developing a high-energy lithium-ion battery to power a range of electric vehicles. They aim to meet growing demand for greener transport and to help Europe establish a competitive advantage in battery cell production.

A tiny battery solution with huge potential for Europe | Research and Innovation (europa.eu) Pioneering EU-funded research on new solid-state batteries is paving the way for tiny yet powerful batteries for safer and better space applications. Industry partners are advancing with plans to commercialise thin-film energy-storage technologies and processes at the heart of the project.

Technology:

Pioneering photolithography for 7 nm chips | Research and Innovation (europa.eu) Cutting-edge photolithography technology developed by an EU-funded consortium has enabled the launch of a new generation of high-performance smartphones featuring powerful and efficient 7 nm-node mobile processors

Cloud technology:

Building a cloud-based hub for all things research | Research and Innovation (europa.eu) The EU is developing a dedicated cloud repository for all the scientific research happening in Europe. To ensure easy access to and reuse of this information, the EU-funded EOSC-hub project developed an intuitive user interface and other tools. Researchers can now take advantage of the wealth of information already stored on the cloud, ultimately benefiting citizens as science becomes more open.

Sustainable technology:

Innovative metal recycling for sustainable tech | Research and Innovation (europa.eu) EU-funded researchers are developing low-polluting techniques for recovering valuable metals from communications and green technology waste. This urban mining could help to reduce pollution and ensure a secure supply of metals critical to a low-carbon, connected economy.

Hydrogen:

[Using hydrogen to reduce industry's carbon footprint | Research and Innovation (europa.eu)]
The steel industry is one of the world's biggest greenhouse gas emitters. To change this, the EU and industry-funded H2Future project is showing how a steel production plant can operate using green hydrogen made from renewable electricity. Once finalised, this new technology could play a key role in helping Europe meet its goal of becoming climate-neutral by 2050.

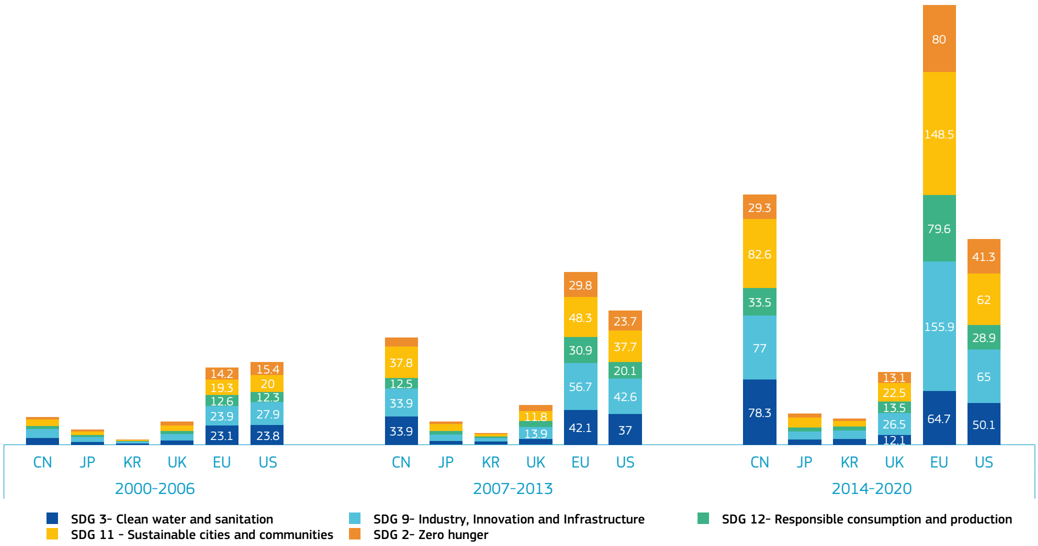
Pharmaceutical:

[Replacing an enzyme to control a very rare disease | Research and Innovation (europa.eu)]
Until recently, there was no treatment specific to alpha-mannosidosis, one of the many rare diseases that jointly affect some 30 million citizens in Europe alone. Today, there is as EU-funded research developed enzyme-replacement therapy to stop the illness in its tracks, and this medicine is on the market.

1.2 R&I is essential for adapting our territories, food, water systems, infrastructure, and our ways of producing and consuming

By providing us with real-time information and future scenarios, research can help us to foresee where and when populations could be affected by future shocks. Scientists, including the wide research community involved in the drafting of the IPCC reports, rely on the latest state-of-the art technologies and techniques such as remote sensing, imagery processes, soil evolution and water-streams mapping and modelling to understand and predict nature-related hazards, reduce error estimation in scenarios for the future and provide accurate evidence for policy development. The volume of publications on food, water, industry and infrastructure, including sustainable cities and communities, as well as on responsible consumption and production have significantly increased over the past two decades (Figure 3.12). From 2014 to 2020, Europe was a leader in publications related to sustainable cities and communities (1), responsible consumption and production (2), industry, innovation and infrastructure (3), with the EU share being respectively 43 %, 40 % and 41 % of the global scientific output in these three fields. China has been catching up at a very high growth rate and has been in the lead in terms of number of publications related to clean water and sanitation in the 2014-2020 period and has overpassed the EU in terms of quality as well (Table 3-2).

Figure 3-12: Number of scientific publications (frac. count) in food, water systems, industry and infrastructure, sustainable cities and communities and responsible consumption and production



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Science-Metrix using Scopus database.

Note: [1]The data labels are expressed in thousands of publications and the publications for each SDG are not mutually exclusive. Fractional counting used.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-3-12.xlsx

Table 3-2: Percentage of highly cited publications per SDG, per country/region, 2018

	CN	JP	KR	EU	UK	US
SDG 2 – Zero hunger	**13.6**	10.5	5.7	14.6	21.9	17.0
SDG 6 – Clean water and sanitation	**16.6**	9.0	13.0	12.5	15.4	13.0
SDG 9 – Industry, Innovation and Infrastructure	**16.1**	9.4	8.9	15.7	23.5	20.0
SDG 11 – Sustainable cities and communities	**13.4**	5.8	8.9	12.2	17.1	15.3
SDG 12 – Responsible consumption and production	**15.3**	7.2	8.8	13.6	20.7	15.0

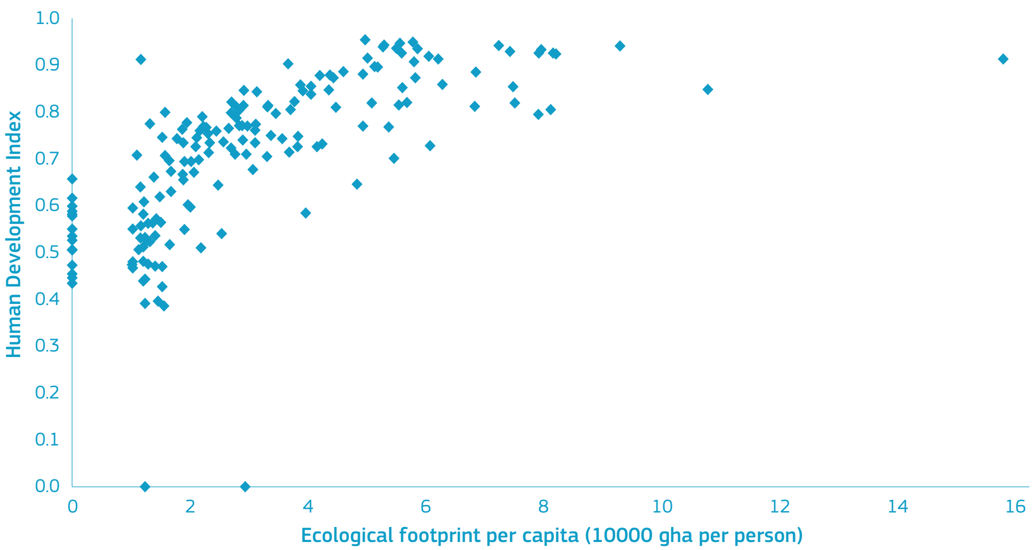
Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Science-Metrix using Scopus database.

Research and innovation can help to avoid a trade-off between human development and ecological preservation through the development of innovative business models and sustainable and responsible ways of producing and consuming. In most countries there is increased pressure on the ecological resources and pollution rates due to urban expansion, unsustainable pathways of consumption and production, globalisation and population growth (Kassouri and Altıntaş. 2020). This leads to a clear correlation between human development and environmental footprint (Figure 3.13; UNDP, 2020), which may create a trade-off as both preserving our ecosystems and improving human well-being are at the centre of the SDG agenda. Technological progress can deliver solutions to this potential trade-off.

The circular economy, for example, proposes an innovative model in which materials are circulated in closed-loop production systems to reduce depletion and waste (Ellen MacArthur Foundation, 2012). In the EU, the circular material use rate went from 8.4 % in 2004 to 12.8 % in 2020, whereas the value-added and employment in recycling and secondary raw materials sectors, as defined by Eurostat, remained almost unchanged between 2011 and 2018 (0.97 % of GDP and 1.7 % of total employment) (Eurostat, 2021). Furthermore, some projects under the EU's R&I framework programme aim at increasing knowledge on lifestyles compatible with the respect for planetaries boundaries. For example the EU's 1.5 Lifestyles project connects an analysis of individual lifestyle perspectives with an investigation of structural influences on lifestyle choices and impacts. Transforming towards global sustainability requires a dramatic acceleration of current progress. Hence, **there is growing interest in finding positive tipping points at which small interventions can trigger self-reinforcing feedbacks**

Figure 3-13: Relation between the Human Development Index and ecological footprint (2017)

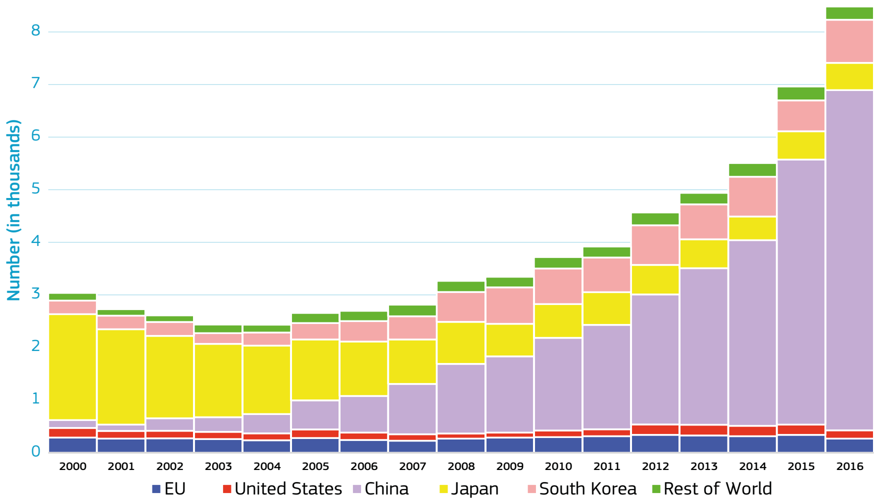


Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on World Bank and World Population review.
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-3-13.xlsx

that accelerate systemic change (Lenton et al., 2021). A better understanding of technical/social tipping points will be essential also to enable the transition to a sustainable and circular bioeconomy and a building block of a 1.5 Lifestyle.

The **EU's share of patents related to recycling and secondary raw materials is only 7.5%, while China has become the leader in patented innovations in these sectors within less than 15 years, reaching a 74% share in 2016** (Figure 3.14). The adoption and deployment of circular solutions are often associated with deep process transformation and long-term investments, which may need public support. Digital solutions are also essential for providing the information necessary for the introduction of circular solutions. They have enabled more potential for resource efficiency and productivity gains, such as smart grids to energy networks and automated manufacturing techniques (Stern and Valero, 2021). Digital solutions are also critical for raw materials supply security and resilient value chains. At the European level, the circular economy is being promoted and facilitated through the Circular **Economy Action Plan** (CEAP)[13], which was adopted by the European Commission in 2020 as one of the main building blocks of the European Green Deal and which introduces a set of legislative and non-legislative measures targeting areas where action at the EU level brings real added value.

Figure 3-14: Evolution number of the patents related to recycling and secondary raw materials, 2000-2016



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit based on Eurostat (CEI_CIE020).

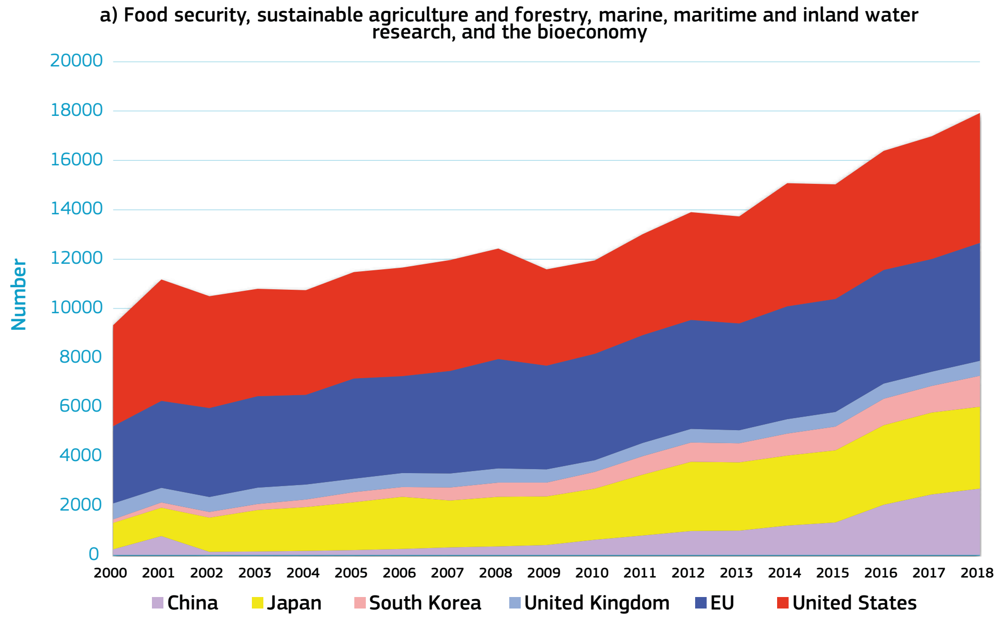
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-3-14.xlsx

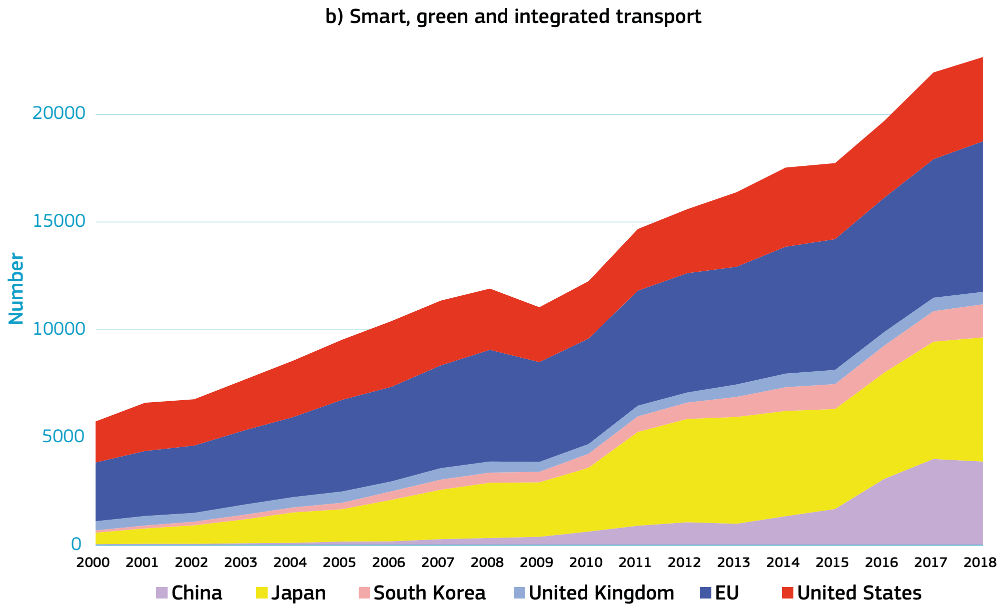
13 Circular economy action plan (europa.eu)

Despite the growing need for adaptation in our food and water systems, patenting activity in food security, sustainable agriculture, water and the bioeconomy has experienced lower growth rates over the past two decades compared to other areas. The overall volume of patents in food security, maritime and inland water and bioeconomy have increased from 2000 to 2018 (Figure 3.15). The increase in the EU and US happened at a much slower pace than for areas such as smart transport or climate action. China and Japan have multiplied their volume of patents in these areas by respectively per 10 times and 7.5 times between 2000 and 2018 (Figure 3.15). But in the UK, the volume has stagnated. Besides, the shares of patents dedicated to these areas have decreased in every major region. **Such declines may be linked with the stagnation of efforts towards adaptation**, which has been documented by a joint report from the World Bank and the International Bank for Reconstruction and Development (2020). These tendencies stand in contrast with the trends for climate change and clean energy technologies, whose shares in total innovation nearly doubled from 2000 to 2011 (Figure 3.9), but then experienced a decline until 2015. Considering the growing adaptation needs in our food and water systems, as well as the importance of the bioeconomy for the green transition, these tendencies raise concerns and justify more policy support.

Patenting activity in **smart, green and integrated transport has experienced an increase in volume both worldwide and at country/regional level, even if the sector's share in the total number of patents has remained almost constant**. In these sectors, the deployment and adoption of innovative solutions should be a key focus. Horizon Europe integrated the need to transform our ways of consuming, and several projects, which will assess different lifestyle options, have already been launched. As an example, the EU-funded FULFILL project will explore the contribution of lifestyle changes and citizen engagement in decarbonising Europe and fulfilling the goals of the Paris Agreement.

Figure 3-15: Evolution in the number of patent applications[1] filed under PCT in sustainable agriculture and forestry, marine and inland water research, bioeconomy and transportation, 2000-2018





Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Science-Metrix using EPO PATSTAT database.

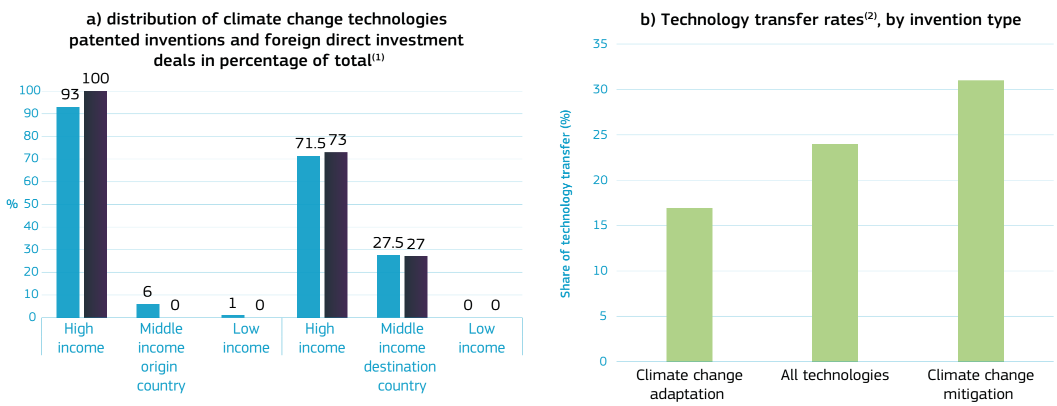
Note: [1]Fractional counting used. 2020 Societal Grand Challenge (SGC) considered over the total patents applications filed for all the SCGs.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-3-15.xlsx

Intermediaries and R&D organisations are critical in developing adaptation pathways fit to local specificities and for coping with the mismatch between territories' adaptation needs and technological capacity. Collaborations between industry, public institutions and R&D organisations are critical to get technical guidance and advice to adapt to the shocks to come (Huggel et al., 2015). Knowledge production needs to be done also at the local level. Besides, as value chains are now scattered worldwide, there is also a challenge to capture the international spillovers of EU consumption and production, and technology transfer is critical. Recent research has demonstrated a clear mismatch between adaptation needs, particularly those linked to climate change, and the technological capacities of countries, regions and communities (Dechezlepretre et al., 2020).

Only 17% of patented climate adaptation[14] inventions cross at least one border, which is significantly below the average for all technologies (24%) and about half that of mitigation

Figure 3-16: Technology transfer rate of adaptation technologies, cumulated volume 2010-2015



Science, Research and Innovation Performance of the EU 2022

Source: Dechezlepretre at al. Invention and Global Diffusion of technologies for climate change adaptation: a patent analysis. 2020 International Bank for Reconstruction and Development / The World Bank based on Zephyr database (Bureau Van Dijk, Brussels) and World Patent Statistical Database (PATSTAT) (European Patent Office).

Note: (1)The figure display the percentages of patents filed in both an origin country and at least one destination country and the FDI consider 243 deals in total. (2)The technology transfer rate is defined as the share of patented inventions that are filed in at least two different patent offices.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-3-16.xlsx

14 Defined using the Y02A category of the European Patent Office which identifies all patents in PATSTAT pertaining to 'technologies for adaptation to climate change'.

technologies (31 %) (Figure 3.16). Besides, **while 93 % of patented inventions in the field of climate adaptation originated from high income countries**, only 27.5 % of patents are filed in middle-income countries and none in low-income countries (data refer to the 2010-2015 period).

A similar distribution is observed for foreign direct investment related to climate adaptation: 100 % originates from high income countries, 27 % involve a middle-income country and none involves a low-income country (Figure 3.16; Dechezlepretre et al., 2020).

Finally, by matching technological capacities and risks as raised in the latest IPCC reports, it appears **that countries with strong technological capacities typically face lower adaptation needs, and reversely countries where adaptation needs are high are less equipped.**

Universities and research centres could play a critical role in supporting the diffusion of solutions for adapting our systems. Public policies can support collaboration and partnerships between research centres, industry and public authorities. Such an approach has been integrated in Horizon Europe's strategic planning, which features both European Partnerships and Missions (see Part 3 of this chapter). Furthermore, universities should be supported in their independence and ability to experiment with new models of education and societal interaction, in order to foster both technological innovation and innovative policy ideas to emerge and be taken up[15]. **The European Commission also adopted its new EU strategy on adaptation to climate change in 202**1. It sets out how the European Union can adapt to the unavoidable impacts of climate change and become climate resilient by 2050. The strategy has four principle objectives: to make adaptation smarter, swifter and more systemic, and to step up international action on adaptation to climate change.

15 https://ec.europa.eu/info/publications/transformation-post-covid-future-european-universities_en

Box 3-3: The contribution of the European framework programme for R&I to the knowledge base of recent IPPC reports[16]

To analyse the contribution of EU funding to the IPCC's evidence base, the paper uses the references of published IPCC reports, cross-checking them with databases containing publications originating from EU-funded research.

This analysis focuses on the reports of the IPCC's 6th assessment cycle and processes the references of the reports published so far: three special reports (*Global Warming at 1.5 °C, published in October 2018, Climate Change and Land from August 2019 and Ocean and Cryosphere in Changing Climate*, published in September 2019) and the contribution of Working Group I to the Sixth Assessment Report (*AR6 Climate Change 2021: The Physical Science Basis*, published in draft form in August 2021). For publications from EU-funded projects, a dataset combining, on the one hand, publications reported by grant holders as contained in the EU open data portal and, on the other hand, publications indexed in the OpenAire Research Graph[17]. Only data from the last two funding programmes: the 7th Framework Programme (FP7, 2007-2012) and Horizon 2020 (H2020, 2013-2020) are used.

Matching yielded over 2 500 unique publications to which FP7 or H2020 has contributed (Figure 3.17). Both the full set of references from IPCC reports and the subset which is linked to EU framework programme funding were matched to Microsoft Academic Graph (MAG). Overall, 87 % of all unique DOIs could be matched to MAG (and 99 % for those with EU funding). We further matched the publications to the country of affiliation of the authors. As a result, we got over 21 000 publications with a country affiliation (80 % of all records with DOIs and 92 % of records matched in MAG). This is the subset which will be used for most of this analysis. It includes over 2 400 publications linked to FP7 or H2020 funding (from over 640 projects).

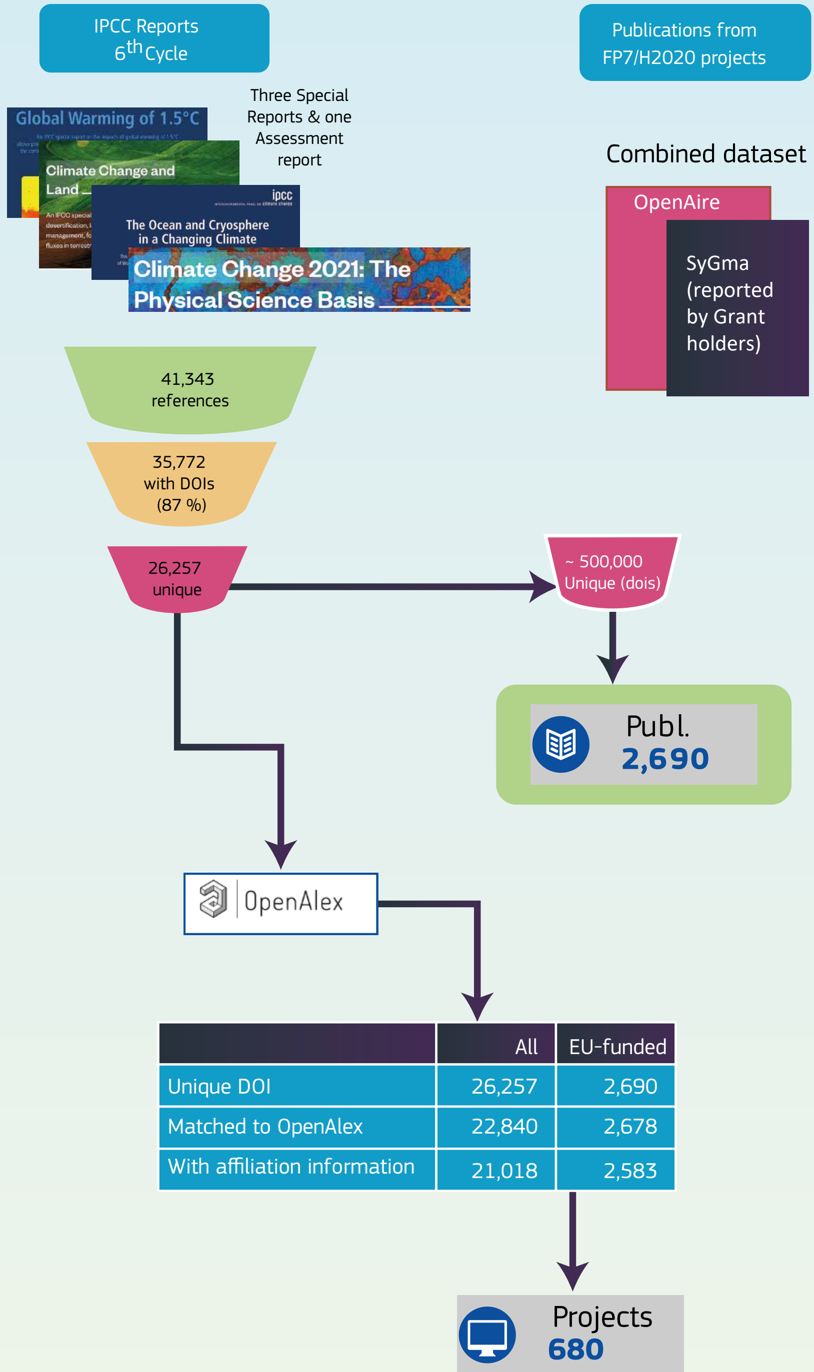
The data shows that the weight of EU-funded results in IPCC references is fairly constant across all the reports – deviating slightly from the means for all reports of 11.5 % and 21.4 % (for all references and for references from framework programme countries, respectively). We notice, however, the higher share of EU-funded research in the references of the most recent Working Group I[18] contribution to AR6. They make up 14 % of all references and a quarter of all references from framework programme countries.

16 Source: Mugabushaka A.M., Rakonczay Z. The contribution of the European Framework Programme for R&I to IPPC reports. Working paper 2022/03. R&I paper series.

17 OpenAIRE Research Graph is an open resource that aggregates a collection of research data properties (metadata, links). OpenAIRE - Research Graph

18 The IPCC Working Group I (WGI) examines the physical science underpinning past, present, and future climate change.

Figure 3-17: Linking IPCC publications to EU-funded projects and publications

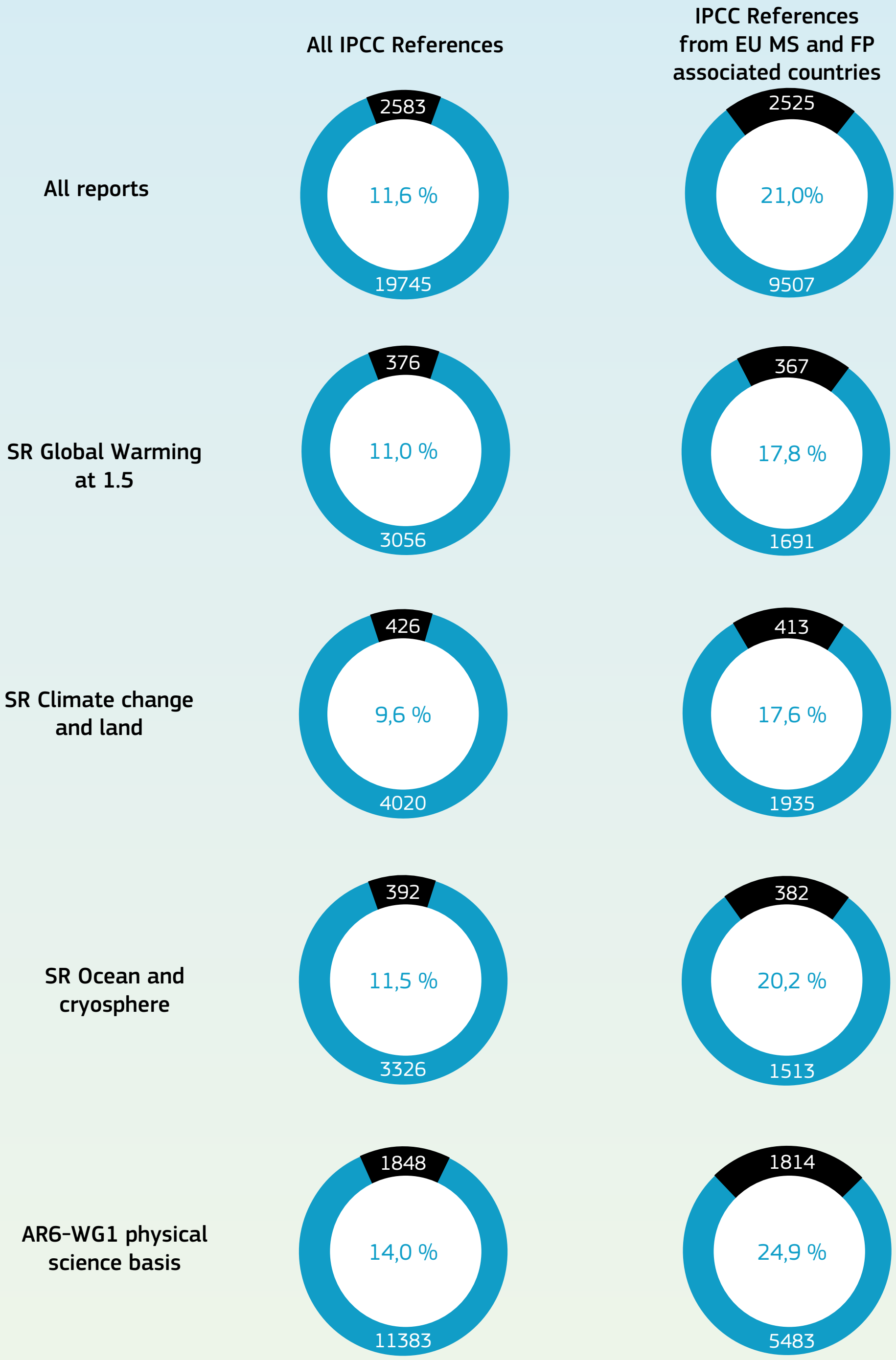


	All	EU-funded
Unique DOI	26,257	2,690
Matched to OpenAlex	22,840	2,678
With affiliation information	21,018	2,583

Source: Authors' elaboration.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-3-17.xlsx

Figure 3-18: Evolution of the number of patents related to recycling and secondary raw materials, 2000-2016

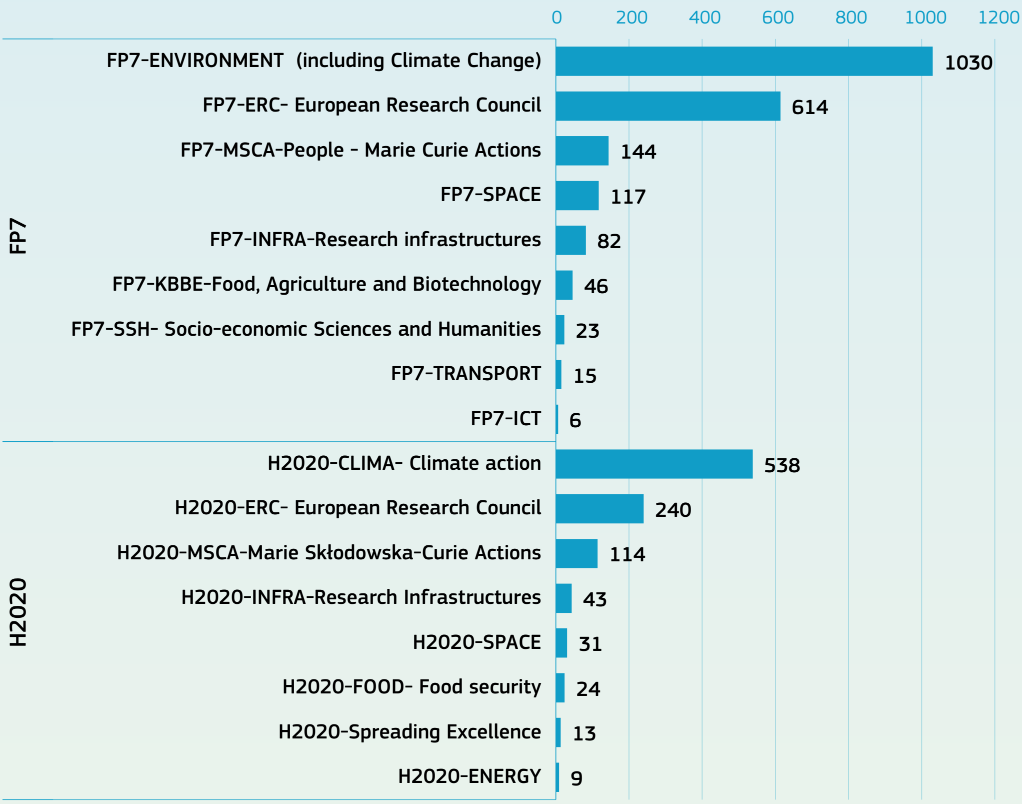


Source: Authors' elaboration.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-3-18.xlsx

The sub-programme with the highest number of publications referenced in IPCC reports is environment (FP7-ENVIRONMENT), both in FP7 (over 1000 publications) and in H2020 (over 300 publications). It is followed by the European Research Council (ERC) with about 600 and 200 publications for FP7 and H2020 respectively. Other sub-programmes with a high number of publications are Marie Skłodowska-Curie Actions (PEOPLE/MSCA), Space (SPA, LEIT-SPACE), and Infrastructure (INFRA).

Figure 3-19: Publications referenced in IPCC reports by FP sub-programmes

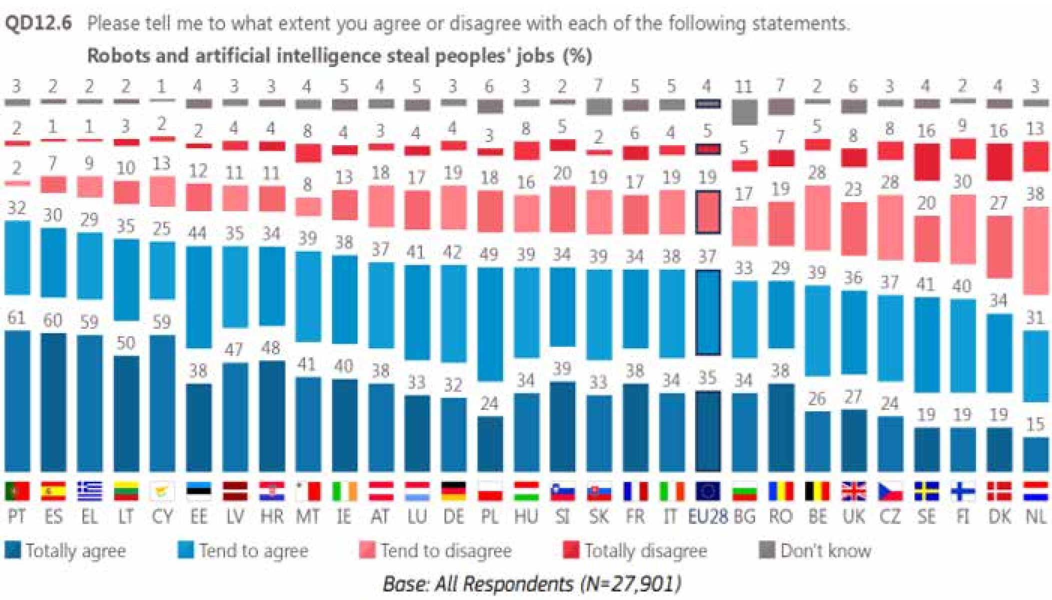


Source: Authors' elaboration.
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-3-19.xlsx

1.3 R&I driving the path from inequalities to inclusiveness?

The disruptive nature of technological change can generate challenges in terms of increased inequality through wage and income disparities, regional disparities, and 'winner takes most' markets and industries. These can seriously affect people's support for democracy (Milner, 2021). There is evidence from the EU and the US about innovation potentially leading to inequality, especially in terms of wages and earnings (Breau et al., 2014; Florida and Mellander, 2016; Lee and Rodriguez-Pose, 2013, 2016). While digitalisation has been accelerating over the past decades, aggregate productivity growth has been slowing down (also known as the productivity paradox) and income inequalities have been increasing. Technological change can affect inequalities through several channels (OECD, 2018). The persistent digital divide in Europe (See Chapter 5.3 – Investments in ICT and digital) limits the potential for less-skilled people, less-digitalised firms and less-connected regions to benefit from this change. At the same time, new technologies affect labour markets, can displace labour and create an upgrading in skills requirements (See Chapter 4.3 – Skills in the digital age) (Bessen, 2015; Ford, 2015; World Economic Forum, 2016). There are also 'winner takes most' dynamics due to the nature of technological change, with firms in sectors characterised by network externalities benefiting from first-mover advantages, strong economies of scale and network effects, which has culminated in the rise of superstar firms (Autor, Dorn et al., 2020).

Figure 3-20: Eurobarometer on the impact of robotisation and artificial intelligence on jobs (2017)



Source: Eurobarometer (2017).

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-3-20.xlsx

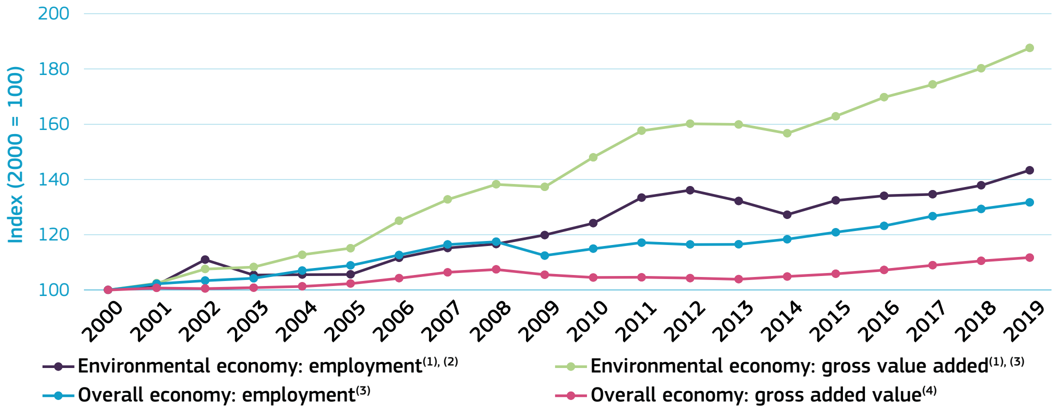
While the consequences of technological progress in the labour market are a concern for Europeans, there are reasons to expect positive developments, as national industries with a higher adoption of robots tend to be more resilient in terms of employment than the rest. Technological change features a creative destruction process, implying that new jobs are created and old ones are destroyed, which can lead to anxiety among workers. Some 72% of respondents to a Eurobarometer survey (Eurobarometer, 2017) agreed with the statement 'robots and artificial intelligence steal peoples' jobs'. With not all jobs being equally exposed to automation, these perceptions can also create concerns in terms of income inequality and social cohesion. It also appears that new technologies have been the main factor explaining the decline in labour's share of national income and increasing inequality, as that income has instead gone to the owners of capital (IMF, 2017; EEA, 2019). However, the history of automation and technological change is not only about the displacement of human labour by automation technologies.

New technologies counterbalance these displacement effects by creating new tasks in which labour has a comparative advantage, reinstating labour into a broader range of tasks and changing the task content of production in favour of labour (Acemoglu and Restrepo, 2018). Recent evidence for Europe also shows that national industries with a higher robot adoption tend to be more resilient in terms of employment than the rest (Klenert et al, 2020).

The transition towards a climate-neutral and environmentally sustainably economy is also expected to significantly impact Europe's labour markets (ESDE 2019). Technical progress and the intended transitions can lead to people losing their jobs in some industries, with heavy social consequences. Policies that aim at achieving a less polluting and more resource efficient economy can be expected to create structural changes in the nature of demand and production processes, affecting businesses and regions, and creating and destroying jobs in different sectors of the economy (OECD, 2017). Hence, making the transition just requires support to affected sectors, adapted labour policies and the right educational frameworks to close occupation shortages and skill gaps (European Commission, 2020). As a tool to ensure that the green transition happens in a fair way, the Just Transition Mechanism provides targeted support to help mobilise around EUR 55 billion over 2021-2027 in the most affected regions to alleviate the socio-economic impact of the transition. Solutions such as those developed by BioeconomyRevier[19] will provide insights to be replicated in other regions throughout Europe.

19 https://www.biooekonomierevier.de/

Figure 3-21: Evolution of employment and gross value added of the EU environmental economy, 2000-2019



Science, Research and Innovation Performance of the EU 2022

Source: Eurostat (online data codes: env_ac_egss1, env_ac_egss2, nama_10_gdp and nama_10_a10_e)

Note: The environmental economy encompasses activities and products that serve either of two purposes: environmental protection – that is, preventing, reducing and eliminating pollution or any other degradation of the environment, or resource management – that is, preserving natural resources and safeguarding them against depletion. (1) Eurostat estimates. (2) In full-time equivalents. (3) Million euro, chain-linked volumes, reference year 2010 (at 2010 exchange rates). (4) Thousands of persons.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-3-21.xlsx

Net-zero-aligned and circular economy investments can generate jobs quickly and encourage entrepreneurial activity (Unsworth *et al.*, 2020) as they can lead to activities that are both labour-intensive and quick to implement (examples include retrofitting buildings, intensifying broadband and restoring degraded land). While the environmental economy[20] is rather small in Europe (2.2 % of GDP), it has grown rapidly since 2000, outperforming the overall economy (Figure 3.21): the value added and employment of the green economy increased respectively by 80 % and 40 % between 2000 and 2018.

The number of green jobs[21] in the EU was 4.4 million in 2018. The largest increase in green jobs over 2000-2018 was in the domain of renewables and energy-efficiency, with a million full-time equivalent jobs created over the period (from 0.6 to 1.6 million). The second largest contribution to the increase in environmental employment came from waste management from 0.8 to 1.2 million). By contrast, employment related to wastewater management decreased from 0.7 million to 0.5 million over the same period.

20 Encompasses activities and products that serve either of two purposes: environmental protection – that is, preventing, reducing and eliminating pollution or any other degradation of the environment, or resource management – that is, preserving natural resources and safeguarding them against depletion.

21 Jobs in the environmental economy sector, which encompasses activities and products that serve either of two purposes: environmental protection – that is, preventing, reducing and eliminating pollution or any other degradation of the environment, or resource management – that is, preserving natural resources and safeguarding them against depletion.

Figure 3-22: Number of scientific publications[1] in socially-related SDGs (poverty, health and well-being, education, gender, decent work, inequality, peace, justice) – SDGs 1, 3, 4, 5, 8, 10, 16

Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Science-Metrix using Scopus database.

Note: [1] The data labels are expressed in thousands of publications and the publications for each SDG are not mutually exclusive. Fractional counting used.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-3-22.xlsx

At the same time, R&I is also a crucial factor in supporting the just transition and the social dimension of sustainable development in general. R&I is needed to increase our knowledge about current developments in European societies, and to develop solutions for the future as a means of supporting and improving governance systems, modernising public authorities, reducing inequalities and promoting social justice. Increased R&I activity also goes hand in hand with upskilling and reskilling, and more widely with investments in education, in order to contribute best to a just transition. R&I is an integral part of the EU's response to well-being-related challenges such as an ageing population and healthcare systems under pressure. While the US is a global leader in scientific publications on socially-related SDGs (Figure 3.22), the EU still shows a strong performance in this area, as well as registering steady growth since 2000.

The R&I agenda is becoming more human-centric. As the Lamy report (2015) pointed out, EU innovation policy must be based on a definition of innovation that acknowledges and values all forms of new knowledge – technological, but also business models, financing, governance, regulatory and social – which help generate value for the economy and society and drive systemic transformation. Such considerations are also in line with unleashing the values and potential of the Industry 5.0 agenda, which is characterised

Table 3-3: Percentage of highly cited publications per SDG, by country/region, 2018

	CN	JP	KR	EU	UK	US
SDG 1 – No poverty	12.2	3.9	5.7	9.8	18.6	14.0
SDG 3 – Good health and well-being	13.0	6.9	9.5	11.5	16.0	15.7
SDG 4 – Quality education	10.2	4.2	5.1	10.3	14.8	11.8
SDG 5 – Gender equality	9.3	7.2	4.9	10.0	14.6	13.3
SDG 8 – Decent work and economic growth	16.3	6.4	7.2	12.9	19.9	16.2
SDG 17 – Peace, justice and strong institutions	11.8	3.7	6.4	10.8	13.9	13.2
SDG 10 – Reduced inequalities	12.1	7.1	7.2	9.8	17.4	14.1

Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Science-Metrix using Scopus database.

by a shift of focus from technology-driven progress to a thoroughly human-centric approach (Breque et al., 2021).

New technologies and market-based solutions may not be sufficient in remedying major challenges like climate change, biodiversity loss or growing inequalities (IPCC et al., 2021; UNEP, 2021; EEA, 2021). Emerging technologies, nature-based solutions (EEA, 2021), social innovations and broader shifts in cultural repertoires are highlighted as essential parts of transformative change towards sustainable futures (Folke et al., 2021).

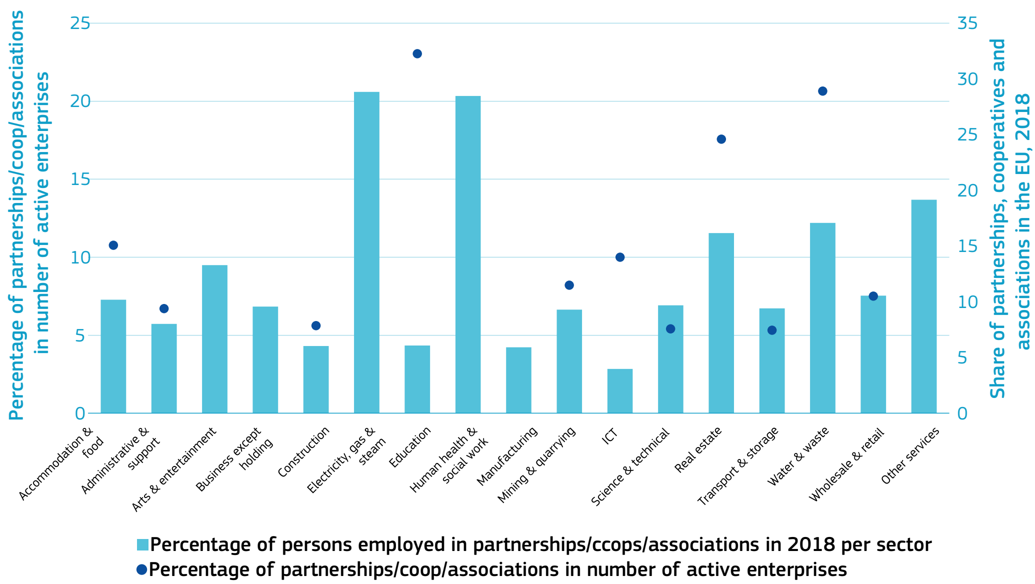
Social innovation has appeared as a successful approach for deep transformation of our systems and practices (EEA, 2021). According to the OECD (2015), social innovation refers to the design and implementation of new solutions that imply conceptual, process, product, or organisational change, which ultimately aim to improve the welfare and wellbeing of individuals and communities. It has the potential to offer novel approaches to contemporary crises that differ from traditional technology-based solutions (Haskell and al., 2021), and would then be complementary to these in achieving the SDGs. Stakeholder engagement, citizen participation, citizen empowerment and cross-sectoral collaboration are key aspects of social innovation (Chatfield and Reddick, 2016). This human dimension is indeed seen as fundamental for transforming our society and for facilitating the design, adoption and diffusion of socially-responsible innovative solutions.

Social economy enterprises, partnerships, cooperatives, public-owned enterprises and associations have proven to be innovative in dealing with socio-economic and environmental problems, while contributing to eco-

nomic development (OECD, 2015) and are often cited as key players for social innovation (European Commission, 2020). There are more than 1.9 million active partnerships, cooperatives and associations across the EU, employing more than 34.8 million persons, about 10.5% of the total workforce in 2018 (Figure 3.23). These actors operate in all sectors of the economy. They are particularly active in education, health care and social work activities and employ 28% of the persons working in those sectors. The European Commission has identified that 3.1 million firms in Europe, composed by 99.9% of SMEs, operate within the proximity, social economy and civil security ecosystem. This ecosystem employs 22.9 million persons across the EU and represents 6.54% of EU value-added (EUR791 billion). As they listen to the motivations and requests of local actors, social economy organisations can indeed act as a catalyst for social creativity by developing innovative services and business models (Social Economy Europe, 2015). At the European level, the European Pillar of Social Rights supports the development of such entities and several funding instruments at the EU level have been designed to target employment, social inclusion, social innovation and training. These include ESIF+ and ERDF e.g. urban innovative actions (URBACT) targeting housing and social infrastructure.

Financial resources are assumed to be critical in the start-up and scaling of social innovation, and often rely on diverse funding sources (Haskell et al., 2017). The lack of funds was described as a constraint for social innovation's long-term success (McCarthy et al., 2014), but more generally for

Figure 3-23: Share of partnerships, cooperatives and associations in the EU, 2018



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Eurostat (online data code: BD_9AC_L_FORM_R2).

Note: [1]Data on employees in Greece and Austria are provisional, data on the Netherlands, Portugal, Malta, Poland is not available across all sectors, so aggregates have been computed without these.

Data on number of active enterprises are not available in a few sectors (not showcased) – Arts, Education, ICT, Other service acts, human health & social works - //ec.europa.eu/eurostat/web/products-datasets/-/bd_9ac_l_form_r2

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-3-23.xlsx

sustainable innovation. **At the EU level, the InvestEU Social Window will reduce the risk of investments and improve the institutional capacity of financial intermediaries with the objective to improve access to finance to social stakeholders via a guarantee and an equity instrument**. The Council of Europe Development Bank also issued a EUR 500 million 7-year Social Inclusion Bond in April 2021 (CEB, 2021). The New European Bauhaus, launched in 2020, also has a great potential to accelerate social innovation by creating communities, fora and platforms to discuss, exchange and establish synergies for driving our society towards more resilience and inclusiveness. Finally, through its co-creation process, **Horizon Europe supports directly both collaboration on innovative activities and social innovation**, such as for example the EU-funded PROSPERA project, which will explore new narratives for innovation that would accordingly change and increase the scope of the innovation concept itself in cultural and institutional transformation, and subsequently in social life and social order.

Box 3-4: Does innovation support for the green transition require new action types?

In the SRIP2020[22], Frank Geels described "transformative innovation and socio-technical transitions to address grand challenges". In this more recent framing of innovation policy, the policy rationale is no longer correcting market failures or strengthening interaction between stakeholders, but "*promoting system transformation, which incumbent actors are slow or reluctant to do.*" The key features of the approach are "*nurturing radical innovation and new pathways & shaping the directionality of innovation*".

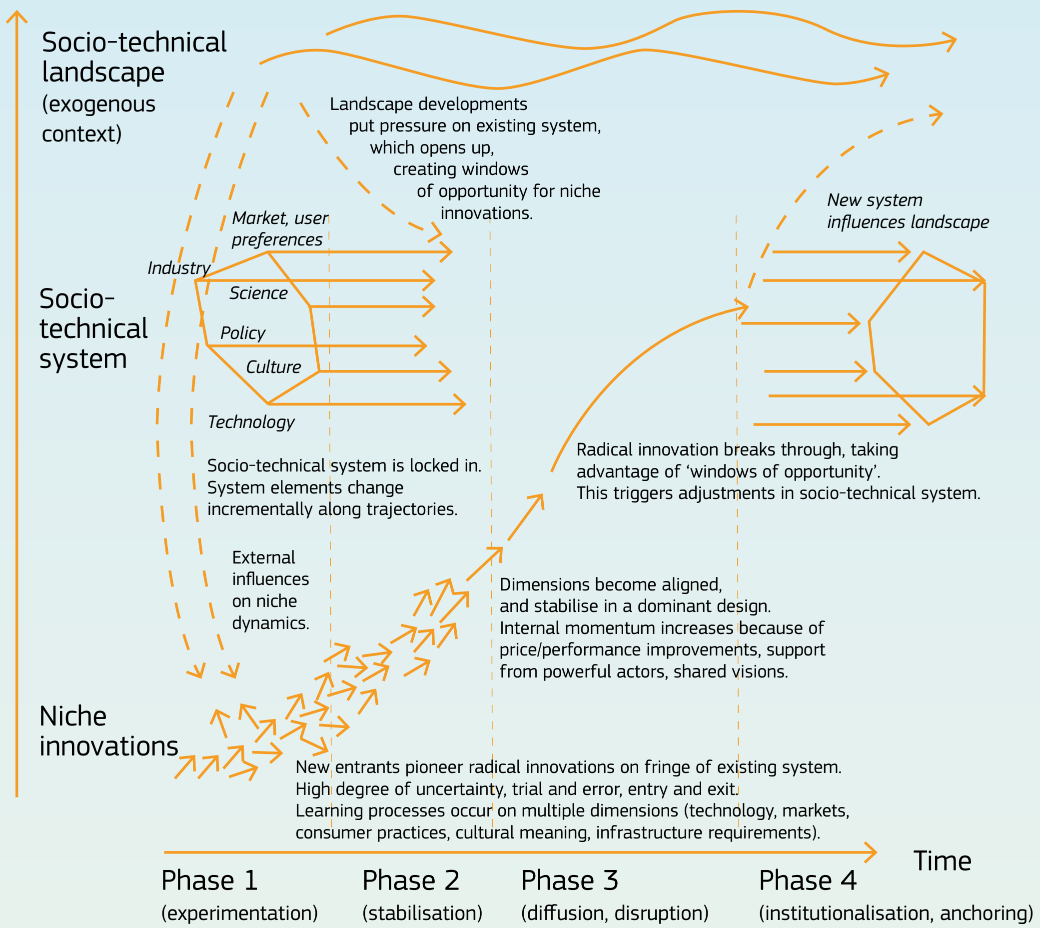
Large parts of the green transition are not happening in traditional product markets but in public services (i.e. services provided by of entities owned by municipalities, regions or the nation state or by commercial service providers contracted or licensed by authorities); or the transition affects the public good (infrastructure, ecosystems and ecosystem services).

This engages quite different stakeholders in innovation processes than for habitual product or service innovation in B2B or B2C markets.

Geels (2020) recognises that a multi-level perspective in socio-cultural transitions should engage different stakeholder networks in different stages of the transition process and (implicit) at different geographic scales. The dimensions of locational and local stakeholder networks are discussed in the regional section (See Chapter 2.2 – Zoom in). Further, the question arises if innovation policy and innovation support for system's transformation requires additions to its policy toolbox. Notably, if the scaling of innovative solutions doesn't happen in traditional B2B or B2C markets but realises in an enlarging physical space and geographic scale.

22 https://ec.europa.eu/info/sites/default/files/srip/2020/rec-19-003_srip_chap-9.pdf

Figure 3-24: Multi-level perspective on socio-technical transitions



Source: Substantially adapted from Geels, 2002: 1263

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-3-24.xlsx

Niche creation and 'experimentation' with new approaches will happen locally supported of local authorities that see opportunities. The 'stabilisation' of an innovation will also happen on local scale if the novelty has proven added value and no strong voice speaks against it. Latest in the diffusion and disruption phase that happens in a larger physical space an arising dominant design encounters resistance from incumbent stakeholders. This will delay institutionalisation of the innovation. This happens in B2B and B2C markets as much as in public services. But the administrations' regulatory power is much stronger related to public goods and services as they act not only as contractor ('procurement of innovation') but often as service provider through own economic activities and / or local regulator through by-laws.

In order to foster product and service innovation on established markets, public support should not be provided beyond 'technology readiness level 8' (TRL8), as support at a later stage would distort the market, which would not be in the public interest. But, does this argument of supremacy of non-distorted markets over aspect of public interest still apply if innovation policy asked to provide directionality to future development? Miedzinski et al. (2019)[23] describe this phenomenon as 'tilting the playing field', which aims to create 'targeted demand'.

Research in transitions and their governance goes a step further and emphasises the need for '*innovation arenas*' in niche and transition management (Köhler et al, 2019)[24]. These engage in "*bringing together actors from science, policy, civil society and businesses and develop cooperative rather than competitive relationships between them*".

Innovation policy framed in this way would require a portfolio of action types much broader than what is needed for "*bringing research results to the market*". An innovation arena could include for example a negotiation to abandon technologies, tilt markets accordingly or it could link innovation policy much closer to legislative activities.

In practice first steps in this direction are happening: '*Regulatory testbeds*' and '*innovation deals*' are policy instruments which can be launched at European level in specific contexts. However, they have not yet been translated into project types for the research and innovation framework programme or used in the context of Horizon missions. They could contribute to innovation in the governance of transition processes be creating 'legislative experimentation grounds' and create the above mentioned 'innovation arenas'.

In the context of Horizon Europe internal guidance to topic drafters has been developed on phrasing expectations with respect to 'societal readiness'. The guidance does not follow the same logic as 'technological readiness levels' with respect to market introduction of technologies, but 'societal readiness' shall trigger a reflexion on the phasing of a topic during a socio-technological transition process and on the societal issues at stake during this phase.

'Regulatory testbeds', 'innovation deals' and 'societal readiness' are three novelties that could develop into new action types for Research and innovation support in a green transition as they can engage diverse stakeholders across the physical space from European down to local.

23 Microsoft Word - SDG policy roadmapping framework (final draft 19 June).docx (ucl.ac.uk)

24 Köhler et al, 2019 - An agenda for sustainability transitions research: State of the art and future directions

2. A systemic approach for transformative R&I policies

2.1 Policy context

The adoption of the Sustainable Development Agenda, its 17 SDGs and 169 targets (UN, 2015) **has emphasised the necessity to include social justice and human welfare implications in systemic transformation**. The problems we face today are complex and interconnected, thus requiring solutions from multiple perspectives. Therefore, R&I policies are increasingly expected to provide novel instruments and solutions to interrelated but, often times, conflicting goals (Kanger et al., 2020), implicating different policy domains and levels of governance (regional, national, and European). **Under these circumstances, innovation experts and scholars have put forward a strong claim for policymakers to provide the *directionality* of change**. Namely, policymakers have been strongly encouraged to put forward a harmonised package of policy and regulatory measures tailored specifically to stimulate innovation and focus on well-defined objectives, as well to promote responsible research and innovation (RRI) and adaptive governance (EEA, 2019) to tackle specific societal challenges in a defined timeframe.

R&I policies follow several objectives, such as the twin transitions, which can be compatible or even mutually reinforcing. However, this is not automatic. Evidence at the regional level shows that the digital and green technological transitions are not always mutually compatible in decreasing GHG emissions.

The overall impact of digital technologies is beneficial only for regions above a certain endowment/strength of environmental technologies (Bianchini et al., 2020). There is also evidence of digitalisation being a driver for energy consumption, as it is the case with data hubs) and critical raw materials extraction (EEA, 2019). Besides, **while many sustainability driven technologies promise positive outcomes, technological innovations may have unintended consequences when scaled up to the system level** (e.g. indirect land use change, loss of biodiversity and increased competition for land resulting from bioenergy production or from the use of biomass for contributing to climate mitigation through sustainable bio-based products) (EEA, 2019). The EEA's reports (2001, 2013) give examples of innovations' negative side effects. For example, biofuels during the 1990s and 2000s created competition with food production for land and resulted in land-use change, affecting ecosystems and biodiversity, for example through deforestation or the widespread uptake of bisphenol a with endocrine-disrupting properties without understanding its health implications. Green/climate policies and industrial transition policies need to be coordinated and tailored to specific conditions, including across countries.

The 2021-2027 EU R&I framework programme, **Horizon Europe**, has taken some further steps towards achieving the Green Deal. It **will support research and innovation activities that fully respect climate and environmental standards and priorities of the EU and cause no significant harm to any of them**.

The adoption of the EU's Sustainable Finance Taxonomy Regulation 2020/852 creates a common science-based classification system defining which economic activities can be considered as environmentally sustainable. Research and innovation activities' compliance with the '**do no significant harm**' **(DNSH) principle**[25] will ensure consistency with the European Green Deal objectives and promote the transition to a safe, climate-neutral, climate-resilient, more resource-efficient and circular economy. At the programming stage, work programme preparation guidance and topic screening has been introduced to ensure that the Horizon Europe Work Programme aligns with the European Green Deal's objectives and the DNSH principle. Additionally, while DNSH consideration remains voluntary at the project level, references to the DNSH principle in the work programme and the grant application forms aims to raise researchers' awareness about the environmental risks linked to their research. It is intended as an encouragement for them to design their projects in a way that does not significantly harm environmental objectives and to identify and mitigate potential environmental harms from the outset.

Horizon Europe also includes a new impact-oriented framework programme strengthening evidence informed R&I policymaking. The new data-driven analytical and monitoring systems aims to go beyond tracking input and outputs towards measuring impact, with the introduction of **Key Impact Pathways** to provide deeper analytical insights for medium- and long-term impacts, in addition to the dissemination and exploitation tools (CORDIS[26] and the Horizon Results Platform[27]).

Similarly, the evaluation of the framework programme is being conducted in a holistic approach which does not focus on single instruments or sub-parts of the programmes but looks at the impacts in different thematic areas across the whole framework programme, areas based on Horizon 2020 and Horizon Europe's strategic objectives. Among other dimensions, the analysis will look into the degree to which the framework programme has contributed to a resilient and innovative Europe and the **green, digital and industrial transitions**, using for instance relevant data from technology roadmaps and other efforts in this field.

In the light of these developments, how to determine the right policy mix to induce a deep transformation of our society? The **SRIP report 2020** pointed out that sustainability transitions are directed towards solving specific problems and meeting specific goals. Therefore, **a truly transformative R&I policy is about directionality**. Recent debates about mission-oriented innovation policy emphasise the importance of inspiring visions which provide long-term directionality. Challenging, yet doable, missions with more specific targets (which enable accountability) are accompanied by financial instruments to enable concrete action (Mazzucato, 2018) (SRIP, 2020: 578). EU Missions under Horizon Europe aim to give direction to the EU's R&I policy and support the European Commission's priorities, e.g. the EU Green Deal, by providing concrete and cross-cutting solutions to the most pressing challenges, such as health and climate change.

25 As defined in Articles 17 of Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020 on the establishment of a framework to facilitate sustainable investment, and amending Regulation (EU) 2019/2088

26 CORDIS | European Commission (europa.eu)

27 Funding & tenders (europa.eu)

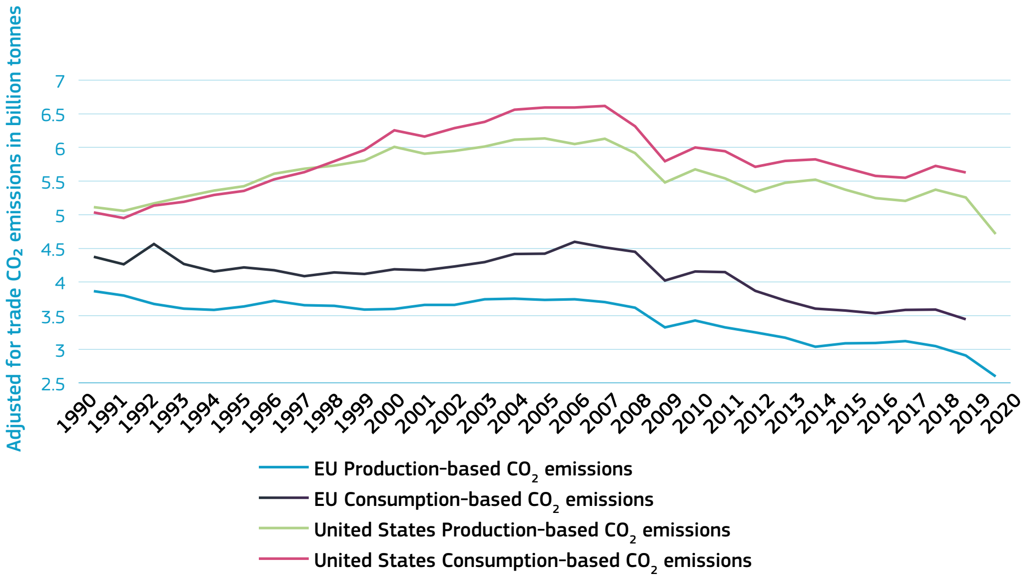
Missions operate across multiple policy domains (e.g. environment, agriculture, health and R&I) seeking to link and coordinate different policy tools, regulations, and funding programmes, while mobilising private and public stakeholders, which includes citizens and public authorities at different levels of government. Missions provide concrete instruments for European society, Member States and regions to navigate the way forward to sustainability and succeed.

At the same time, **the European Commission has called for transformative R&I policy to deliver technological and societal change while ensuring sustainable development for all** (ERA SWD, European Commission, 2020). 'Tackling the grand challenges of our time requires a clear "design" process developed in the public sector, aimed at translating ambitions and aspirations in clear missions and pathways that will channel the allocation of resources.' (p. 22). The emphasis on **'a clear design process'** is in line with scholars' advice to leverage change through policy intervention along the transition processes to enable deep transformations. **Deep transformations require not only R&I policy support to disruptive innovations but also and, most importantly, to diffusion, upscaling and replication**, i.e. when radical innovations are adopted and diffused into markets, businesses, society and the policy environment (SRIP, 2020). In addition, deep transformation requires the understanding the limits and potential in local natural and human capital, and the deployment of tailored transition pathways. In concrete terms, this would first translate into two directions. First, **ex-ante policy experimentation could be more widely incorporated into policymaking processes** (Von Wirth et al. 2019). Second, **policy instruments could be gradually introduced to support the different stages of the change** (from niche adoption of innovations through uptake, upscaling and outscaling), while those that are not needed anymore should be phased out.

Given the complexity of transition and transformation processes (i.e. complex and interrelated socio-technical systems, goals and interests involved), **the structures governing R&I policy processes could be designed for mobilising and supporting such deep transformations across societal and economic systems**. Therefore, a **whole government approach** is needed to ensure coordination and integration among different stakeholders and levels of government, as well as different policy domains. The SRIP report 2020 called for a horizontal policy coordination to better align R&I policies with sector-specific policies (e.g. energy, transport) that are key to provide focus, vision and ad-hoc instruments for deployment and diffusion of innovations (e.g. wind and solar PV, combined heat and power (CHP)). This is also referred to as 'sustainability transitions governance' (Fagerberg, 2018; Turnheim et al., 2020). Some countries, e.g. Finland (Innovation Council) and Norway (i.e. Innovation Norway), have established innovation bodies that involve both public and private actors in setting up the goals and direction of the green and sustainable transitions (Fagerberg, 2018).

Beyond R&I policies, other policies aim at boosting the shift towards more sustainable and resilient systems. Western countries have put in place strict environmental regulations to fulfil such objectives. Such approaches may create incentives for businesses to implement structural changes and upgrade global value chains. But they may also have some side effects. Ben-David et al. (2021), using data on 1970 multinational firms headquartered in 48 countries and their CO_2 emissions in 218 countries during the 2008–2015 period, found that tightening environmental policies in home countries incentivise multinational firms to shift polluting activities abroad (Figure 3.25). At the same time, they discovered that higher foreign emissions levels do not completely outweigh the reduction at home, as they emit less overall CO_2 globally. Both the US and the EU produce more CO_2 if one also considers the CO_2 production of goods made abroad and then imported to be consumed locally. However, both the US and the EU have made significant progress, reducing their production- and consumption-based CO_2 emissions in the last fifteen years. Such outcomes, likely the result of both political will and technological/economic capacity, testify that it is not necessary the case that countries pollute more as they get richer (EEA, 2020b).

Figure 3-25: Evolution of EU and US production- and consumption-based CO_2 emissions, 1990-2020



Source: DG Research and Innovation, Chief Economist – R&I Strategy & Foresight Unit based on Our World In Data and Global Carbon Project (2021).

Note: consumption-based emissions are emissions that have been adjusted for trade (i.e. territorial/production emissions minus emissions embedded in exports, plus emissions embedded in imports).

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-3-25.xlsx

Besides, **directed R&I policies towards the green transition are more widely accepted politically than environmental regulations**. As an example, policy attempts to increase fuel prices have been met sometimes with fierce opposition by civil society. A key example is the "Gilets Jaunes" movement in France, where an often-cited quote from a protester ('The elites are talking about the end of the world, while we are talking about the end of the month[28].' a growing literature demonstrates that, in the context of inequalities and the feeling of neglect, tackling climate change is not a priority for many.

Carbon pricing policies could gain stronger popular support if revenues were distributed across society in ways that are equitable and perceived to be so (Stern and Valero, 2021). It also calls for social policies in the EU and anticipation of the distribution of taxes and transfers resulting from environmental measures.

Read more in Chapter 10 – Part 2 on Research and Innovation Policies for the Green Transition

(Eugénie Dugoua, LSE)

This chapter presents a deeper look into the arguments of a long-standing debate. Should we put research and innovation at the centre of the green transition, or, on the contrary, rely on a cultural shift that changes consumption patterns rather than finding cleaner means of production?

It investigates selected R&I policies that can help foster a transition towards green technologies, considering both supply-side policies, such as R&D funding, and demand-side policies, such as carbon pricing and clean technology standards, explores their complementarities and proposes a few key take-aways: the urgency to invest in the deployment of green technologies, the critical role of both investments in R&D and carbon pricing.

28 Rérolle, 2018. Gilets Jaunes Les élites parlent De Fin Du monde, Quand Nous On Parle De Fin Du Mois(2018)Le Monde

Box 3-5: Transformative R&I for sustainable development: Analysis of SRIP 2020 principles in practice

Andrea Ferrannini, Roberto Martino

The **ambition for European R&I policy is to act as a leverage for transformation in the transition towards sustainable development**, empowering individuals, communities and Member States to meet societal needs and build sustainable and inclusive societies. To realise this ambition, European R&I policy needs to fully embrace the principles underpinning transformative change towards sustainable development – **transformation, directionality, co-creation, diffusion, and uptake** (SRIP, 2020) – and make them operational, going beyond a consolidated narrative.

The following analysis explores how **these principles are reflected and embedded in the design and implementation of EU policies** across different domains, thus contributing to understand how current and future European R&I policy effectively contributes to the sustainability agenda.

This research combines a **state-of-the-art review** of the literature and policy discussions in Europe on transformative R&I with the **analysis of five selected case-studies** of current EU policy interventions. These case-studies were purposively selected – among others – due to their focus on innovation processes and practices across different dimensions of sustainable development. The investigation of each intervention is based on the combination of **extensive desk-based analysis of available public documentation** (e.g., work programmes, regulations, evaluations and assessments, reports and publications, brochures, websites, promotional materials) with the **collection of direct in-depth insights through semi-structured interviews to key informants**, namely internal staff (heads of units and officers) within related European Commission's DGs and Agencies.

The following matrix reports the main findings. The analysis demonstrates **innovation processes are at core of a transformative change towards sustainable development** across different EU policy domains. In particular, the analysed policies promote a combination of radical and incremental innovative solutions to **transform production processes, behaviours, and business/institutional models**. Furthermore, they provide **a clear direction** for the transformative process, bringing together bottom-up solutions with overall priorities while **enabling collective action for a better society** involving a wider set of actors, governance levels and countries. The policies aim at **advancing and disseminating knowledge** across European economies and societies, pushing for **market, institutional and societal uptake of sustainable solutions**, their scale-up and replication.

Notwithstanding relevant spaces for improvement, especially in terms of directionality and uptake, the analysis of these policies shows that R&I objectives, stakeholders, action, resources, and processes contribute to **empowering European individuals, communities, and societies with innovative solutions**, expanding knowledge and information, raising awareness and enhanced capacities to pursue sustainable human development today and in the upcoming future.

Table 3-4: EU policies and transformative principles in practice

Case-study	**European Innovation Eco-systems (EIE)**	**European Digital Innovation Hubs (EDIHs)**	**LIFE Programme**	**European Urban Initiative (EUI)**	EU Programme for Employment and Social Innovation (EaSI)
Main conclusion: how does each intervention embrace the transformative R&I principles	It **promotes the development of good practices within and between ecosystems,** favouring **the flow of knowledge and ideas with transformation potential.**	It enables the **uptake of digital technologies at the frontier, involving regional stakeholders in the innovation ecosystem, facilitating the connection of EU-wide actors and the deployment of specialisation strategies.**	It directs **innovation efforts in market-based solutions, policies and public attitudes** towards the transition to a carbon-neutral, circular and sustainable economy.	It fosters the **transformation of policy design in local institutions towards innovative and integrated urban solutions,** leveraging knowledge sharing and uptake.	It enhances **an enabling environment for social policy innovation** to foster a just and socially inclusive transition.
TRANSFORMATION	It sits in the general sustainability framework of **Horizon Europe and the Green Deal.** It promotes mutual learning and linkages between public authorities, start-ups, and funding bodies. It promotes the embedment of **innovation procurement in national and local strategies.**	It aims at transforming private and public entities by identifying, **diffusing, and uptaking the technologies** of the Digital Europe Programme (DEP). It contributes to the twin digital and transitions to make Europe more competitive and just.	It operates to transform **local economies, public governance**, and the general **public's acceptance and behaviours** towards green economy and sustainable development. LIFE projects focus on incremental innovations and close-to-market processes in local contexts.	It enables transformation in local institutions by expanding **in-house capabilities** and a **shared knowledge base** for integrated sustainable urban development. It promotes **new radical innovative proposals** and targets **incremental solutions** fitting the **specificities of local contexts.**	It promotes experimentation and the upscaling of **social innovation to transform policies and institutions** so they can address societal challenges. It fosters the development of **microfinance for micro-enterprises in** support of a sustainable and inclusive **transformation of businesses.**
DIRECTIONALITY	Thematic lines are consistent with **the framework provided by the Green Deal**. The priority setting brings together a **top-down** (Pillar 3 of Horizon Europe) and a **bot-tom-up** (stakehold-ers' engagement) approach. The definition of measurable indi-cators on impact is ongoing. **It complements** the actions carried out by the **Euro-pean Innovation Council (EIC)** and the **European Institute of Tech-nology (EIT).**	Hubs' trajectories depend on **general** priorities (e.g. DEP) and **regional** specificities (e.g. smart specialisation strategies), contributing to the RRF, Cohesion Policy and sectoral policies. It foresees a **detailed set of targets**, in terms of inputs, outputs and impacts. Hubs are expected to support companies by helping them with contacts and access to **financial institutions and intermediaries**, filling information gaps.	It develops a comprehen-sive response to **environment-, energy- and climate-related global challenges**, contributing also to the **SDGs** and to **Horizon Europe's Missions.** It combines **local specific priorities** with **objectives and targets stated in supra-national policy frameworks.** Its implementation strongly relies on **synergies and complementar-ities** with other **EU funding programmes**	It contributes to **Cohesion Policy's vision** of an (urban) Europe that is smarter, greener, more connected, more social and closer to citizens. A **set of potential indicators of outcomes** is under scrutiny for both the overall objective and for each group of actions. Specific goals are set to **maximise complementar-ities with actions under URBACT IV and the European Regional De-velopment Fund (ERDF).**	Its priorities are based on **strong contextual evidence** referring to **weakened economic and employment** performances, **enhanced risks of social exclusion** resulting from the COVID-19 outbreak. It foresees **indicators to monitor** the achievement of its operational objectives. The focus on societal challenges is the link with other ESF+ funding **instruments, InvestEU, Erasmus+, and Horizon Europe.**

CO-CREATION	It complements the top-down strategy with bottom-up contributions. Stakeholders were involved in an **extensive consultation process** at different stages of the policy design, whose outcomes strongly contributed to the definition of the Work Programme. The **EIC Forum** brings together public representatives, experts, and stakeholders, and it contributes to the evolution of its priorities.	Policy implementation embraces a **co-creation** and **participatory** approach, involving both local and international partners. The hubs' embeddedness in the regional ecosystem, the capacity-building approach, and the co-funding mechanisms place the policy at the **crossroads of different policy domains. Cooperation among hubs located in different EU regions** is encouraged to benefit from external knowledge.	The 2021-2027 **programme** is based on both **stakeholders' consultation** and the **participatory assessment** of the 2014-2020 period. A **whole-of-society approach** is ensured by engaging multiple actors **within local communities** in each project. The success of Strategic Integrated Projects and Strategic Nature Projects depends on **close cooperation between national, regional, and local authorities and the non-state actors.**	Its design benefitted from an **extensive consultation process**, including a public consultation, the appointment of an external expert and an Expert Working Group, also drawing from the impact assessment of the predecessor Urban Innovative Action. The policy benefits from the established use of **interactive methods and an online platform** where interested stakeholders may contribute to the working groups.	The annual work programme is informed by **consultation with Member States, a Technical Working Group**, and **strategic dialogues** with key EU-level organisations. The implementation builds on a **shared commitment** and the **strategic composition of partnerships. Networking and capacity-building activities across countries** are key for developing an **integrated EU labour market.**
DIFFUSION	The policy is about the **exchange of talents, competence, knowledge, and technology** (soft side), addressing the bottlenecks in the implementation of R&I policy through the creation of networks among ecosystems and using the EIC Forum. Expected outcomes include improved **flows of innovation resources, knowledge, and talent** between innovation ecosystems at various levels of development.	**The European network of EDIHs** allows local stakeholders to access knowledge, funds, expertise, and innovation opportunities, integrating them in global value chains. Knowledge spill-overs across countries are expected to reinforce the Single Market and reduce the digital divide in the EU. The hubs support local public authorities in the digital transition.	Projects help businesses testing small-scale solutions and supports the sharing of best practices, paving the way for a **large-scale deployment.** The dissemination strategy at European level ensures **open-access to knowledge and practices** relying on a wide and consistent set of tools. Dissemination strategies are also carried out **by Member States** and regions, along with a **continued** monitoring, even after a project's life cycle.	It foresees **sharing mechanisms** to provide local stakeholders with open access to the created knowledge and practices. It enables and encourages the **'reuse of public sector information and the promotion of big, linked and open data'** stemming from the three strands of actions. A single **network of contact points** favours dissemination in Member States and ensures policy support.	**Communication and dissemination** activities are fundamental to assist in the **upscaling, replicating and/or mainstreaming of results** achieved by projects. Strong efforts are devoted to make all produced knowledge and best practices (including all analytical activities) **open and accessible** to institutional and societal actors.
UPTAKE	**Dedicated funding** is allocated to ensure that outcomes from projects are assimilated. **The EIC Forum** is defined as a place to collect feedback from stakeholders concerning **uptake and implementation** and to **transform the policy priorities according to stakeholders needs.**	The European network of EDIHs is itself **facilitating and fostering the uptake of digital technologies by companies.** The activities foreseen in the hubs – including the creation of the European network – are also meant **to contribute to building the digital capacity of public bodies.**	The focus on **ready-to-be implemented solutions favours market uptake.** Institutional uptake of relevant policy actions is fostered by a **national, regional, and local policy framework** on environmental issues. The focus on **awareness** and **acceptance, consumer engagement and behavioural change** fosters societal uptake.	It aims at enabling and nurturing the **systematic uptake** of tested innovative solutions, good practices, and toolkits, using projects' outputs as inputs in the learning and disseminating process. The **implementation rate** of sustainable urban development strategies in cities is among the **outputs indicators** proposed for quantifying the impacts of the policy.	It aims at translating stronger evidence **in policymaking and upscaling, while replicating and/or mainstreaming social experimentation.** Social and institutional uptakes are pursed through a robust **communication and dissemination strategy** and assessed using **outcome indicators.**

Source : Authors' elaboration

2.2 What is needed to enable transformative R&I for sustainability ?

European Missions are an example of R&I policy innovation and hold the potential of enabling deep societal transformations. However, if the sustainable transformation is to be achieved, the policymaking process and policy instruments have to be adapted to the goal. Systems thinking is advocated from multiple sides but putting it into practice is more complicated (e.g. Mazzucato 2018, 2019; ESIR policy brief 2022). Donella Meadows, who was a member of the Club of Rome and a systems thinking apprentice, formalised **a list of leverage points to intervene in a system and provoke change**[29]. Meadows' work can be a guideline for policymakers to navigate and implement change in the policymaking processes. Meadows' leverage points **start with the easiest to implement 'constants, parameters and numbers' (e.g. taxes, subsidies and standards)**, to end with the three most difficult ones to fulfil, but that also hold the greatest potential for transformation. The three deepest leverage points are **changes in goals, mindset and power to transcend the dominant or established paradigms within a system. Paradigms are the sources of a system's** core features, such as goals, mindsets and beliefs, policy instruments, regulatory measures, stakeholders involved and resources employed, market dynamics and so on (Meadows, 1999). These three deepest, leverage points can be exploited by, for instance, introducing formerly excluded stakeholders and visions within policymaking, but also by adopting methods that allow for better understanding complexity and operating in highly complex contexts, and experimenting with new tools and practices.

So how do you change paradigms? [...] In a nutshell, you keep pointing at the anomalies and failures in the old paradigm [...]. [...] you work with active change agents and with the vast middle ground of people who are open-minded. Systems folks would say you change paradigms by modelling a system, which takes you outside the system and forces you to see it whole. We say that because our own paradigms have been changed that way.

(Meadows, 1999: 18).

Future foresight, experimentation, systems methodologies (e.g. system dynamics, Life Cycle Assessment) and co-creation participatory exercises can bring novel ideas into the policymaking and challenge dominant visions. Experimentation, both in the form of co-creation (e.g. niche development, living labs, stakeholders engagement platforms) and ex-ante policy instruments and designs evaluation (test new ideas, see what works and evaluate impacts) is becoming more widely used[30]. Scholars call for governance that is built around 'provisional, flexible, revisable, dynamic and open approaches that include experimentation, learning, reflexivity and reversibility (Kuhlmann & Rip, 2014)' (p. 230). **Experiments can support *upscaling*, through testing and embedding novel technologies in mainstream ways of doing, thinking and organising** (Laakso et al., 2021). Living Labs are an example of these experimental interventions. Living Labs are widely used in urban contexts but there is also an increasing number in rural areas that deal with bioeconomy-related innovations[31]. The Living Labs are sites where a variety of stakeholders come together and design, test, and learn about actual innovations and transition processes.

29 Leverage Points: Places to Intervene in a System - The Donella Meadows Project

30 Nesta | The Innovation Foundation; Research, Consultancy & Education for Transition - DRIFT (eur.nl); Homepage - APRE

31 ULL represent sites in cities that allow stakeholders to design, test and learn from socio-technical innovations in real time. Participation, experimentation and learning are put centre stage.

For example, **Maere Living Lab (green sector – agriculture) and Val Living Lab (blue sector)** in Mid-Norway (Trøndelag) are a network of established farms combined with a unique educational arena where students, researchers, innovators, industrial partners, and farmers participate and find innovative solutions to produce bioproducts and reuse materials in a circular economy approach. **Sustainability transitions practitioners suggest six policy intervention points to support the deep transformation process, from niche development to incumbent structures (European Commission, 2020).** Depending on the directionality and goals of R&I policy design, instruments are best adapted to potential challenges (e.g. strong discontent and resistance from stakeholders, conflicting interests) to mitigate uncertainty while boosting the transition process. The six policy intervention points and examples of related measures are:

- Stimulate different niches to allow for different alternatives of systemic change (e.g. R&D investments, public procurement, foresight and future visions, regulatory shielding, demand-pull subsidies in China);

- Accelerate the niches to support innovations to enter into the market (e.g. creation of innovation platforms, market-based policy instruments, advice systems for small and medium enterprises, provision of venture capital funds);

- Transform the regime, namely incumbent institutional and technological structures, social practices and culture (e.g. taxes, mandatory requirement to replace fossil-fuel energy infrastructure in public buildings in Norway, removing subsidies for certain industries);

- Address the broader repercussions of regime transformation on multiple scales (regional, societal, global) such as economic repercussions on existing industry, adverse environmental effects (e.g. biodiversity degradation), and social conflicts. Responsible Research and Innovation, embedded in the precautionary principle, could prevent unintended consequences of innovation. Examples of measures are information campaigns, financial support to help the industry phasing out older technologies, policies to tackle structural unemployment;

- Provide coordination to multiple regime interaction implies that different but interrelated socio-technical systems in transition mutually influence each other. For example, privately owned gasoline cars and the fossil-based energy infrastructure mutually reinforce CO_2 emissions and over reliance on few sources of energy, thus affecting energy security and societal resilience. Re-balancing this dynamic would entail diversifying the energy technology portfolio (see measures suggested before) and e.g. support car sharing, improve public transport networks, or link the conversion of gasoline to renewable energy.

- Tilt the landscape means to influence global frameworks and agreements towards more sustainable clauses to trigger positive effects on sustainable innovations uptake and upscaling. Examples of such global efforts are the Paris Agreement and the banning of chlorofluorocarbons (CFCs).

Box 3-6. A virtual case study: The transformation from Industry 4.0 to Industry 5.0 as a potential case of transformative R&I policy

The expert group on the economic and societal impact of research and innovation (ESIR) has extensively accompanied the efforts of DG R&I the during the COVID-19 crisis, outlined as an opportunity for change at the economic, societal and policymaking level. With the Policy Brief Industry 5.0: *a Transformative Vision for Europe*[32], ESIR sets up a strong case for R&I policy to accompany the evolution of the European industrial landscape towards sustainability, productivity and well-being.

Industry 5.0 demarcates itself from Industry 4.0 in its paradigm by putting sustainability at the centre as opposed to a focus on enhanced productivity through dematerialisation for the former. From the points outlined in this chapter, ESIR experts drew several policy recommendations illustrating the paradigm shifts upcoming or necessary for the transition from Industry 4.0 to 5.0, as illustrated in the table below. These policy recommendations relate to systemic change. As such, only a partial uptake of these policies is likely to hinder the transition, as mutual interaction across systems is a key aspect of systemic change.

Table 3-5: ESIR policy recommendations illustrating the paradigm shifts upcoming or necessary for the transition from Industry 4.0 to 5.0

Stimulate different niches to allow for different alternatives of systemic change	▸ Make a green and social industrial strategy the cornerstone of the Green Deal to address the challenges of the twin green and digital transitions. ▸ Rethink the role of the public sector in enabling the transition to Industry 5.0 (objectives, instruments, policy coherence, partnerships, interactions). ▸ Encourage a deep transformation of business models where sustainability is a natural component and driver of international competitiveness.
Accelerate the niches to support innovations to enter into the market	▸ A regulatory system that effectively guides accelerated compliance, adoption and best practice. ▸ Create a one-stop shop for companies to interact with the public sector on industrial transformation (streamline and expedite processes, facilitate interaction with different agencies and public sectors. ▸ Encourage more flexible, genuinely experimental and risk-embracing approaches to innovation development and deployment in partnership with industry. ▸ Reduce bureaucracy for SMEs seeking access to R&D support. ▸ Greater incentives for cross-pollination across research and innovation stages and across sectors.

32 https://ec.europa.eu/info/publications/industry-50-transformative-vision-europe_en

Transform the regime, namely incumbent institutional and technological structures, social practices and culture	▶ Full re-orientation of the Better Regulation agenda towards a post-GDP paradigm.
Address the broader repercussions of regime transformation on multiple scales (regional, societal, global) such as economic repercussions on existing industry, other forms of adverse environmental effects, and social conflicts.	▶ Reduced labour taxation (particularly for lower income workers), internalising pollution costs through environmental fiscal reform, considering the role of higher corporate and digital taxation; and discussing the application of a universal basic dividend or income logic.
Provide coordination to multiple regime interaction, as different but interrelated socio-technical systems in transition will mutually influence each other.	▶ A system of due diligence for all value chains that bring their products into the EU Single Market. ▶ Redesign other EU policies on the basis of resiliency principles which could bring mutual influence from agricultural and industrial systems for example. ▶ Put in place a coherent approach between policies covering industrial installations (IED), assets (taxonomy), supply chains (due diligence), products (product policy), materials (CEAP), pricing (ETS, CBAM, environmental fiscal reform), sectors and systems (agriculture, energy, forestry, nutrition, mobility, healthcare and housing and trade).
Tilt the landscape: to influence global frameworks and agreements	▶ Adoption of metrics and indicators that allow for the measurement of progress towards the vision. ▶ Change regulatory frameworks covering eco-design and BREFs (Best Available Technique Reference Documents).

Source : Authors' elaboration

3. Conclusions: for a deep transformation of our systems

The European Green Deal calls for the transformation of entire support systems for human and planet welfare in food, housing, manufacturing, energy infrastructure and transport. It also calls for a much more central role for innovation policy in orchestrating the transformation. Realising this promise requires not only more intensified innovation efforts, but also more extensive actions on innovation that transverse policy portfolios and levels of governance.

The market for nature investment and therefore demand for financing products will remain limited without regulation that obliges investment and/or creates reasonably predictable revenue streams. Natural capital is far from being an established asset class in the sense of depth of market and track-record. For the foreseeable future there will also not be uniformity among end beneficiaries and intermediaries. The Transition Performance Index demonstrates that efforts still need to be made at all levels of governance and across the globe.

In this chapter, we bring insights on **the role, the state of play and trends of research and innovation to preserve natural capital, transit to clean and circular production and consumption systems and adapt them to climate change, and to also achieve inclusiveness and fight inequalities.** The EU leads or is amongst the top international players in both scientific knowledge production and patenting activity related to sustainable development goals, such as biodiversity protection, sustainable cities and communities, responsible consumption and production, clean and smart energy, infrastructures, transport, water, food systems, education, good health and decent work. However, some international trends are worrying, such as the net decline of patenting activity in clean energy from the mid-to-end of the 2010s, or the low rate of circular economy solutions uptake and of technology transfer, most particularly climate change adaptation technologies.

A truly transformative R&I policy is about directionality, which is intended to provide a shared vision. **The European Missions** under Horizon Europe are an example of directed R&I policy innovation which **hold the potential of enabling deep societal transformations and ensuring prosperity within the planet's boundaries.** Emerging technologies, social innovations as well as a diverse portfolio of active stewardships of human actions in support of a resilient biosphere are highlighted as essential parts of such transformations" (Folke et al., 2021). **Future foresight, experimentation, systems methodologies** (e.g. system dynamics, LCA) and co-creation participatory exercises **are critical** as they bring novel ideas into policymaking and challenge dominant perceptions. Climate and biodiversity policies, inclusive policies and industrial transition policies need to be coordinated, including across countries, and tailored to specific conditions.

The integration of the '**do no significant harm' (DNSH) principle** in the EU's R&I framework programme will ensure its consistency with European Green Deal objectives and promote the transition to a safe, climate-neutral, climate-resilient, biodiversity-positive, more resource-efficient and circular economy. Finally, the **new impact-oriented framework** programme, which introduces Key Impact Pathways in the monitoring and evaluation framework will provide deeper analytical insights for medium- and long-term impacts and **facilitate evidence informed R&I policymaking.**

References

Audretsch, D., Keilbach, M. (2004), 'Entrepreneurship Capital and Economic Performance', *Regional Studies*, 38(8), pp. 949-959.

Becker, B., Kesidou, E. (2021), *Going green and failing: Evidence from propensity score matching on types of eco-innovation and project failure*. 8th European Conference on Corporate R&D and Innovation 2021

Ben-David, I., Jang, Y., Kleimeier, S., Viehs, M. (2021), 'Exporting pollution: where do multinational firms emit CO_2?,' *Economic Policy*, 36 (107), pp. 377–437.

Bianchini, S., Damioli, G., Ghisetti, C. (2020), *The two make a pair? Digital and green transition in European regions and their impact on greenhouse gas emissions*. INNOVA MEASURE IVWorkshop. 29th September 2020.

Boyer, J., Touzard, J-M. (2021), 'To what extent do an innovation system and cleaner technological regime affect the decision-making process of climate change adaptation? Evidence from wine producers in three wine clusters in France,' *Journal of Cleaner Production*, 315(28218).

Breque, M., De Nul, L., Petridis, A. (2021), *Industry 5.0. Towards a sustainable, human-centric and resilient European industry*, European Commission, DG Research and Innovation, Policy Brief. Publications Office of the European Union, Luxembourg.

Brookings (2021), *Brookings Impact Bonds Snapshot*. January 2021.

Chatfield, A.T., Reddick, C.G. (2016), 'Smart city implementation through shared vision of social innovation for environmental sustainability: a case study of Kitakyushu, Japan'. *Soc. Sci. Comput. Rev.*, 34 (6), pp. 757-773.

Coetzee, B. W. T., Gaston, K. J., Chown, S. L. (2014), 'Local Scale Comparisons of Biodiversity as a Test for Global Protected Area Ecological Performance: a Meta-Analysis'. PLoS ONE, 9 (8).Cojoianu ,T. F., Clark, G. L., Hoepner, A.G.F., Veneri, P., Wójcik, D. (2020), 'Entrepreneurs for a low carbon world: How environmental knowledge and policy shape the creation and financing of green start-ups', *Research Policy*, 49(6).

Colombelli, A., Quatraro, F. (2017), 'Green start-ups and local knowledge spillovers from clean and dirty technologies', *Small Bus. Econ*, pp. 1-20

Council of Europe Development Bank (2021), '7-year Social Inclusion Bond Benchmark Press Release'. CEB issues 8 th April 2021

Cowie, P., Townsend, L., Salemink, K. (2020), 'Smart rural futures: Will rural areas be left behind in the 4th industrial revolution?' *Journal of Rural Studies*, 79, pp. 169-176.

Dechezleprêtre, A., Fankhauser, S., Glachant, M., Stoever, J., Touboul, S. (2020), *Invention and Global Diffusion of Technologies for Climate Change Adaptation: a Patent Analysis*, International Bank for Reconstruction and Development / The World Bank.

Duranton, G. (2001), 'Endogenous labor supply, growth and overlapping generations', *Journal of Economic Behavior & Organization*, 44(3)3, pp. 295-314.

Ellen MacArthur Foundation (2013), *Towards the CE: economic and business rationale for an accelerated transition.*

European Commission (2015), *LAB – FAB – APP Investing in the European future we want*, Report of the independent High Level Group on maximising the impact of EU Research & Innovation Programmes, European Commission, DG Research and Innovation, Publications Office of the European Union, Luxembourg.

European Environmental Agency, (2001), [Late lessons from early warnings: The precautionary principle 1896-2000], Environmental Issue Report No 22/2001, European Environment Agency.

European Environmental Agency/ European Political Strategy Centre, (2019), From Words to Action: How Can EU Policy Drive Sustainability Transitions? Background Paper EEA-EPSC High-Level Workshop,

European Environmental Agency, (2019b)., *The European environment — State and outlook 2020: Knowledge for transition to a sustainable Europe*, European Environment Agency..

European Environmental Agency, (2013), [Late lessons from early warnings: Science, precaution, innovation], EEA Report No 1/2013, European Environment Agency, accessed 5 July 2021.

European Environmental Agency, (2019), *Drivers of change of relevance for Europe's environment and sustainability*, EEA Report No 25/2019.

European Environmental Agency, (2019), *Sustainability transitions: policy and practice*, EEA Report No 9/2019

European Environment Agency, (2020), The *European environment – state and outlook 2020*.

European Environment Agency. (2020b). EEA Report No 1/2020

European Environmental Agency, (2021), *With people and for people: Innovating for sustainability*, European Environment Agency. Briefing.

European Environmental Agency, (2021), *Creating a resilient economy within environmental limits*, EEA Report No 11/2021.

European Environmental Agency, (2021), *Nature-based solutions in Europe: Policy, knowledge and practice for climate change adaptation and disaster risk reduction*, EEA Report No 1/2021

European Commission, (2019), The European Green Deal. COM(2019) 640 final

European Commission (2020), Science, Research and Innovation Performance of the EU Report. European Commission, DG Research and Innovation,European Commission. (2020). A New ERA for Research and Innovation Staff Working Document, 2020, R&I paper series, policy paper

European Commission. (2020). Commission staff working document impact assessment. Stepping up Europe's 2030 climate ambition Investing in a climate-neutral future for the benefit of our people. Brussels, 17.9.2020 SWD(2020) 176 final

Fagerberg, J., (2018), Mobilizing innovation for sustainability transitions: a comment on transformative innovation policy. Research Policy. Volume 47, Issue 9, 2018, Pages 1568-1576. ISSN 0048-7333.

Fanning, A.L., O'Neill, D.W., Hickel, J., Roux N., (2021), 'The social shortfall and ecological overshoot of nations', *Nature Sustainability*, 5, pp. 26–36

Folke, C. Polasky, S., Rockström, J., Galaz, V., Westley, F., Lamont, M., Scheffer, M., Österblom, H., Carpenter, S.R., Chapin III, F.S., Seto, K.C., Weber, E.U., Crona, B.I., Gretchen, C.D., Sadgupta, P., Gaffney, O., Gordon, L.J., Hoff, H., Levin, S.A. Lubchenco, J., Steffen, W., Walker, B.H. (2021). 'Our future in the Anthropocene biosphere'. *Ambio*. 50, pp. 834–869.

Fritsch, M., Wyrwich, M. (2021). 'Is innovation (increasingly) concentrated in large cities? An international comparison', *Research Policy*, 50(6).

Füssel, H-M. (2007), 'Vulnerability: a generally applicable conceptual framework for climate change research', *Global Environmental Change*, 17(2), pp. 155-167.

Giarola, S., Molar-Cruz, A., Vaillancourt, K., Bahn, O., Sarmiento, L., Hawkes, A., Brown, M. (2021), 'The role of energy storage in the uptake of renewable energy: a model comparison approach', *Energy Policy*, 151.

Haskell, L., Bonnedahl, K.J., Stål, H. I. (2021), 'Social innovation related to ecological crises: a systematic literature review and a research agenda for strong sustainability', *Journal of Cleaner Production*, 325.

Hrovatin, N., Dolšak, N., Zorić, J. (2016), 'Factors impacting investments in energy efficiency and clean technologies: empirical evidence from Slovenian manufacturing firms', *Journal of Cleaner Production*, 127, pp. 475-486

Huang, W., Cui, S., Yarime, M., Hashimoto, S., Managi, S., (2015), Improving urban metabolism study for sustainable urban transformation, *Environmental Technology & Innovation*, 4, pp. 62-72.

Huggel, C., Scheel, M., Albrecht, F., Andres, N., Calanca, P., Jurt, C., Khabarov N., Mira-Salama D., Rohrer M., Salzmann N., Silva Y., Silvestre E., Vicuña L., Zappa M. (2015). A framework for the science contribution in climate adaptation: Experiences from science-policy processes in the Andes. Environmental Science & Policy. Volume 47. Pages 80-94.

International Energy Agency (2019), *Global patent applications for climate change mitigation technologies – a key measure of innovation – are trending down.*

International Energy Agency (2021), *Patents and the Energy Transition*, IEA, Paris

International Monetary Fund, (2017a), *Understanding the downward trend in labour income shares', in: World economic outlook: gaining momentum*, International Monetary Fund, Washington, DC.

International Energy Agency, (2021), Net Zero by 2050. *A Roadmap for the Global Energy Sector*, IEA Publications.

Kanger, L., Sovacool, B. K., Noorkõiv, M. (2020), 'Six policy intervention points for sustainability transitions: a conceptual framework and a systematic literature review', *Research Policy*,49(7))

Kassouri, Y., Altıntaş, H. (2020). Human well-being versus ecological footprint in MENA countries: a trade-off?. *Journal of Environmental Management*. Volume 263. 110405.

Kuhlmann, S., & Rip, A. (2014), *The challenge of addressing Grand Challenges: a think piece on how innovation can be driven towards the "Grand Challenges" as defined under the prospective European Union Framework Programme Horizon 2020*. European Research and Innovation Area Board (ERIAB).

Laakso, S., Heiskanen, E., Matschoss, K., Apajalahti, E-L., Fahy, F., (2021), 'The role of practice-based interventions in energy transitions: a framework for identifying types of work to scale up alternative practices', *Energy Research & Social Science*, 7.

Lenton, T., Benson, S., Smith T., Ewer T., Lanel V., , Petykowski E., Powell T W. R., Abrams J.F., Blomsma F., Sharpe S., (2021), *Operationalising Positive Tipping Points towards Global Sustainability*. Global Systems Institute. University of Exeter. Working paper series number 2021/01

Leonard, M., Pisani-Fery, J., Shapiro, J., Tagliapietra, S., Wolff, G. (2021), *The geopolitics of the European Green Deal*, Policy brief, European Council of Foreign Relations. Lucertini, G., Musco, F. (2020), 'Circular Urban Metabolism Framework', One Earth, 2 (2), pp. 138-142.

Markaki, M., Belegri-Roboli, A., Michaelides, P., Mirasgedis, S., Lalas, D.P. (2013), 'The impact of clean energy investments on the Greek economy: An input–output analysis (2010–2020)', *Energy Policy*, 57, Pp. 263-275.

Mazzucato, M. (2019), *Governing Missions in the European Union*, European Commission Directorate-General for Research and Innovation.

Meadows, (1999), *Leverage points: places to intervene in a system*, Sustainability Institute.

Midgley, G., Lindhult, E. (2017), *What is systemic innovation?* Research memorandum, University of Hull Business School.

Al-Ajlani, H., Cvijanović, Es-Sadkix N., V., Müller, V. (2021), *EU Eco-Innovation Index 2021*, Policy brief, July 2021.

NESTA, (2013), *Systemic Innovation: a discussion series.OECD (2015), Greening Steel: Innovation for Climate Change Mitigation in the Steel Sector*. OECD Publishing, Paris.

OECD (2015), Social Innovation. OECD website.OECD (2020), *Beyond Growth: Towards a New Economic Approach*, New Approaches to Economic Challenges, OECD Publishing, Paris.

O'Neal, L., Perkins, A., (2021), 'Rural exclusion from science and academia', *Trends in Microbiology*, 29(11), pp. 953-956.

Özdurak, C. (2021), 'Will clean energy investments provide a more sustainable financial ecosystem? Less carbon and more democracy', *Renewable and Sustainable Energy Reviews*, 151.

Perera, A.T.D., Mauree, D., Scartezzini, J-L,. (2017), 'The energy hub concept applied to a case study of mixed residential and administrative buildings in Switzerland', Energy Procedia, 122. pp.181-186

Probst, B., Touboul, S., Glachant, M. (2021), 'Global trends in the invention and diffusion of climate change mitigation technologies', *Nat Energy*, 6, pp. 1077–1086.

Rissman, J., Bataille, C., Masanet, E., Aden, N., Morrow, W.R., Zhou, N., Elliott, N., Dell, R., Heeren, N., Huckestein, B., Cresko, J., Miller, S.A., Roy, J., Fennell, P., Cremmins, B., Koch Blank, T., Hone, D., Williams, E.D., de la Rue du Can, S., Sisson, B., Williams, M., Katzenberger, J., Burtraw, D., Sethi, G., Ping, H., Danielson, D., Lu, H., Lorber, T., Dinkel, J., Helseth, J. (2020), 'Technologies and policies to decarbonize global industry: Review and assessment of mitigation drivers through 2070', *Applied Energy*, 266.

Schippl, J., Truffer, B. (2020), 'Directionality of transitions in space: Diverging trajectories of electric mobility and autonomous driving in urban and rural settlement structures', *Environmental Innovation and Societal Transitions*, 37, pp. 345-360.

Smit, B., Wandel, J. (2006), 'Adaptation, adaptive capacity and vulnerability', *Global Environmental Change*, 16(3), pp. 282-292.

Social Economy Europe, (2015), *Social Economy…Taking back the initiative*.

Stern, N., Valero, A., (2021), 'Innovation, growth and the transition to net-zero emissions', *Research Policy*, 50(9).

Stock, J. (2021), *Driving deep decarbonization*,Finance & Development September 2021.

Takalo, S.K., Tooranloo, H. S., Shahabaldini Parizi, Z., (2021), 'Green innovation: a systematic literature review', *Journal of Cleaner Production*, 279.Turnheim, B., Asquith, M.,

Geels, F., (2020), 'Making sustainability transitions research policy-relevant: Challenges at the science-policy interface', *Environmental Innovation and Societal Transitions*, 34, pp. 116-120.

United Nations (2015), *Transforming our world: the 2030 Agenda for Sustainable Development.*

United Nations (2019), The Future is now. Science for achieving sustainable development.United Nations Development Programme (2020), Human Development Report 2020.

Von Wirth, T., Fuenfschilling, L., Frantzeskaki, N., Coenen, L. (2019), 'Impacts of urban living labs on sustainability transitions: mechanisms and strategies for systemic change through experimentation', *European Planning Studies*, 27(2), pp. 229 257.

Wan, D., Xue, R., Linnenluecke, M., Tian, J., Shan, Y. (2021), 'The impact of investor attention during COVID-19 on investment in clean energy versus fossil fuel firms', *Finance Research Letters*, 43.

CHAPTER 4

BUSINESSES AND SKILLS IN THE DIGITAL AGE

CHAPTER 4.1

PRODUCTIVITY

KEY FIGURES

11 %
overall labour productivity growth from 2010 to 2019 in the European Union

50 %
of productivity levels in the European Union is explained by human capital

8 %
of productivity growth in the European Union is explained by R&D

19 %
of productivity growth in the European Union is explained by software and computerised information

KEY QUESTIONS WE ARE ADDRESSING

- Why is productivity relevant for society?
- What are the main drivers of productivity in the EU?
- How can we explain the productivity slowdown?

KEY MESSAGES

What did we learn?

- Productivity and economic growth are important for boosting competitiveness, socio-economic development and tackling poverty.
- Economic growth can be enabled within a sustainable and inclusive economic model, supported by a broader diffusion and uptake of digital and clean technologies, as well as significant investments in breakthrough technologies.
- It is possible to decouple economic growth from environmental damage.
- The EU outperforms its international competitors in directing its accumulated wealth toward the achievement of the UN's Sustainable Development Goals.
- Human capital is the most crucial contributor toward labour productivity, followed by physical capital and R&D investments.
- Control of corruption is the main framework condition driving higher productivity levels.
- Despite the huge potential of the ICT revolution, there is a secular stagnation in productivity growth. This productivity puzzle is partly explained by increasing productivity polarisation, declining business dynamism and the high cost of human capital for firms adopting new digital technologies.
- The COVID-19 pandemic has impacted the economy, industries, firms and individuals in very diverse and uneven ways. The most negatively affected have been low productivity sectors, low-income households and young people.

What does it mean for policy?

- Enhanced productivity in combination with political and electoral will can be the means to achieve inclusive growth and desirable outcomes.
- Human capital policies will be important to improve future productivity and wellbeing.

- Organisation management, physical capital, international trade and competition can positively affect economic growth and productivity.
- Tackling corruption and easing access to finance are low-cost policy tools to improve productivity levels.
- The disproportionally large impact of COVID-19 on youth and other specific groups calls for specific attention and includes compensatory policies to mitigate the risks to inclusive growth.

1. Productivity, economic growth and well-being

Productivity is an important economic indicator that is closely linked to economic growth, competitiveness and living standards within an economy. All measures of productivity refer to the efficiency with which we are able to transform input such as resources into output such as products. In other word, productivity is efficiency in production: how much output is obtained from a given set of inputs.

Productivity is typically measured as Labour Productivity or Total Factor Productivity (TFP):

- TFP is a proxy for technological progress. It represents the efficiency with which factors of inputs (labour and capital) are combined. It depicts the effect in total output not accounted for by labour and capital inputs through other factors such as technology, efficient organisational management and the quality of institutions. TFP is computed through an accounting exercise, following the methodology introduced by Solow (1957).
- Labour Productivity is a proxy of the efficiency and quality of human capital in the production process for a given economy. It is measured as the total volume of output (measured in terms of Gross Domestic Product, GDP) produced per unit of labour (measured as the number of employed persons or as hours worked) during a given time reference period.

Economic growth and productivity are relevant to the goals of tackling poverty and freeing individuals from misery. Economic growth is often the main contributor to poverty reduction (White and Anderson 2001, Dollar and Kraay 2002). Kraay (2004) finds that economic growth (measured by growth in average incomes) explains around 70 % of the changes in poverty (measured by the headcount ratio) in the short term, and around 97 % in the long term. Within the European Union, Beugelsdijk et al. (2018) find that a large part of the persistent differences in economic development across subnational European regions can be attributed to differences in TFP. Productivity positively affects firms' financial performances (Grifell-Tatjé et al., 2018). It enhances corporate financial performance through lower costs, to the benefit of consumers through lower prices (Syverson 2011). At the same time, productivity can be employed to achieve desirable societal objectives (see Box 4.1).

Isaksson et al. (2005) describe productivity as a key element for raising living standards and reducing poverty. Amartya Sen (1999) and Acemoglu (2008) reach similar conclusions by arguing that economic development is deeply linked to economic growth, with however the institutional and political dimension playing a crucial role in the redistribution effort of such generated resources.

'Without productivity growth there would be no social advancement. Without productivity gains there cannot be welfare gains. Yet, it must be admitted that productivity gains are only the wherewithal to welfare improvement. Economic mechanisms may offer a productivity outcome and propose a distribution between consumers (by way of price reductions) and factors connected to production (by way of remuneration of their services). But how this distribution will actually occur, and how effectively it will be directed to welfare improvement, is another story. Here, it is the interplay of socio-political processes that will have the last word.' (Isaksson)

'Productivity is not everything, but in the long run it is almost everything. A country's ability to improve its standard of living over time depends almost entirely on its ability to raise its output per worker.' (Krugman)

Box 4-1 Productivity and societal objectives

Productivity can also be a useful tool to achieve desired societal objectives. Figure 4.1-1 depicts the relationship between different productivity measures and various measures of meritorious societal objectives: Sustainable Development Goals Index[1] (SDG Index), Human Development Index[2] (HDI) and Environmental Performance Index[3] (EPI). The scatterplots contain cross-country level data for 193 nations, related to the last available year.

Economic growth makes it possible for nations to choose to invest in policies and ambitious programmes that lead to environmentally and socially desirable outcomes. Figure 4.1-1 shows that the Sustainable Development Goals Index (SDG Index) is positively correlated with per capita gross domestic product and total factor productivity. Figure 4.1-1 also shows that the Human Development Index (HDI) is positively correlated with per capita gross domestic product and total factor productivity. Third, and finally, Figure 4.1-1 shows that the Environmental Performance Index (EPI) is positively correlated with per capita gross domestic product and total factor productivity.

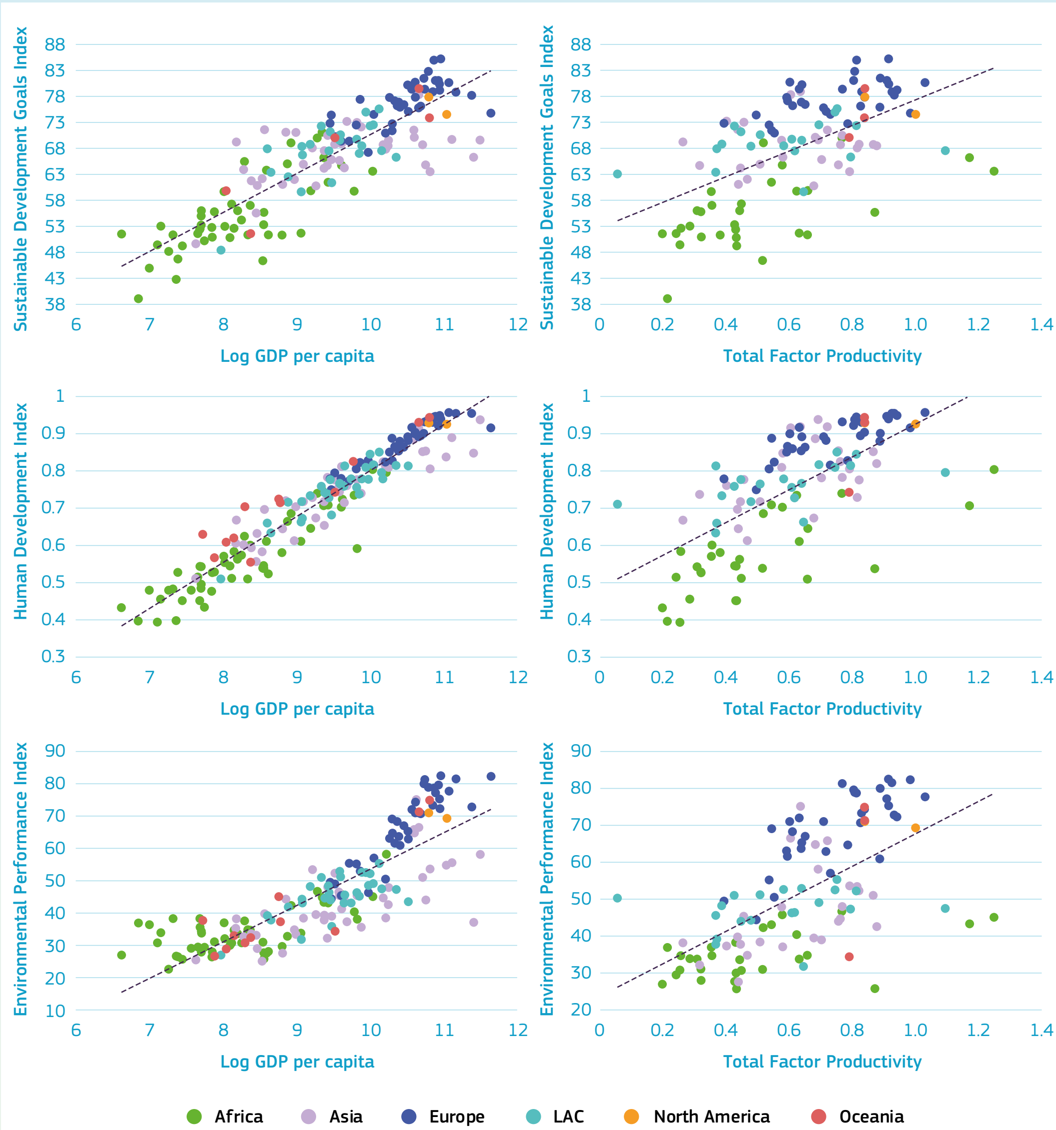
Even though the presented plots do not represent causal evidence, they are an instructive descriptive depiction of the relationships at play. Interestingly, we can observe that European countries are, in most of the cases, above the fitted line, meaning that they are overperforming their peers in term of sustainable/meritorious use of their generated wealth.

1 In 2015, the United Nations introduced the 17 Sustainable Development Goals (SDGs). The SDGs provided a shared blueprint for peace, prosperity, people and the planet. They measure how well countries are performing in terms of improving health and education, reducing inequality and poverty, tackling climate change and preserving oceans and forests. The SDG Index is a composite index introduced by Schmidt-Traub et al. (2017) to provide a standardised and quantitative measure of SDG baselines for 149 countries. It synthesises 63 global indicators plus 14 additional indicators for OECD countries into an overall assessment of countries' SDG performances.

2 The Human Development Index (HDI) is a composite index developed by the United Nations Development Programme. It measures the average achievement of 195 countries on three dimension of human development: long and healthy life, education and decent standard of living.

3 The Environmental Performance Index (EPI) is a composite index for country performance on sustainability issues developed by the Center for Environmental Law & Policy of Yale University. EPI ranks 180 countries on environmental health and ecosystem vitality, employing 32 indicators of environmental performance related to Air Quality, Sanitation & Drinking Water, Heavy Metals, Waste Management, Biodiversity, Fisheries, CO_2, etc.

Figure 4.1-1: Productivity vs societal and environmental outcomes, 2019



Source: DG Research and Innovation – Common R&I Strategy and Foresight Service - Chief Economist Unit's own elaboration.
Note: GDP per capita, PPP (constant 2017 international $) is collected from the World Bank's database. TFP level at current PPPs is collected from the Penn World Table version 10.0. Overall, up to 193 countries are plotted.
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Yet productivity should not be interpreted as panacea for all issues in society, rather as a tool to generate the necessary resources to invest in the public and private goods. In other words, higher levels of productivity and economic performance on their own do not ensure the achievement of societal goals. A higher productivity level increases countries' resources and tools to reach a goal, given that nations want to do so. The political will to employ economic means toward desirable goals remains a political choice, one that depends on electoral outcomes. Having the resources is a necessary but non-sufficient condition.

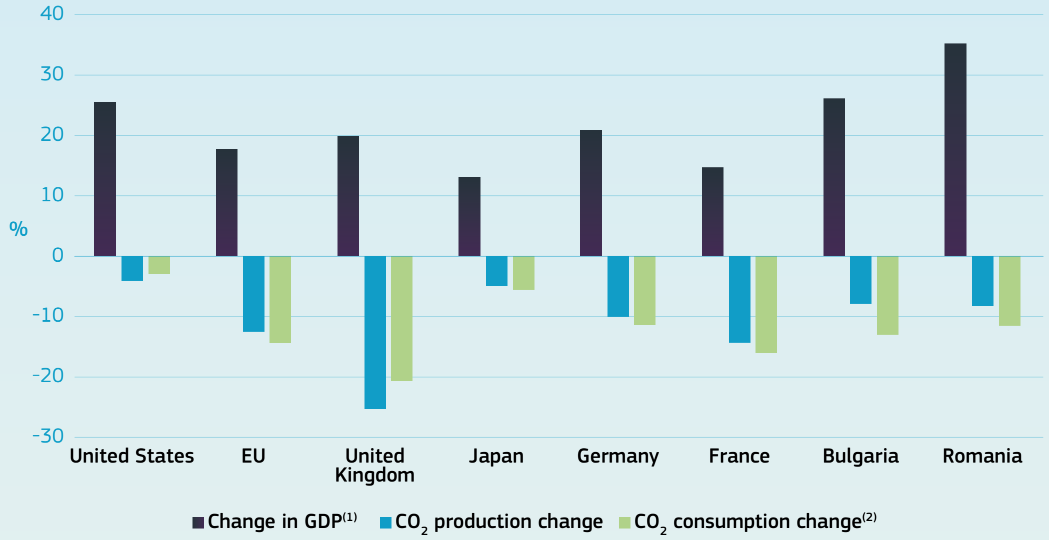
With the adoption of the European Green Deal, the European Commission has showed a strong will to employ economic means toward the achievement of the Paris Agreement objectives in line with UN's Sustainable Development Goals. The Intergovernmental Panel on Climate Change (IPCC) report[4] has been taken into consideration for the construction of the EU's strategy for long-term greenhouse gas emission reduction[5]. The European Commission's communication *A clean planet for all* highlights how the EU's climate policy strategy should engage all sectors of the economy and society, ensuring that the transition toward emission neutrality is socially fair, enhances the competitiveness of the EU's economy and industry on global markets, and secures quality jobs, sustainable growth, eradicate poverty, while providing synergies with other environmental challenges, such as air quality and biodiversity loss[6].

The new EU annual sustainable growth strategy (ASGS) is structured around four dimensions: environmental sustainability, productivity, fairness and macroeconomic stability. It represents the EU's ambition to transform to a fair and prosperous society with a resource-efficient and competitive economy[7]. Climate change related damage is likely to negatively affect future labour productivity, with high related economic and social costs. Hence, employing economic means, as well as research and innovation, to succeed in the twin transition is increasingly seen as a crucial policy priority for the EU.

Addressing the climate and environmental crisis is the defining challenge of our time and it is an opportunity to relaunch our economies in a sustainable manner. To do so, it is fundamental to put the economy on the right track to long-term sustainable growth and employment aiming at reaching climate neutrality by 2050 and decoupling economic growth from resource use (European Commission, 2021). Recent data shows that increasing economic prosperity while reducing CO_2 emissions is possible. In the last 10 years, different countries managed to improve their GDP while reducing their CO_2 emissions (both adjusted and non-adjusted for trades). Such a result was possible for both rich economies, such as the US, Germany, France, UK and Japan, and emerging economies, such as Bulgaria and Romania (see Figure 4.1-2). As an example, from 2009 to 2019 Germany's GDP grew by 21%, while CO_2 emissions fell by around 10%. During the same time period, Bulgaria saw its GDP growing by 26%, while its CO_2 emissions falling by 8%.

4 See here for more.
5 Cutting emissions by at least 55% by 2030 and achieving climate neutrality by 2050.
6 See here for more.
7 See here for more.

Figure 4.1-2: Percentage change in GDP and CO_2 emissions between 2009 and 2019



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Source: Global Carbon Budget – Global Carbon Project (2021) and World Development Indicators – World Bank.

Note: (1) Gross Domestic Products is expressed as PPP (constant 2017 international dollars).

(2) Consumption-based emissions are national emissions which have been adjusted for trade (i.e. territorial/production emissions minus emissions embedded in exports,- plus emissions embedded in imports).

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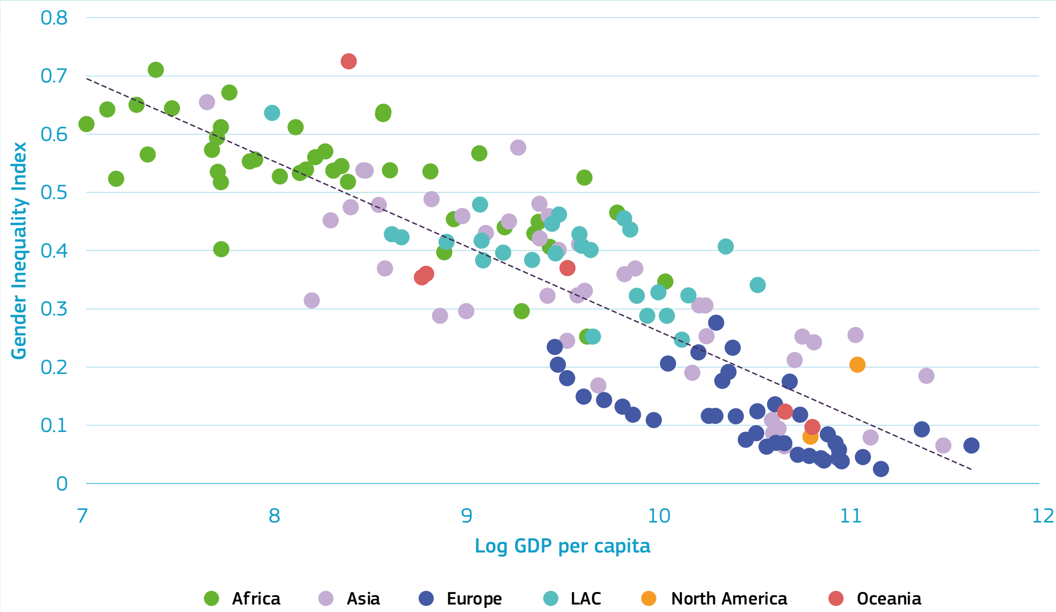
Higher levels of productivity worldwide are also associated with less gender inequality. Indeed, the countries were women are treated fairer are also those that perform better economically, and societies become more productive as they treat women better. Hudson et al. (2012) uses micro and macro data from around the world to highlight how nations fail when women are treated unequally, as they end up being less meritocratic, less stable and more violent. Figure 4.1-3 depicts the relationship between productivity and gender inequality, confirming that superior levels of productivity are associated with lower levels of gender inequality. European countries are, in most of the cases, below the fitted line, meaning that they are over performing their peers in term of gender equality given a similar obtained wealth.

Figure 4.1-3: **Productivity vs gender inequality, 2019**



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Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit based on the Gender Inequality Index (higher levels of the GII imply more gender inequality) produced by the United Nations and GDP per capita, PPP (constant 2017 international $) collected from the World Bank database.

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Less clear is evidence of the effect of productivity growth on income inequality. Indeed, the empirical evidence is so far rather mixed and inconclusive. Easterly (1999) finds that economic growth has a positive impact on different indicators of quality of life. Lopez (2004) finds that regardless of their impact on inequality, pro-growth policies lead to lower poverty levels in the long term, even though mixed distributional effects in the short term are possible. Dollar and Kraay (2002) find that the average incomes of the poorest quintile rise proportionately with average incomes. Ravallion and Chen (1997) find that changes in inequality and polarisation are uncorrelated with changes in average living standard.

The effect of inequality on productivity growth is mixed too. Alesina and Rodrik (1994), Persson and Tabellini (1994), and Perotti (1996) find a negative relationship between inequality and growth. Li and Zhou (1998), Forbes (2000), and Banerjee and Duflo (2003) find a positive relationship. Barro (2000) finds no relationship. More recently, Ostry, Berg and Tsangarides (2018) find that low inequality (as long as this is not obtained through extensive redistribution policies) is positively correlated with faster and more durable growth. Banerjee and Duflo (2003) find an inverted U-relationship between growth rates and inequality. Van der Weide and Milanovic (2014) find that high levels of inequality reduce the income growth of the poor, while increasing the income growth of the rich.

To sum up, the existing evidence presents productivity and economic growth as important for boosting competitiveness, socio-economic development and tackling poverty, while their link with inequality is yet to be clarified. The unclear link between productivity and inequality is likely driven by the major role played by institutions and citizens' political preferences regarding the reallocation decisions of the resources generated by the economic system. This makes productivity a useful metric for policymakers to measure economic competitiveness and resource capacity to address politically defined objectives.

2. The main drivers of productivity

Given the importance of productivity, a central issue for policymakers is to uncover its main drivers. In other words, **how can we boost productivity?**

There are both firm level and institutional drivers of productivity. At the firm level, it has been found that innovation, management practices and human capital are key determinants of higher productivity. In the aggregate, a stable macroeconomic environment, property right enforcement, openness to trade, effective government, and properly regulated markets are other key factors (Grifell-Tatjé et al. 2018, Syverson 2011, Bartelsman and Doms 2000).

Innovation is a crucial driver of productivity. Innovation boosts productivity through the development and deployments of new products and processes. This enables firms to generate greater output with the same input, which increases the production of goods and services, culminating in higher incomes for employees and entrepreneurs. Innovation usually starts on a small scale, for example when a new technology is first applied by the company where it has been developed. However, to realise the full benefits, innovations needs to spread across the economy and benefit companies in different sectors and of different sizes. This process of innovation diffusion will boost productivity and income levels. Innovation at the firm level can be divided into different categories: product, process, organisational and marketing innovation. Empirically, regardless of the innovation measurement employed, innovation has been found to explain differences in productivity not only across firms, but also across industries and nations (Mohnen and Hall 2013, van Leeuwen and Klomp 2006, Raymond et al. 2015). In addition, the number of patents a company introduces has been positively associated with productivity (Balasubramanian and Sivadasan 2011). Belderbos, Carree, and Lokshin (2004) find that R&D cooperation with competitors, suppliers, customers, and universities and research institutes raises productivity levels.

As already mentioned, other important drivers of productivity are:

- **Human capital.** The importance of human capital for individual wage and productivity has been extensively studied in economics micro-level analysis reveals a strong positive link between measures of human capital (such as education attainment, professional training and experience) and productivity (Abowd et al. 2009, Beaulieu et al. 2014, Chang et al. 2016). See Chapter 5.4 for more.

- **Organisation management.** Different studies have explored the role of management practices and firms' organisation on productivity. Bloom and Van Reenen (2007) interviewed 732 medium-sized firms in the United States, France, Germany, and the United Kingdom and ranked them based on their use of 'best managerial practice' (using management consultancy evaluation tools). The finding shows that the presence of best practices is strongly associated with firm-level productivity, profitability, and survival rates. Bloom et al. (2013) run a management field experiment on large Indian textile firms. The authors provided free consulting on management practices to randomly chosen treatment plants, and compared their performance to a set of control plants. The adoption of such management practices was found to raise firms' productivity. Among the reasons for the lack of adoption of 'managerial best practices' are information barriers, transition costs and the sorting of less competent managers into dysfunctional companies.

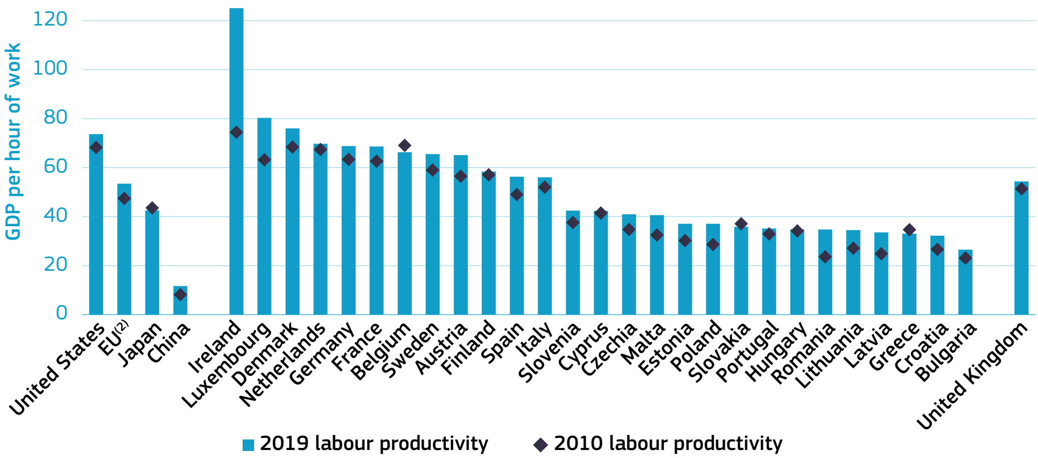
- **Physical capital.** Investment in tangible goods, such as land, buildings, machinery and equipment, improves firms' productivity.

- **Trade.** International trade, both import and export activities, represents a relevant driver of productivity growth. Theoretically, the positive impact of international trade on innovation and productivity comes from both knowledge spillovers and increased competition (Silva, Afonso, and Africano 2012, Bas and Strauss-Kahn 2014). Empirically, both exporting firms and importing firms have been found to be more productive than non-exporting and non-importing ones (Bartelsman and Doms 2000, De Loecker and Goldberg 2014, Kasahara and Lapham 2013). This is not only because of self-selection of more productive firms into importing or exporting activities (Bernard and Jensen 1999), but there is also an additional positive impact of export on productivity thanks to 'learning by exporting effects' (Atkin, Khandelwal and Osman 2017, De Loecker 2007). Similar 'learning by importing effects' are detected by Augier, Cadot, and Dovis (2013) and Kasahara and Rodrigue (2008).

- **Competition.** Competition can affect productivity through Darwinian selection and the escape-competition mechanism. Darwinian selection raises average productivity by pushing less productive firms out of the market, while fiercer competition increases the incentives for firms to innovate in order to escape competition (Aghion 2001, Syverson, C. 2011). Empirically, Aghion, P. (2018) shows an example of escape competition. Aghion (2005) also finds strong evidence of an inverted-U relationship between product market competition and innovation. Schmitz (2005) offers an example of heightened competition. Syverson (2004) shows the importance of pro-competitive environment in the US and Giuseppe Nicoletti and Scarpetta (2006) shows the same in OECD countries. At the same time, poorly regulated markets can generate perverse incentives that diminish productivity. See Chapter 7.2 for more information.

Figure 4.1-4 depicts the labour productivity across European countries, the US, Japan and China. Figure 4.1-5 depicts the Total Factor Productivity levels across European countries, the US, Japan and China. Overall, in the EU labour productivity grew by 11 % from 2010 to 2019. Ireland and Luxemburg present the highest level of labour productivity, yet such results should be taken with caution due to measurement issues of the GDP. Indeed, Ireland's high concentration of foreign multinationals drives its largest productivity gains: many tech giants like Google, Facebook, and Apple book profits in Ireland from other jurisdictions. This inflates the country's GDP, making labour productivity measurement likely overstated. On the other hand, Luxembourg's high productivity levels is driven by financial sector and high share of border workers. The US has a higher level of productivity than EU, the UK and China. Despite China's remarkable economic growth over the last decade, the country still remains behind in terms of productivity per worker, with performances lower than all EU Member States. Total factor productivity figures show a similar trend and ranking to labour productivity ones.

Figure 4.1-4: Labour productivity[1], 2010 and 2019



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Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit own elaboration

Note: [1] Labor productivity is calculated using data from the Penn World Table version 10.0 as gross domestic product (GDP PPP constant 2017) per hour of work by employing the formula: (rgdpo) / (avh * emp). [2] EU is computed by DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit.

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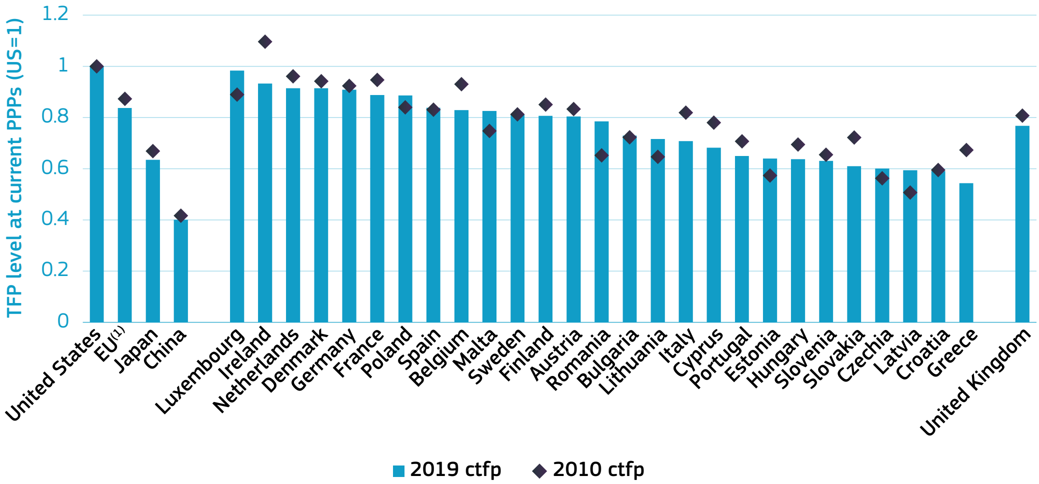
Figure 4.1-5: Total factor productivity, 2010 and 2019



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Source: The Penn World Table version 10.0.

Note: EU[1] is computed by DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit as weighted average based on nominal GDPP

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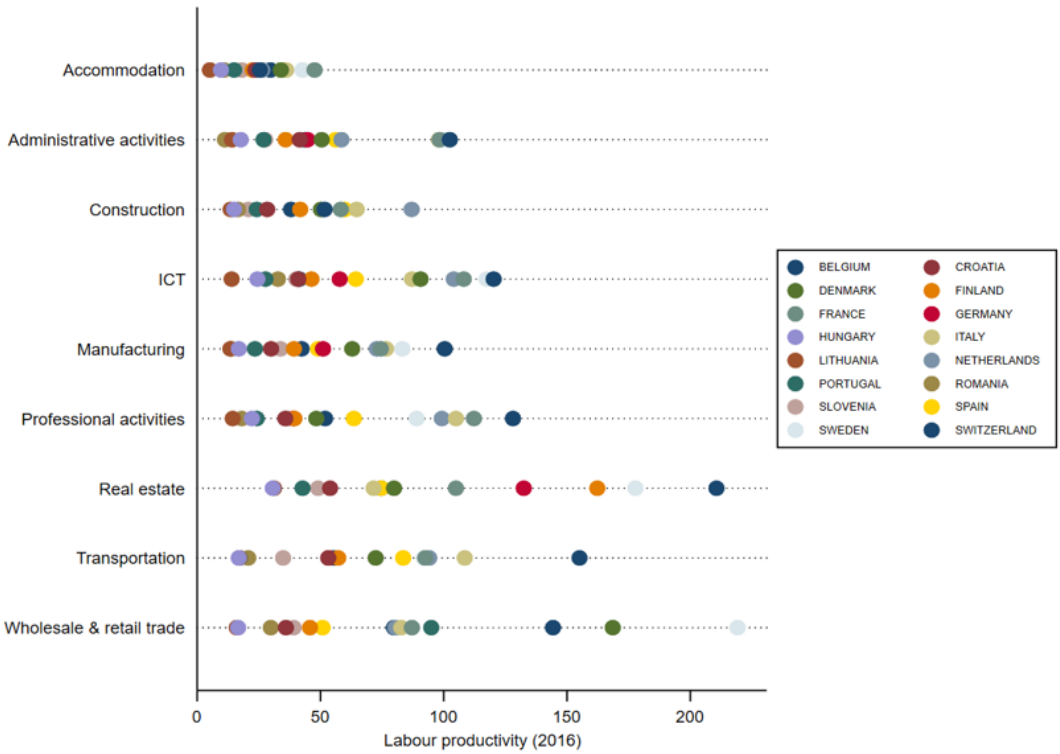
Country level aggregates of productivity hide a vast heterogeneity of productivity levels within countries, across firms and sectors. This implies that the aggregate productivity level of a country does not only depend on its sectoral composition, but also on the underlying productivity distribution across firms. Figure 4.6 depicts such wide variation of productivity levels across European countries and sectors. Looking at unweighted overages, the accommodation and administrative sectors are the least productive, while the wholesale and retail trade sector is the most productive. Countries specialise in different sectors, showing to be more productive in areas where other nations are instead conspicuously less productive.

To understand the current European drivers of productivity, we perform an econometric exercise using country-sector-year data from CompNet's 7th Vintage and country-year data from the World Bank and Eurostat databases (see Box 4.2 for more details).

Figure 4.1-6: Cross-country-sector labour productivity heterogeneity



Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit own elaboration based on CompNet's 7th vintage dataset.
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Box 4-2: Computing the contribution of human capital to labour productivity in the EU

Firstly, we define a Cobb Douglas production function with a Human Capital term $Y=A \times K^{z} \times (H \times L)^{1-z}$ where Y represents the produced output, A is the level of efficiency in the use of the inputs (TFP), K is the physical capital, L is the work force and H is the human capital (cost of human capital) embedded in the workforce. The output elasticity of capital (labour) is indicated by z (1-z). By dividing the production function by L and taking the logs of the components, we obtain a formula for labour productivity, which can be estimated by implementing a simple OLS regression:

$$Log\left(\frac{Y}{L}\right) = z \times log\left(\frac{K}{L}\right) + (1 - z) \times log(H) + log(A)$$

Hence, we regress labour productivity on capital intensity, human capital stock, and some proxies of TFP such as allocative efficiency (measured by the OP gap[8]), concentration (measured by the Herfindahl-Hirschman Index - HHI), credit availability (measured by the share of unconstrained firms), research and development investments (measured as share of GDP) and degree of corruption (measured with the Worldwide Governance Indicators of the World Bank).

Table 1 shows the marginal effects of the different drivers of labour productivity using sector-country-year level data from 1999 to 2017 for 18 EU member states. To compute such estimation a panel regression model with fixed effects is employed.

8 A developed by Olley and Pakes (1996), by computing the extent to which firms with higher productivity have a larger market share. The OP gap is computed as the covariance of the change in productivity and firm size with respect to the mean.

Table 4.1-1: Regression results

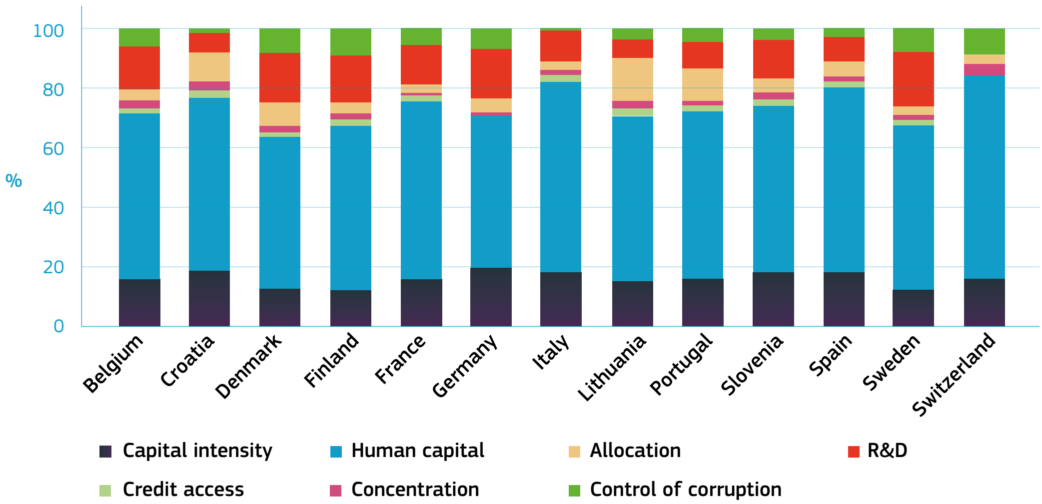
VARIABLES	(1) Productivity	(2) Productivity	(3) Productivity
Capital Intensity	0.100*** (0.00926)	0.114*** (0.0134)	0.122*** (0.0130)
Human Capital	0.562*** (0.0223)	0.423*** (0.0364)	0.410*** (0.0335)
Credit Access	0.143*** (0.0246)	0.0814*** (0.0178)	0.0576*** (0.0155)
Concentration	0.374 (0.240)	0.452* (0.245)	0.588*** (0.188)
Allocation	0.672*** (0.0306)	0.584*** (0.0431)	0.543*** (0.0427)
R&D Investments	0.174*** (0.0189)	0.165*** (0.0112)	0.162*** (0.00998)
Control of Corruption	0.0622** (0.0295)	0.0951*** (0.0168)	0.103*** (0.0169)
Constant	1.108*** (0.0872)	1.574*** (0.115)	1.615*** (0.109)
Observations	5,250	5,227	5,132
R-squared	0.888	0.975	0.982
Country FE	YES	YES	YES
Sector FE	YES	YES	YES
Year FE	YES	YES	YES
Country × Sector FE	NO	YES	YES
Sector × Year FE	NO	NO	YES

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit's own elaboration based on CompNet's 7th vintage dataset, World Bank and Eurostat data. Note: robust standard errors in parentheses *** p<0.01, ** p<0.05, * p<0.1

Using the estimated marginal effects of Table 4.1-1, we construct the relative contribution of each observed driver toward labour productivity, as shown in Figure 4.1-7.

Human capital is the most crucial contributor toward labour productivity, followed by physical capital and R&D investments. On average it accounts for around 50% of the explained variation in labour productivity across European countries. Research and development investments account for around 15% of the explained variation in labour productivity. Physical capital accounts for around another 15% of the explained variation, while credit access, market concentration, allocative efficiently and government corruption jointly account for the remaining part (see Figure 4.1-7).

Figure 4.1-7: **Explained contribution to labour productivity (2016)**



Source DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit's own elaboration based on CompNet's 7th vintage dataset, World Bank and Eurostat data.
Notes: The contribution shares to labour productivity are derived from the regression estimate of Table 1, column 3
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Box 4-3: Intangible Capital and Labour Productivity Growth – A Cross-Country Sectoral Growth Accounting Approach - Felix Roth (University of Hamburg)

Figure 4.1-8 displays the results of an econometric cross-country sectoral growth accounting (CCSGA) approach. The estimation approach at the sectoral level is developed by Roth in the Horizon 2020-funded GLOBALINTO project (Roth and Sen 2021) and resembles an extension of the author's earlier work at the country level as developed within the FP7-funded INNODRIVE project (Roth 2022, Roth 2020 and Roth and Thum 2013). Figure 4.1-8 is based on the following model specification:

$$Q_{c,j,t} = A_{c,j,t} K^{a}_{c,j,t} R^{\beta}_{c,j,t} L^{y}_{c,j,t} \varepsilon_{c,j,t} \qquad (1)$$

where $Q_{c,j,t}$ is real value added, $K_{c,j,t}$ is the tangible capital stock, $R_{c,j,t}$ is the intangible capital stock, $L_{c,j,t}$ is labor, $A_{c,j,t}$ is TFP and $\varepsilon_{c,j,t}$ is the error term in country c in sector j at time t.

Dividing both sides of the equation by labour, and taking the logarithm and the first differences of both sides and modeling TFP growth with the help of Nelson-Phelps-type control variables yields the following equation[9]:

$$(\text{In } q_{c,j,t} - \text{In } q_{c,j,t\text{-}1}) = c + gH_{c,t} + mH_{c,t} \frac{(q_{max,t} - q_{c,t})}{q_{c,t}} + \text{n } (1 - ur_{c,t}) + \text{p}\textstyle\sum_{i=1}^{k} X_{i,c,t} + \mu_t$$
$$+ \text{ a } (\text{In}k_{c,j,t} - \text{In}k_{c,j,t\text{-}1}) + \beta \, (\text{In}r_{c,j,t} - \text{In}r_{c,j,t\text{-}1}) + \text{u}_{c,j,t}{}^{9} \qquad (2)$$

where c captures a constant, $H\_(c,t)$ captures the innovation capacity, $H_{c,t} \frac{(q_{max,t} - q_{c,t})}{q_{c,t}}$ represents a catch-up term, the term $(1\text{-}ur_{c,t})$ accounts for business cycles and $X_{i,c,t}$ refers to control variables i that might effect TFP growt in a country at time t. μ_t are time-fixed effects. I derive equation (3) by differentiating in equation (2) for three distinct intangible capital dimensions: i) computerized information (ci), ii) innovative property (ip) and iii) economic competencies (ec):

$$(\text{In } q_{c,j,t} - \text{In } q_{c,j,t\text{-}1}) = c + gH_{c,t} + mH_{c,t} \frac{(q_{max,t} - q_{c,t})}{q_{c,t}} + \text{n } (1 - ur_{c,t}) + \text{p}\textstyle\sum_{i=1}^{k} X_{i,c,t} + \mu_t$$
$$+ \text{ a } (\text{In}k_{c,j,t} - \text{In}k_{c,j,t\text{-}1}) + \beta \, (\text{In}ci_{c,j,t} - \text{In}ci_{c,j,t\text{-}1}) + \gamma \, (\text{In}ip_{c,j,t} - \text{In}ip_{c,j,t\text{-}1}) +$$
$$+ \, \delta \, (\text{In}ec_{c,j,t} - \text{In}ec_{c,j,t\text{-}1}) + \text{u}_{c,j,t} \qquad (3)$$

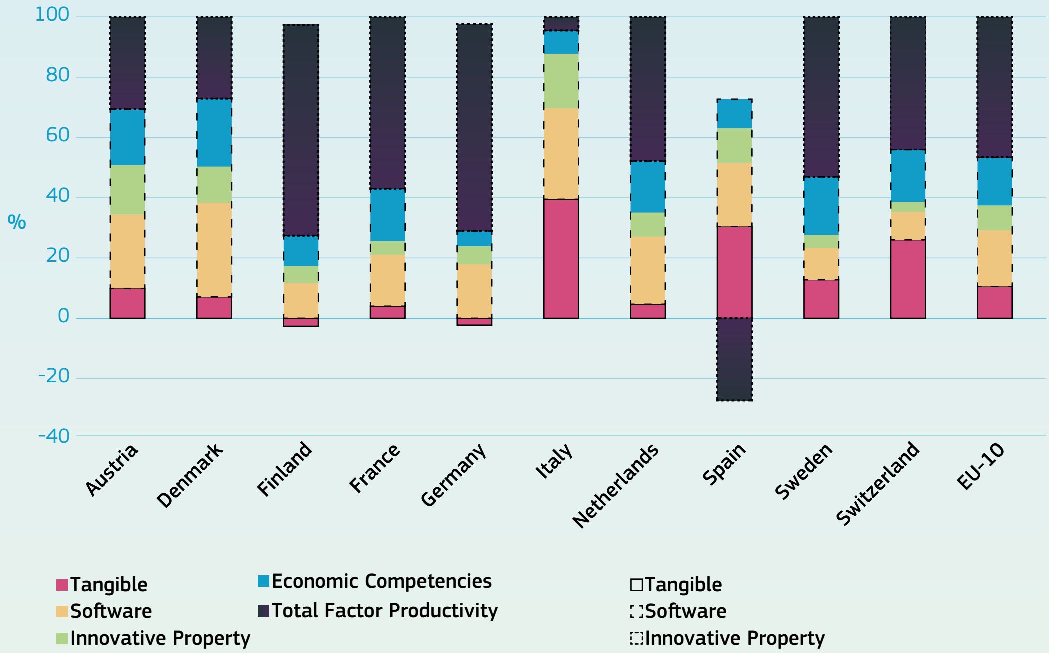
where $(\ln ci_{c,j,t} \text{-} \ln ci_{c,j,t\text{-}1})$, $(\ln ip_{c,j,t} \text{-} \ln ip_{c,j,t\text{-}1})$ and $(\ln ec_{c,j,t} \text{-} \ln ec_{c,j,t\text{-}1})$ are the intangible capital services growth for computerised information (including software), innovative property (including research and development and design and other product developments) and economic competencies (including advertisement, market research and branding, vocational training and organizational capital).

Figure 4.1-8 clarifies three facts. First, on average in the industries of the market economy of the EU-10 countries (Austria, Denmark, Finland, France, Germany, Italy, the Netherlands, Spain, Sweden and the UK), TFP (47%) and intangible capital deepening of the three combined intangible dimensions (43%) explain the main share of labour productivity growth. Tangible capital deepening (10%) only plays a minor role. Second, among the three dimensions of intangible capital, software plays the dominant role (19%), followed by economic competencies (16%) and innovative property (8%).

9 where: $u_{c,j,t} = (ln\varepsilon_{c,j,t} \text{-} (ln\varepsilon_{c,j,t\text{-}1})$

Third, the sources of growth show very heterogonous patterns within industries of the market economy of the individual EU10 countries. Whereas intangible capital deepening plays the dominant role in the industries of the market economy in Austria, Denmark, Italy and Spain[10], TFP plays the dominant role in Finland, France, Germany, Sweden and the United Kingdom. In the Netherlands, intangible capital deepening and TFP are equally important.

Figure 4.1-8: Cross-country sectoral growth accounting results for three intangible capital dimensions, 1995-2017



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Source: Roth and Sen 2021, Stehrer et al. 2019.

Notes: Figure 4.1-8 displays the cross-country sectoral growth accounting results as displayed in regression 4 in Table 4 in Roth and Sen (2021). It is based on the estimates of equation 3 in Box 4.3 using a random-effects robust VCE estimator and 1 897 sectoral observations for the market economy in the EU-10 from 1995-2017. EU-10 includes the United Kingdom.

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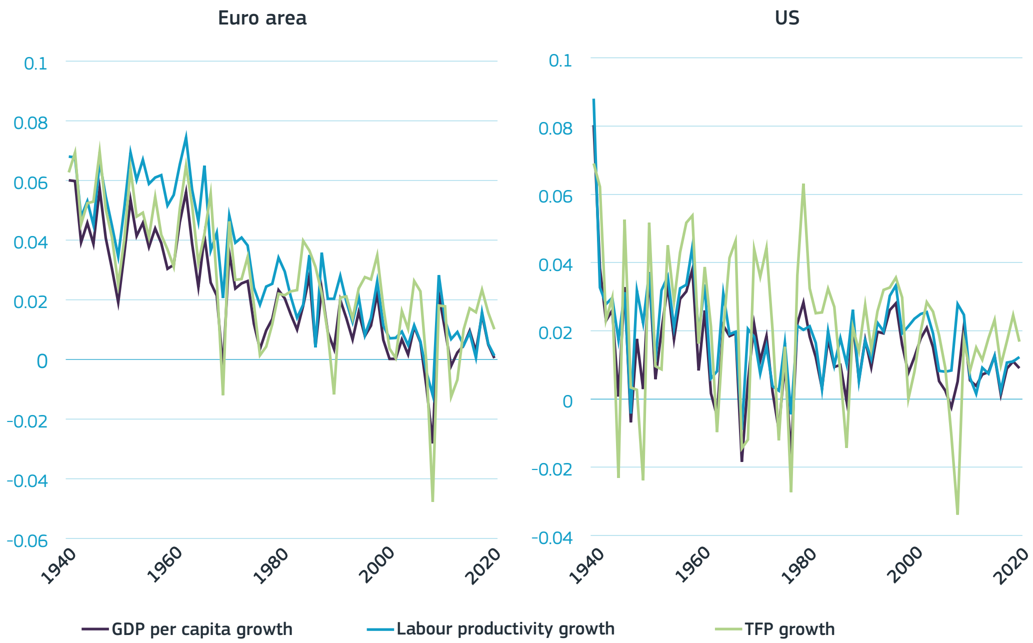
10 The negative TFP growth rate in Spain resembles weaker technological progress and innovation. Reasons might be increased rigidities in labour, product and capital markets, as well as negative reallocation effects towards less productive sectors.

3. The EU productivity paradox of the digital era

In 1987, Robert Solow famously stated: 'You can see the computer age everywhere but in the productivity statistics.' Indeed, theoretically, the development of digital technologies should strengthen productivity growth. Yet, despite the information technology (IT) revolution, productivity growth has been diminishing, and then stagnating, over the previous decades.

Figure 4.1-9: Productivity growth slowdown, 1950-2019



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Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit's own elaboration based on the Long-Term Productivity Database.

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A sizable part of the literature on this productivity paradox, or Solow paradox, has attempted to answer the question: **why are digital technologies not leading to higher productivity growth?**

- **Measurement error:** Different authors have argued that some of the observed productivity slowdown is attributable to the difficulties to measure productivity in a service economy, heavily relying on intangibles (McGrattan 2020, Haskel and Westlake 2017, Popović 2018, Syverson, 2017).

- **Long-lag argument:** The productivity implications of a new technology are only visible with a long lag (Triplett 1999). It takes time for new technologies to diffuse and become adopted. This particularly applies to ICT, which requires costly organisational changes and employees' upskilling (Arvanitis 2004, Maliranta and Rouvinen 2004, Brynjolfsson, Rock and Syverson 2019).

- **From micro to macro:** Firm level data shows how the introduction of digital technologies boosts productivity (Hubbard 2003, Bartel et al. 2007). These increases, however, translate into limited impact on aggregate productivity growth, likely due to co-occurring dynamic and competitive effects such as organisational factors, the availability of skills, firm dynamism and polarisation (Pilat 2005).

- **Decline of technical change embodied in capital:** The stagnation of productivity growth is linked to the reduction in the possibilities to achieve productivity growth via capital-embodied technical change (Schubert and Neuhäusler 2018). In this line of research, Castellani et al. (2019) explain the higher levels of productivity of US firms, when compared to EU firms, with the higher capacity to translate R&D into productivity gains of US firms, while EU firms achieve productivity gains more through capital-embodied technological change. The authors argue that such transatlantic differences may be related to the different industrial structures in the US and the EU, with the US economy being disproportionally characterised by high-tech industries, which present higher returns from R&D, and the EU relying more on medium- and low-tech industries, which rely more on capital-embodied technical change.

- **ICT is not plug and play:** Turning investment in ICT into higher productivity is not straightforward. It consistently requires complementary investments and changes in human capital, managerial practice and way of doing business (Pilat 2005, Arvanitis 2004, Maliranta and Rouvinen 2004). Brynjolfsson et al. (2019) show how digital transformation turns out to be particularly difficult for non-frontier firms, with non-trivial adjustments costs, organisational changes, and new skills required, potentially leading to negative returns during the process of adjustment and experimentation.

- **Increasing productivity polarisation:** There is an increasing divergence among OECD countries, industries and firms in the uptake of digital technologies. While a few leading firms push the technological frontier forward, many laggard firms cannot keep up (Calvino et al. 2018, Berlingieri et al. 2017). Andrews et al. (2016) argue that such uneven uptake and diffusion of new technologies throughout the economy is an important source of the productivity slowdown. Sorbe et al. (2019) identify in the features of digital technologies a driver of such polarisation: less productive firms find it harder to attract workers with the right skills to help them adopt digital technologies efficiently, amplifying a cycle that is self-enforcing.

- **Declining business dynamism:** In the last decades, OECD countries have faced declining business dynamics (entry and exit of firms), an increase of zombie firms (firms that would typically exit in a competitive market), as well as an increase in resource misallocation (Criscuolo et al., 2014, McGowan and Millot 2017a, McGowan and Millot 2017b). The lack of exit from the market of less productive firms has generated a drag on aggregate productivity growth.

- **Secular stagnation argument:** In contrast with the long-lag hypothesis, a parallel branch of research argues that most of the economy has already benefitted from the internet and web revolution during the early nineties. According to Gordon (2015), current productivity growth is not unusually low. Instead, productivity growth in the period 1930-1980 was unusually high (thanks to general purpose technologies, including electricity, the internal combustion engine, the telephone, wireless, chemical engineering, and the conquest of infectious diseases). Furthermore, Popović (2018) and Gordon (2015) identify other structural factors, such as education, socioeconomic decay and national debt, as explanations for the productivity slowdown.

Most of the presented explanations of the productivity paradox are complementary and are each not sufficient on their own to explain the paradox, yet jointly able to provide a nuanced understanding of the reasons behind the pattern of subdued productivity growth.

4. The productivity challenge posed by COVID-19

The COVID-19 pandemic has impacted the economy, industries, firms and individuals in very diverse and uneven ways. The effects of some of such disparities are likely (and to a certain extent already have) to lead to serious consequences on the productive capacity of nations. Indeed, if social distancing and lockdowns have propelled the adoption of digital technologies, then firms and households that could not adjust to the new situation have taken the lion share of the costs.

To deal with the necessary restrictive measures, leader firms accelerated the uptake of available digital technologies, shifting working practice from face-to-face to digital. On the other hand, smaller and laggard firms have found such a transition more difficult due to lack of skills, awareness of digital tools and organisational stiffness. This may further widen the productivity gap between leading and laggard firms, particularly in a situation where business dynamism is declining and market cleansing is slowed down through government support to zombie firms.

The impact of the pandemic has also been unequal by sector, with winners and losers. The hospitality sector was among the hardest hit, while digital companies flourished. At the same time, larger companies had more liquidity to perform the necessary adjustments to deal with the pandemic, while smaller firms ran into liquidity problems more quickly (Riom and Valero 2020, Canton et al. 2021). Interestingly, being the low productivity sectors the most affected by COVID-19 (accommodation, restaurants and household services), the reallocation of activity across sectors generated by the pandemic has partially offset the within firm negative effect on aggregate productivity in the short term (Bloom et al. 2021, OECD 2021a).

Digitalised firms were better able to absorb the COVID-19 shock thanks to their higher capabilities to employ digital solutions and teleworking (Andrews et al., 2021). Yet, it is still unknown if a permanent and widespread shift to teleworking would positively affect productivity. Initial studies find a positive effect of teleworking, while pointing out that this effect

Read more in Chapter 12 – Part 2 on 'Productivity growth after the pandemic: understanding long-term trends to tackle the COVID-19 challenges' (Francesco Manaresi, Ilaria Goretti, Chiara Criscuolo, OECD)

Selective review of the policies that can mitigate the long-term effects of the pandemic's unprecedented demand-and-supply shock that has generated a strong push towards the digitalisation of firms, as well as a threat of further productivity divide. Indeed, the ability of firms to invest in digital and intangible assets has been very heterogeneous, with investments in firm digitalisation driven by the already more digitalised firms.

is likely momentary. The long-term impact of teleworking on productivity will instead be dependent on the type of task performed, with some task more effective if done online and other face to face (Barrero et al. 2021; Bloom et al. 2021; Criscuolo et al. 2021; Taneja et al. 2021). Teleworking productivity enhancements could take place thanks to the reduction of logistics costs for long-distance collaboration, and the execution of repetitive tasks that do not need complex human interactions, whereas productivity losses could derive from less productive, large team meetings, reduced informal interaction and face-to-face contact necessary for innovative activities, more difficult managerial oversight, employee strain associated with isolation and telework-fatigue, as well as reduced team spirit.

Support measures related to productivity were broadly effective in alleviating liquidity shortages for productive firms, while being associated with mild negative selection effects (Demmou and Franco 2021). Evidence from European countries showcase that a substantial part of the support was allocated to firms in the middle of the productivity distribution (Altomonte et al., 2021). Furthermore, firms that were financially vulnerable or over-indebted (zombies) before the COVID-19 outbreak were not more likely to be recipients of public support (Harasztosi et al., 2021; Bighelli et al. 2021). Yet, protracted support may hamper reallocation going forward. Prompt emergency support was effective in also avoiding the exit of highly productive firms from the market as a result of severe lockdowns and containment measures at the onset of the pandemic. But the maintenance of such support could hamper the process of resource reallocation, allowing unproductive firms to stay in the market for unfair reasons.

Regarding the long-run productivity implications of COVID-19, worrying signals come from the impact on human capital. Indeed, school closures aggravated existing inequalities with scarring effects on youth and low-income students. Substitutive online teaching methods failed as a perfect substitute of in-presence teaching, leading to a negative impact on learning outcomes, particularly for individuals from poorer socioeconomic backgrounds (Maldonado and Witte 2020, Cacault et al 2021, Di Pietro et al 2020).

Shop closures worsened the employment situation particularly for women, youth, low-income and low skilled workers (ILO 2021; OECD, 2021b, Bartik et al 2020,) as not all kind of jobs can be done remotely from home (Dingel and Neiman 2020). This phenomenon, compounded with the increases in school dropouts (Fernald and Ochse 2021), can decisively affect the long-term productivity capacity of the workers of the future.

5. Conclusions: productivity, prosperity and innovation

Research and innovation are key engines to foster Europe productivity growth, competitiveness and socio-economic outcomes. Human capital combined with R&D investments drives companies' ability to create, absorb and diffuse innovation. Innovation friendly institutions with easy access to finance and low corruption lower the entry cost of innovation, while increasing the innovation capacity of firms and countries.

Productivity can be an ally toward the achievement of the twin transition, providing the necessary resources to invest in new green and digital technologies necessary to tackle the societal challenges of the modern era. Productivity growth entails more (equal) output with the same (or fewer) resources. Such an improvement in the efficiency of production systems is necessary to reduce the impact of production on the planetary boundaries. At the same time, productivity is not a solution to all our problems, as political consensus is necessary to direct its fruits toward desirable outcomes.

The productivity slowdown of the last decades is a worrying phenomenon, likely explained by low technological diffusion, high human capital and organisational uptake costs for laggard firms and declining business dynamism. Efforts directed at easing the access to productivity enhancing technologies should be enacted thought the EU to increase competitiveness while reducing inequality.

References

Abowd, J. M., Haltiwanger, J., Jarmin, R., Lane, J., Lengermann, P., McCue, K., ... & Sandusky, K. (2009), 5, The Relation among Human Capital, Productivity, and Market Value: Building Up from Micro Evidence. In Measuring capital in the new economy (pp. 153-204), University of Chicago Press.

Acemoglu, D., & Guerrieri, V. (2008), 'Capital deepening and nonbalanced economic growth', *Journal of political Economy*, 116(3), pp. 467-498.

Adalet McGowan, M., D. Andrews and V. Millot (2017a), Insolvency regimes, *zombie firms and capital reallocation*, OECD Economics Department Working Papers, No. 1399, OECD Publishing, Paris, https://doi.org/10.1787/5a16beda-en.

Adalet McGowan, M., D. Andrews and V. Millot (2017b), *The Walking Dead?: Zombie Firms and Productivity Performance in OECD Countries*, OECD Economics Department Working Papers, No. 1372, OECD Publishing, Paris, https://doi.org/10.1787/180d80ad-en.

Aghion, P., Bechtold, S., Cassar, L., & Herz, H. (2018), 'The causal effects of competition on innovation: Experimental evidence', *The Journal of Law, Economics, and Organization*, 34(2), pp. 162-195.

Aghion, P., Bloom, N., Blundell, R., Griffith, R., & Howitt, P. (2005), 'Competition and innovation: An inverted-U relationship', *The quarterly journal of economics*, 120(2), pp. 701-728.

Aghion, P., Harris, C., Howitt, P., & Vickers, J. (2001), 'Competition, imitation and growth with step-by-step innovation', *The Review of Economic Studies*, 68(3), pp. 467-492.

Alesina, A., & Rodrik, D. (1994), 'Distributive politics and economic growth', *The quarterly journal of economics*, 109(2), pp. 465-490.

Altomonte, C., Demertzis, M., Fontagné, L., & Müller, S. (2021), *COVID-19 financial aid and productivity: has support been well spent?*, Bruegel-Policy Contributions, pp. NA-NA.

Andrews, D., C. Criscuolo and P. Gal (2016), *The Best versus the Rest: The Global Productivity Slowdown, Divergence across Firms and the Role of Public Policy*, OECD Productivity Working Papers, No. 5, OECD Publishing, Paris, https://doi.org/10.1787/63629cc9-en.

Andrews, D., J. Hambur and E. Bahar (2021), *The COVID-19 shock and productivity-enhancing reallocation in Australia: Real-time evidence from Single Touch Payroll*, OECD Economics Department Working Papers, No. 1677, OECD Publishing, Paris, https://doi.org/10.1787/2f6e7cb1-en.

Arvanitis, S. (2004), 'Information technology, workplace organization, human capital and firm productivity: evidence for the Swiss economy', *The Economic Impact of ICT: Measurement, Evidence, and Implications*, 3(1), pp. 183-212.

Atkin, D., Khandelwal, A. K., & Osman, A. (2017), 'Exporting and firm performance: Evidence from a randomized experiment', *The Quarterly Journal of Economics*, 132(2), pp. 551-615.

Augier, P., Cadot, O., & Dovis, M. (2013), 'Imports and TFP at the firm level: The role of absorptive capacity', *Canadian Journal of Economics/Revue canadienne d'économique*, 46(3), pp. 956-981.

Balasubramanian, N., & Sivadasan, J. (2011), 'What happens when firms patent? New evidence from US economic census data', *The Review of Economics and Statistics*, 93(1), pp. 126-146.

Banerjee, A. V., & Duflo, E. (2003), 'Inequality and growth: What can the data say?', *Journal of economic growth*, 8(3), pp. 267-299.

Barrero, J. M., Bloom, N., & Davis, S. J. (2021), *Why working from home will stick* (No. w28731), National Bureau of Economic Research.

Barro, R. J. (2000), 'Inequality and Growth in a Panel of Countries', *Journal of economic growth*, 5(1), pp. 5-32.

Bartel, A. P., Beaulieu, N. D., Phibbs, C. S., & Stone, P. W. (2014), 'Human capital and productivity in a team environment: evidence from the healthcare sector', *American Economic Journal: Applied Economics*, 6(2), pp. 231-59.

Bartel, A., Ichniowski, C., & Shaw, K. (2007), 'How does information technology affect productivity? Plant-level comparisons of product innovation, process improvement, and worker skills', *The quarterly journal of Economics*, 122(4), pp. 1721-1758.

Bartelsman, E. J., & Doms, M. (2000), 'Understanding productivity: Lessons from longitudinal microdata', *Journal of Economic literature*, 38(3), pp. 569-594.

Bartik, A. W., Cullen, Z. B., Glaeser, E. L., Luca, M., & Stanton, C. T. (2020), *What jobs are being done at home during the COVID-19 crisis? Evidence from firm-level surveys* (No. w27422). National Bureau of Economic Research.

Bas, M., & Strauss-Kahn, V. (2014), 'Does importing more inputs raise exports? Firm-level evidence from France', *Review of World Economics*, 150(2), pp. 241-275.

Belderbos, R., Carree, M., & Lokshin, B. (2004), 'Cooperative R&D and firm performance', *Research policy*, 33(10), pp. 1477-1492.

Berg, A., Ostry, J. D., Tsangarides, C. G., & Yakhshilikov, Y. (2018), 'Redistribution, inequality, and growth: new evidence', *Journal of Economic Growth*, 23(3), pp. 259-305.

Berlingieri, G., P. Blanchenay and C. Criscuolo (2017), *The great divergence(s)*, OECD Science, Technology and Industry Policy Papers, No. 39, OECD Publishing, Paris, https://doi.org/10.1787/953f3853-en.

Bernard, A. B., & Jensen, J. B. (1999), 'Exceptional exporter performance: cause, effect, or both?', *Journal of international economics,* 47(1), pp. 1-25.

Beugelsdijk, S., Klasing, M. J., & Milionis, P. (2018), 'Regional economic development in Europe: the role of total factor productivity', *Regional Studies*, 52(4), pp. 461-476.

Bighelli T., Di Mauro F. and Lalinsky T. (2021), *COVID-19 government support and its consequences for productivity: cross-country evidence*, CompNet policy brief (link).

Bloom, N., & Van Reenen, J. (2007), 'Measuring and explaining management practices across firms and countries', *The quarterly journal of Economics*, 122(4), pp. 1351-1408.

Bloom, N., Eifert, B., Mahajan, A., McKenzie, D., & Roberts, J. (2013), 'Does management matter? Evidence from India', *The Quarterly Journal of Economics*, 128(1), pp. 1-51.

Bloom, N., Mizen, P., & Taneja, S. (2021), *Returning to the office will be hard*, VoxEU Column.

Brynjolfsson, E., Rock, D., & Syverson, C. (2019), 1. Artificial Intelligence and the Modern Productivity Paradox: A Clash of Expectations and Statistics (pp. 23-60), University of Chicago Press.

Cacault, M. P., Hildebrand, C., Laurent-Lucchetti, J., & Pellizzari, M. (2021), 'Distance learning in higher education: evidence from a randomized experiment', *Journal of the European Economic Association*, 19(4), pp. 2322-2372.

Calvino, F., et al. (2018), 'A taxonomy of digital intensive sectors', OECD Science, Technology and Industry Working Papers, No. 2018/14, OECD Publishing, Paris, https://doi.org/10.1787/f404736a-en.

Canton, E., Colasanti, F., Durán, J., Garrone, M., Hobza, A., Simons, W., & Vandeplas, A. (2021), *The Sectoral Impact of the COVID-19 Crisis. An Unprecedented and Atypical Crisis* (No. 069), Directorate General Economic and Financial Affairs (DG ECFIN), European Commission.

Castellani, D., Piva, M., Schubert, T., & Vivarelli, M. (2019), 'R&D and Productivity in the US and the EU: Sectoral Specificities and Differences in the Crisis', *Technological Forecasting and Social Change*, 138, pp. 279-291.

Chang, C. F., Wang, P., & Liu, J. T. (2016), 'Knowledge spillovers, human capital and productivity', *Journal of Macroeconomics*, 47, pp. 214-232.

Cœuré B. ed. (2021), (link) (Summary of the report in English here).

Criscuolo, C., et al. (2021), 'The role of telework for productivity during and post-COVID-19: Results from an OECD survey among managers and workers', OECD Productivity Working Papers, No. 31, OECD Publishing, Paris, https://doi.org/10.1787/7fe47de2-en.

Criscuolo, C., P. Gal and C. Menon (2014), 'The Dynamics of Employment Growth: New Evidence from 18 Countries', OECD Science, Technology and Industry Policy Papers, No. 14, OECD Publishing, Paris, https://doi.org/10.1787/5jz417hj6hg6-en.

De Loecker, J. (2007), 'Do exports generate higher productivity? Evidence from Slovenia', *Journal of international economics*, 73(1), pp. 69-98.

De Loecker, J., & Goldberg, P. K. (2014), 'Firm performance in a global market', *Annu. Rev. Econ.*, 6(1), pp. 201-227.

Demmou, L. and G. Franco (2021), From hibernation to reallocation: Loan guarantees and their implications for post-COVID-19 productivity, OECD Economics Department Working Papers, No. 1687, OECD Publishing, Paris, https://doi.org/10.1787/2f4a4c20-en.

Di Pietro, G., Biagi, F., Costa, P., Karpiński, Z., & Mazza, J. (2020), *The likely impact of COVID-19 on education: Reflections based on the existing literature and recent international datasets* (Vol. 30275), Publications Office of the European Union.

Dingel, J. I., & Neiman, B. (2020), 'How many jobs can be done at home?', *Journal of Public Economics*, 189, p. 104235.

Dollar, D., & Kraay, A. (2002), 'Growth is Good for the Poor'. *Journal of economic growth*, 7(3), pp. 195-225.

Easterly, W. (1999), 'Life during growth', *Journal of economic growth*, 4(3), pp. 239-276.

European Commission (2021), Annual Sustainable Growth Strategy 2021, COM(2020) 575 final (link).

Fernald, J., Li, H., & Ochse, M. (2021), 'Future Output Loss from COVID-Induced School Closures', *Future*, 2021, 04.

Forbes, K. J. (2000), 'A reassessment of the relationship between inequality and growth', *American economic review*, 90(4), pp. 869-887.

Gordon, R. J. (2015). 'Secular stagnation: A supply-side view', *American economic review*, 105(5), pp. 54-59.

Grifell-Tatjé, E., Lovell, C. K., & Sickles, R. C. (Eds.). (2018), *The Oxford handbook of productivity analysis*, Oxford University Press.

Harasztosi, P., Maurin, L., Pál, R., Revoltella, D., & van der Wielen, W. (2021), *Policy support during the crisis: So far, so good?*, EIB working paper.

Haskel, J., & Westlake, S. (2017), *Capitalism without capital*, Princeton University Press.

Hubbard, T. N. (2003), 'Information, decisions, and productivity: On-board computers and capacity utilization in trucking', *American Economic Review*, 93(4), pp. 1328-1353.

Hudson, V. M., Ballif-Spanvill, B., Caprioli, M., & Emmett, C. F. (2012), *Sex and world peace*, Columbia University Press.

ILO (2021), 'World Employment and Social Outlook: Trends 2021', Geneva, 2021, https://www.ilo.org/wcmsp5/groups/public/---dgreports/---dcomm/---publ/documents/publication/wcms_795453.pdf.

Isaksson, A., Ng, T. H., & Robyn, G. (2005), *Productivity in developing countries: trends and policies*. Vienna, Austria: UNIDO.

Kasahara, H., & Lapham, B. (2013), 'Productivity and the decision to import and export: Theory and evidence', *Journal of international Economics*, 89(2), pp. 297-316.

Kasahara, H., & Rodrigue, J. (2008), 'Does the use of imported intermediates increase productivity? Plant-level evidence', *Journal of development economics*, 87(1), pp. 106-118.

Kraay, A. (2004), *When is Growth Pro-poor?: Cross-country Evidence* (Vol. 3225), World Bank Publications.

Krugman, P. R. (1997), *The age of diminished expectations: US economic policy in the 1990s*. MIT press.

Li, H., & Zou, H. F. (1998), 'Income inequality is not harmful for growth: theory and evidence', *Review of development economics*, 2(3), pp. 318-334.

Lopez, J. H. (2004), Pro-growth, pro-poor: Is there a tradeoff? (Vol. 3378), World Bank Publications.

Maldonado, J. E., & De Witte, K. (2020), 'The effect of school closures on standardised student test outcomes', *British Educational Research Journal.*

Maliranta, M., & Rouvinen, P. (2004), 'ICT and business productivity: Finnish micro-level evidence', *The Economic Impact of ICT; Measurement, Evidence and Implications*, 12(6), pp. 213-240.

McGrattan, E. R. (2020), 'Intangible capital and measured productivity', *Review of Economic Dynamics*, 37, pp. S147-S166.

Milanovic, B. L., Van Der Weide, R. (2014). *Inequality is bad for growth of the poor (but not for that of the rich)* (No. 6963). The World Bank.

Mohnen, P., & Hall, B. H. (2013), 'Innovation and productivity: An update', *Eurasian Business Review*, 3(1), pp. 47-65.

Nicoletti, G., & Scarpetta, S. (2006), *Regulation and economic performance: product market reforms and productivity in the OECD*, Institutions, Development, and Economic Growth, 13, 81.

OECD (2021a), 'Productivity and the COVID-19 pandemic', in OECD Compendium of Productivity Indicators, OECD Publishing, Paris, https://doi.org/10.1787/495e70d8-en.

OECD (2021b), 'OECD Economic Outlook', Volume 2021, Issue 1 (June), OECD Publishing, Paris, https://doi.org/10.1787/edfbca02-en.

Olley, G., and A. Pakes (1996), The Dynamics of Productivity in the Telecommunications Equipment Industry, Econometrica 64, no. 6: pp. 1263–97.

Perotti, R. (1996), 'Growth, income distribution, and democracy: What the data say', *Journal of Economic growth*, 1(2), pp. 149-187.

Persson, T., & Tabellini, G. (1994), 'ls lnequality Harmful for Growth', *American Economic Review,* 84(3), pp. 600-621.

Pilat, D. (2005), The ICT productivity paradox: insights from micro data, OECD *economic studies*, 2004(1), pp. 37-65.

Popović, M. (2018), 'Technological progress, globalization, and secular stagnation', *Journal of Central Banking Theory and Practice*, 7(1), pp. 59-100.

Ravallion, M., & Chen, S. (1997), *What can new survey data tell us about recent changes in distribution and poverty?*, The World Bank Economic Review, 11(2), pp. 357-382.

Raymond, W., Mairesse, J., Mohnen, P., & Palm, F. (2015), 'Dynamic models of R & D, innovation and productivity: Panel data evidence for Dutch and French manufacturing', *European Economic Review*, 78, pp. 285-306.

Riom, C., & Valero, A. (2020), T*he Business Response to Covid-19: the CEP-CBI survey on technology adoption*, Centre for Economic Performance, London School of Economics and Political Science.

Roth, Felix (2020), 'Revisiting Intangible Capital and Labor Productivity Growth, 2000-2015: Accounting for the Crisis and Economic Recovery in the EU', *Journal of Intellectual Capital*, 21(5): pp. 671-90.

Roth, Felix (2022), *Intangible Capital and Growth – Essays on Labor Productivity, Monetary Economics and the Political Economy*, Vol. 1. New York: Springer, forthcoming.

Roth, Felix and Sen, Ali (2021), *Intangible Capital and Labor Productivity Growth – Revisiting the Evidence*, GLOBALINTO Deliverable 6.6 and Hamburg Discussion Papers in International Economics, No.10, University of Hamburg, Chair for International Economics, Hamburg.

Roth, Felix and Thum, Anna-Elisabeth (2013), 'Intangible Capital and Labor Productivity Growth: Panel Evidence for the EU from 1998–2005', *Review of Income and Wealth*, 59(3): pp. 486-508.

Schmidt-Traub, G., Kroll, C., Teksoz, K., Durand-Delacre, D., & Sachs, J. D. (2017), 'National baselines for the Sustainable Development Goals assessed in the SDG Index and Dashboards', *Nature geoscience*, 10(8), pp. 547-555.

Schmitz Jr, J. A. (2005), 'What determines productivity? Lessons from the dramatic recovery of the US and Canadian iron ore industries following their early 1980s crisis', *Journal of political Economy*, 113(3), pp. 582-625.

Schubert, T., & Neuhäusler, P. (2018), *Can depleting technological Opportunities explain the Stagnation of Productivity?* Panel Data Evidence for 11 OECD countries (No. 11-2018), Studien zum deutschen Innovationssystem.

Sen, A. (1999) 'Freedom as development', *Oxford University Press*.

Silva, A., Afonso, O., & Africano, A. P. (2012), 'Learning-by-exporting: What we know and what we would like to know', *The International Trade Journal,* 26(3), pp. 255-288.

Solow, R. M. (1957), 'Technical change and the aggregate production function', *The review of Economics and Statistics*, pp. 312-320.

Sorbe, S., et al. (2019), 'Digital Dividend: Policies to Harness the Productivity Potential of Digital Technologies', OECD *Economic Policy Papers*, No. 26, OECD Publishing, Paris, https://doi.org/10.1787/273176bc-en.

Stehrer, R., Bykova, A., Jager, K., Reiter, O., and Schwarzhappel, M. (2019), *Industry Level Growth and Productivity Data with Special Focus on Intangible Assets*, WIIW Report on Methodologies and Data Construction for the EU KLEMS Release 2019.

Syverson, C. (2004), 'Product substitutability and productivity dispersion', *Review of Economics and Statistics*, 86(2), pp. 534-550.

Syverson, C. (2011), 'What determines productivity?', *Journal of Economic literature*, 49(2), pp. 326-65.

Syverson, C. (2017), 'Challenges to mismeasurement explanations for the US productivity slowdown', *Journal of Economic Perspectives*, 31(2), pp. 165-86.

Taneja, S., Mizen, P., & Bloom, N. (2021), *Working from home is revolutionising the UK labour market*, VoxEU CEPR Policy Portal, 15.

Triplett, J. E. (1999), 'The Solow productivity paradox: what do computers do to productivity?', *The Canadian Journal of Economics/Revue canadienne d'Economique*, 32(2), pp. 309-334.

Van Leeuwen, G., & Klomp, L. (2006), On the contribution of innovation to multi-factor productivity growth, *Economics of Innovation and New Technology*, 15(4-5), pp. 367-390.

White, H., & Anderson, E. (2001), 'Growth versus distribution: does the pattern of growth matter?', *Development Policy Review*, 19(3), pp. 267-289.

CHAPTER 4.2

BUSINESS DYNAMISM

KEY FIGURES

17.5 %
churn rate of EU businesses

3 times
more scale-ups in the US than in Europe

11.8 %
of EU active firms are high-growth firms

38 %
of high-growth start-ups operate in the ICT sector

98
enterprises became unicorns in 2021 in Europe

KEY QUESTIONS WE ARE ADDRESSING

- What is the latest evidence on business dynamism in the EU and how did COVID-19 impact EU firms' entry and exit rates?
- How does the EU perform in terms of start-up, scale-up and unicorn firms as compared to US and other international competitors? What are the main barriers firms face in their scale-up processes?
- Is the EU entrepreneurial ecosystem well equipped to face the challenges of the digital era?

KEY MESSAGES

What did we learn?

- Business dynamism is declining in the EU, raising concerns about the implications for innovation and economic growth.
- The EU keeps lagging behind its main international competitors in terms of number of start-up and scale-up firms.
- The number of EU unicorns is increasing, but still below the level of our main competitors.
- Women are significantly underrepresented in the EU entrepreneurial landscape.

What does it mean for policy?

- Fast-growing firms are essential to the EU digital and green transition. The EU's performance in terms of start-ups, scale-ups and unicorn firms is improving, but efforts are still needed to improve the overall framework conditions for innovative companies to thrive.
- Increasing the diffusion of innovative ideas and new innovations is essential for the EU's recovery. Innovative enterprises were able to better adapt to the COVID-19 shock, confirming their essential role as drivers of economic productivity and growth.
- A significant gender gap is still to be tackled. The empowerment of women entrepreneurs remains a key policy objective to unleash the EU's untapped growth potential.

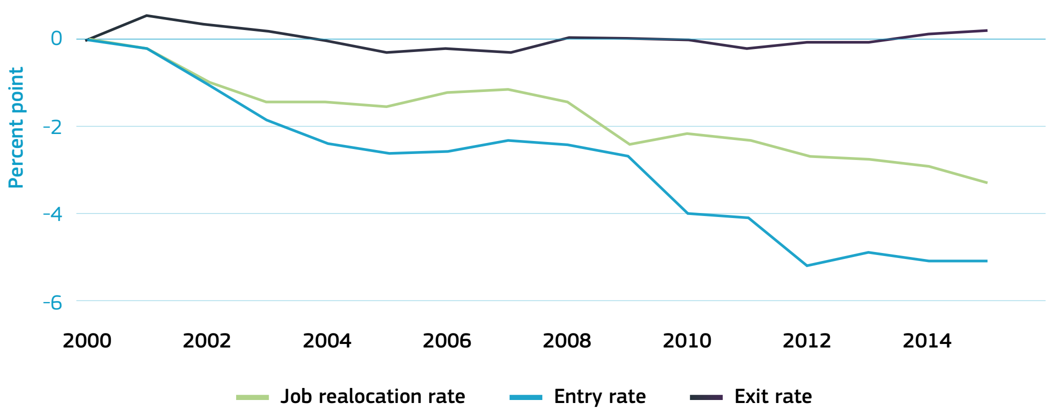
Business dynamism is considered a key driver of aggregate productivity growth. Business dynamism is typically defined as the process through which businesses are born, expand, contract and eventually fail and exit the market (Decker et al., 2018). Overall, there is a wide consensus in the economic literature on the contribution of high-productive firms to aggregate productivity and growth. Through the Schumpeterian process of 'creative destruction', old and less-productive firms make space to new and more productive enterprises, thereby contributing to a more efficient allocation of resources from low-productivity to high-productivity activities (Decker et al, 2016; Bijnesn and Konings, 2018). Haltiwanger et al. (2015) investigated the beneficial effects of business dynamism in the US economy, providing evidence of a higher contribution of high-growth enterprises to job creation, output and aggregate productivity growth. Criscuolo et al. (2014) highlighted the prominent role of young innovative firms in driving the process of creative destruction, while Bravo-Biosca (2016) showed that the positive correlation between a more dynamic firm distribution and higher productivity growth appears to be an empirical regularity observed across different countries.

1. Declining business dynamism: basic facts and potential drivers

Declining business dynamism is a well-established fact. Creative destruction is one of the key drivers of overall productivity growth. In the last decades, there has been a prolific discussion in the academic literature on the declining trend in business dynamism in the US and other economies, in an attempt to identify causes and policy remedies. Economic research documented several aspects related to declining business dynamism (e.g. De Loecker et al., 2021; Markiewicz and Silvestrini, 2021; Akcigit and Ates, 2021). Decker et al. (2016) discuss the pervasive decline in firm dynamics experienced by the US economy in the last decades, noticing that since 2000 the trend has been accompanied by a decrease in the number of high-growth young firms. Haltiwanger et al. (2014) investigated business dynamism in the US high-tech sector, showing that the secular stagnation in US entrepreneurship dynamics also applies to the high-tech industry in the post-2000 period. Furthermore, several studies addressed the issue from a cross-country perspective, finding interesting similarities between the US and other economies. In this regard, a first important contribution is that of Bartelsman et al. (2005) finding similar patterns of business churning across different OECD countries. A further interesting cross-country investigation was provided by Criscuolo et al. 2014, which documented the decline in business dynamism by comparing firm-level data across 18 OECD countries. Bijnesn and Konings (2018) used Belgian data to study the trend in business dynamism, finding patterns similar to the US experience despite the structural differences between the two economies.

Entry and job reallocation rates have been declining across different economies. The birth rate of new firms is typically considered an important indicator to assess the degree of job creation and, thus, economic growth. Unproductive incumbents are pushed out of the market by new entrants (or more productive firms), thereby increasing efficiency and competitiveness, as well as stimulating innovation and the adoption of new technologies. Similarly, evidence on job reallocation rates, which measures the simultaneous level of job creation and destruction in an economy,

Figure 4.2-1: Average trends in job reallocation, entry and exit rates in selected OECD countries, 2000-2015



Science, Research and Innovation Performance of the EU 2022

Source: OECD DynEmp3 database, June 2020.
Note: The figure reports average within-country-sector trends of job reallocation, entry and exit rates, based on data from 18 countries: AT, BE, BR, CA, CRI, DK, ES, FI, FR, HU, IT, JP, NL, NO, NZ, PT, SE and TR. Each point represents average cumulative change in percentage points since 2000.
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is also a useful indicator to capture the evolution of business dynamism over time. Figure 4.2-1 shows that both indicators have experienced a steady decline over time. Entry rates and job reallocation rate have decreased by 0.2 and 0.35 percentage points, respectively, over the period 2000-2015 (Calvino et al., 2020). Furthermore, **the decline in firm entry rates is not homogeneous across countries and sectors:** telecommunications, IT, and scientific R&D[1] reported the strongest decline over the reference period (Calvino et al., 2020).

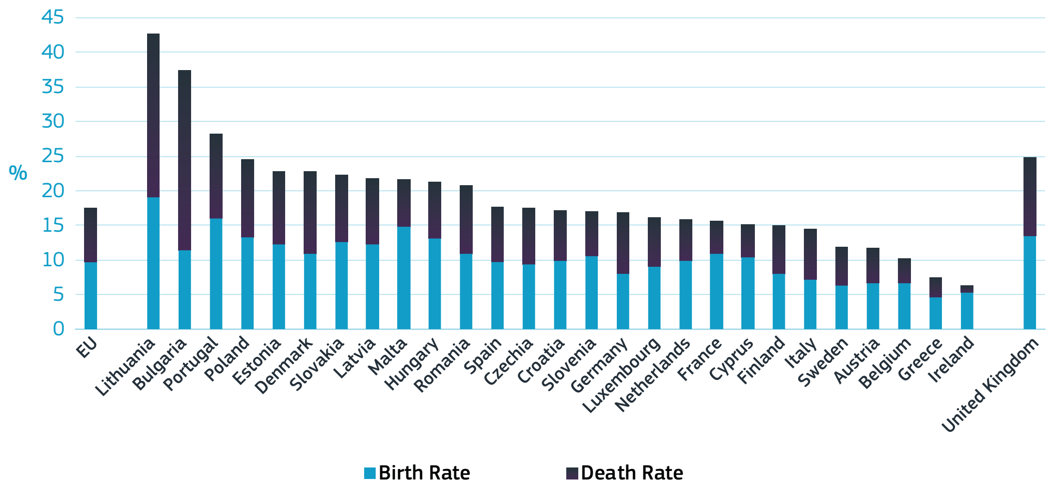
Firms' birth rates are quite heterogeneous across EU countries. Figure 4.2-2 displays the churn rate (measured as birth rates plus death rates) of the EU's business economy in 2018, and across Member States. Focusing on birth rates only, a quite heterogeneous pattern is observed across EU countries. Greece had the lowest share of newly born enterprises in 2018 (about 4.7%), followed by Ireland (5.3%) and Sweden (6.3%).

The highest birth rates were reported in Lithuania (19.0%) and Portugal (16.0%), while other countries such as Croatia, Spain and the Netherlands performed close to the EU average (9.7%). Regarding the share of EU enterprises exiting the market, **in 2008 the average death rate in EU was 7.8%.** Bulgaria and Lithuania reported the highest death rates (26% and 23.7%, respectively). Portugal, Denmark and Poland followed with a share ranging between 11.2% and 12.1%. Among the EU countries showing death rates below average, Belgium, Greece and Ireland reported the lowest, with a share well below 5%.

Understanding the reasons behind declining business dynamism remains a high priority on the policy agenda. A large and growing body of empirical and theoretical works on the decline in business dynamism has proposed several culprits. According to Karahan et al. (2016), the **demographic shifts** followed by the end of the baby-boomer

1 Here defined according to the ISIC v4 classifications, and corresponding to the activities under Section M – Division 72

Figure 4.2-2: Churn rate (birth rate plus death rate) per country, 2018



Science, Research and Innovation Performance of the EU 2022

Source: Eurostat [online data code bd_9bd_sz_cl_r2]
Note: Data for business economy except activities of holding companies.
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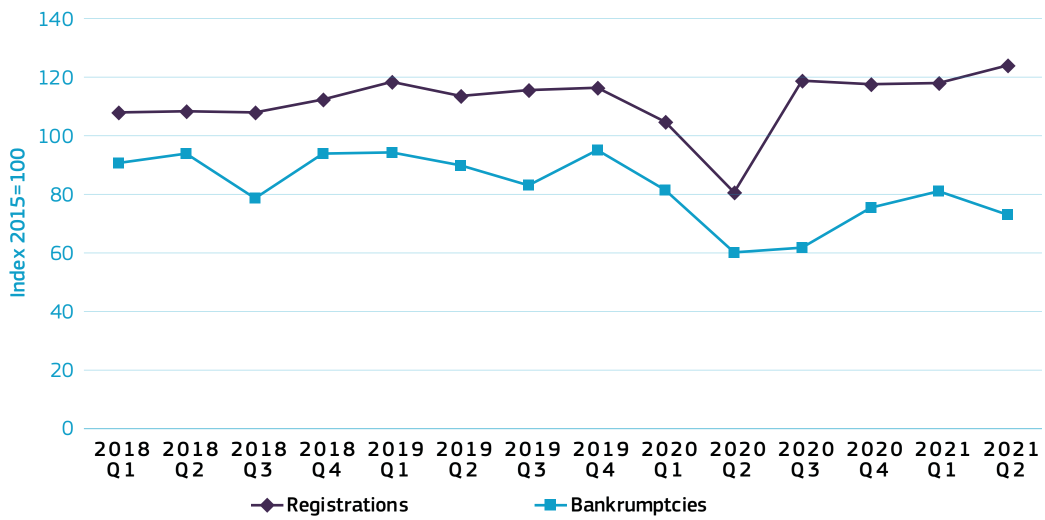
generation have been associated with an increase in labour costs that has negatively affected firms' entry rate. Decker et al. (2018) propose declining responsiveness to shocks as a potential candidate explaining the fall in business dynamism. They argue that the slowdown in factor reallocation is not the result of structural changes in the economy, but rather the outcome of a **declining marginal responsiveness** of firms to idiosyncratic shocks due to increased adjustment costs (Decker et al., 2018). Akcigit and Ates (2021) identify **the decline in knowledge diffusion and ideas implementation** as another potential culprit. Their argument stems from the consideration that innovation plays a leading role in determining productivity growth, but it is not sufficient alone to boost productivity if new technologies are not adequately diffused in the economy. A high level of knowledge diffusion enables laggard firms to learn from market leaders, thereby making it possible for them to catch up on their productivity gap. Akcigit and Ates (2021) argue that the level of knowledge diffusion and ideas implementation in the US economy has been declining over time, making it more difficult for new firms to enter the market, leading to a reduction in entry rates. Yet, De Loecker et al. (2021) argue that the **combination of increasing mark-ups and changes in market structure** leads to a fall in business dynamism.

2. Business dynamism in Europe and the COVID-19 crisis

Soon after the outbreak of the pandemic in the second quarter of 2020, the number of business registrations in the EU fell significantly. Although it is still not possible to entirely assess the overall effects of the COVID-19 pandemic on businesses, preliminary data clearly shows that the lockdown measures have produced a massive change in the way of doing business (see Chapter 1 – COVID-19, recovery and resilience). Figure 4.2-3 displays the number of business registrations in the EU over the period 2018 Q1-2021 Q2. A significant drop in the number of registrations (almost -20% compared to the values of 2015) occurred after the adoption of the first lockdown measures. The sharp decrease in the number of business registrations is particularly worrisome as it could imply missed opportunities in terms of innovation and growth (Fareed and Overvest 2021)[2]. Nevertheless, business registrations started to increase again in the third quarter of 2020 and kept increasing to pre-pandemic levels in the first half of 2021 (Figure 4.2-3).

The number of business bankruptcies has decreased after the outbreak of the COVID-19 pandemic. Figure 4.2-3 also displays business bankruptcies in the EU over the period 2018 Q1-2021 Q2. The number of firms filing for bankruptcies has fallen by more than 30% after the outbreak of the pandemic (2020 Q2) as compared to

Figure 4.2-3: **Business registrations and business bankruptcies in the EU(1), 2018 Q1-2021 Q2 (seasonally and calendar adjusted)**



Science, Research and Innovation Performance of the EU 2022

Source: Eurostat [online data code STS_RB_Q]

Note: (1)Industry, construction and market services (except public administration and defence; compulsory social security; activities of membership organisations)

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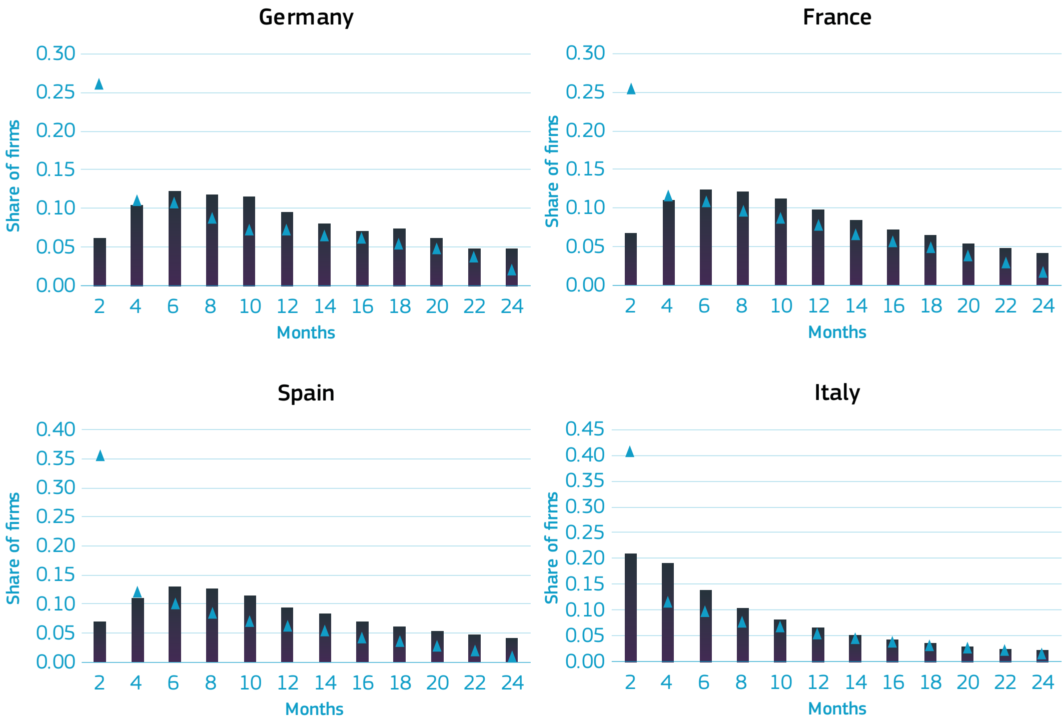
2 Slowdown in business dynamics during the COVID pandemic | VOX, CEPR Policy Portal (voxeu.org)

end-2019. This trend is presumably partially due to the massive policy support provided by national governments and through the EU's programmes. As matter of fact, the COVID-19 pandemic called for unprecedented counteracting policy measures. Gourinchas et al. (2020) estimate that the effects of COVID-19 on firms' survival would have been way more disruptive without the massive policy support mobilised to sustain the economy during the different phases of the pandemic.

Policy measures supporting firms' liquidity mitigated the effects of the pandemic on corporate defaults. In its *Financial Review* of November 2020, the ECB provided evidence of the impact that support measures had on corporate liquidity distress horizons[3]. Figure 4.2-4 looks at four large EU countries, showing that supporting measures have had a stronger impact in Italy and Spain compared to France and Germany. Without policy support, about 40% (Italy) and 36% (Spain) of firms would have been unable to service their liabilities within two months of the COVID-19 shock, against the nearly 25% reported for both Germany and France. **The presence of liquidity buffers were crucial to prevent European firms from entering into severe liquidity distress** (Archanskaia et

Figure 4.2-4: Share of companies that would have faced liquidity distress after the first lockdown with and without policy support



Science, Research and Innovation Performance of the EU 2022

Source: ECB, Financial Review, November 2020 based on Eurostat, Eurosystem Household Finance and Consumption Survey, Bureau van Dijk – Orbis database

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3 'The corporate liquidity distress horizon indicates how long a company would be able to service its current liabilities as they fall due, given its cash holdings and the projected cash inflows and outflows, taking into account the reduced turnover since the outbreak of the pandemic and assuming that liabilities would not be rescheduled.', ECB (2020).

al., 2022). With the first peak of the COVID-19 pandemic, the share of European firms incurring financial distress in the absence of liquidity buffers was around 70%. On the contrary, the share of firms in liquidity distress dropped by 30-40 percentage points when liquidity buffers were deployed (Archanskaia et al., 2022).

The COVID-19 shock has the peculiar characteristic of also potentially endangering viable firms. The shock induced by the pandemic affected the entire economy, possibly also hitting those firms that would have remained viable under other types of disturbances (Laeven et al., 2020). Without the large-scale government support put in place during the different lockdowns, liquidity squeezes connected with a fallout in turnover would have easily turned into insolvency problems, thereby forcing otherwise viable firms to exit the market (Laeven et al., 2020).

Nevertheless, concerns remain on government support keeping unviable businesses afloat, thereby stifling the restructuring process. The support measures issued in response to the pandemic helped to counteract the disruptive effects on the EU economy. Nevertheless, economies in post-lockdown are and will be facing the important challenge of ensuring a smooth phasing out of the support measures, in order to avoid disruptive effects on the economy as a whole (Blanchard et al., 2020). Furthermore, government support may also be used by unviable firms. The specific nature of the COVID-19 crisis makes distinguishing between illiquid and insolvent firms particularly difficult (Laeven et al., 2020). In a recent study, Cross et al. (2021) investigate whether the process of bankruptcies in France was distorted in 2020. They find no significant change in the drivers of bankruptcies, suggesting that the risk of impairing the cleansing effect is not high. As such, the phasing out from the support measures poses the challenge of ensuring business continuity for viable firms with potentially higher debt due to the COVID-19 shock, and progressively reducing the support reaching non-viable entities (Cros et al., 2021).

The presence of zombie firms[4] in the economy is a potential driver of weak productivity performance. The term 'zombie firms', first used by Caballero et al. (2008), is typically used to denote older firms with prolonged difficulties in meeting their interest payments that are still active, although they should already be out of the market (Andrews et al., 2017). There exist three main channels through which zombie firms are found to affect aggregate labour productivity growth (McGowan et al., 2017). First, zombie firms typically exhibit lower levels of labour productivity compared to other firms. Second, zombie firms may crowd-out investment, thereby limiting non-zombie enterprises' access to financial resources. Third, zombie firms are found to hinder the efficient allocation of resources throughout the economy, preventing new and more productive firms from entering the market (McGowan et al., 2017; Andrews et al., 2017; Banerjee and Hofmann, 2020; Laeven et al., 2020).

The share of zombies firms has risen in the last decades. Andrews et al. (2017) undertake a cross-country analysis, showing that the share of zombie firms has increased over the period 2003-2013. Banerjee and Hofmann (2018) found similar evidence across different definitions of zombie firms, showing that the increasing trend may be due to the fact that firms tend to remain in the status of zombie firms longer, rather than exiting the market. Building on this evidence, Banerjee and Hofmann (2020) show that the share of zombie firms across economies has risen since the late 1980s, partially also due to the reduced financial pressure reflected by the low interest rate environment. Looking at EU countries only,

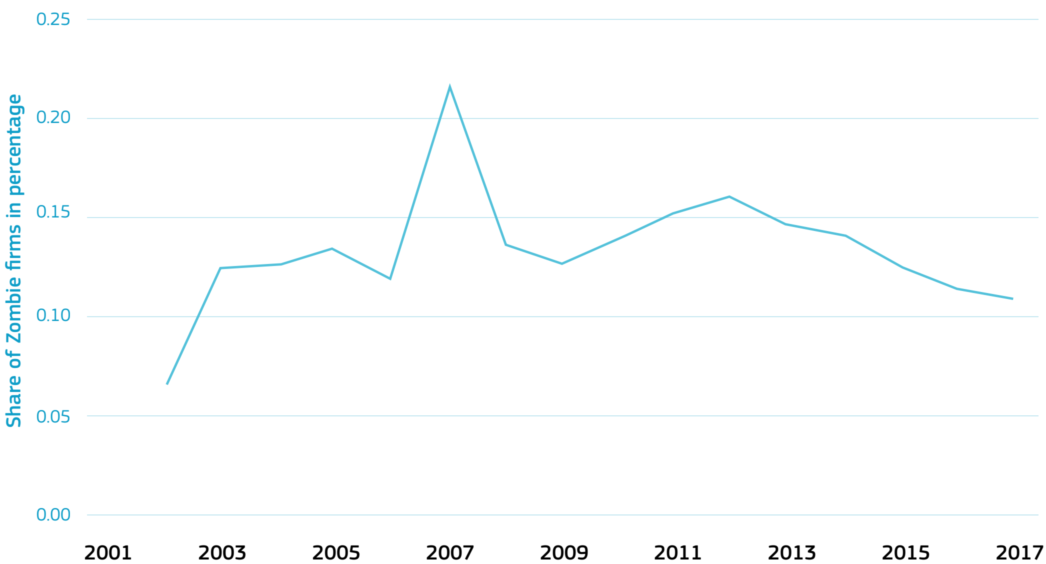
4 Zombie firms are defined as firms aged at least 10 years and with an interest coverage ratio smaller than 1 over three consecutive years.

the share of zombie firms has increased over 2002-2017. Excluding the peak reported in the years of the global financial crisis, the share of zombie firms in the EU has increased from about 6.6% in 2002 to 15.4% in 2012 (Figure 4.2-5). Since 2012, the proportion of non-viable firms in the EU economy has started to decrease. Nevertheless, the share remains well-above the 2002 value, with 10.7% of firms classified as zombie firms in 2017.

The share of zombie firms differs across EU countries. In 2016, the proportion of non-viable firms in the EU ranged between 22.3% in Portugal to slightly less than 3% in Denmark. After Portugal, France, Lithuania and the Netherlands reported the highest shares (respectively 16.2%, 15.2% and about 5.1% of zombie firms), whereas Belgium and Italy accounted for the smallest shares, with 6.1% and 6.9% respectively (Figure 4.2-6).

The way the COVID-19 crisis will keep affecting entry-exit dynamics remains uncertain. Although there exists general consensus on the fact that as less productive firms exit the market, new more productive firms come in, thus driving economic growth (Hopenhayn, 1992), debates remain on how this process is affected by major economic disturbances (Hall, 1995; Caballero and Hammour, 1994). On the one hand, creative destruction may be accelerated by crises, as a severe economic disturbance would amplify the efficient reallocation of resources accelerating entry-exit dynamics in favour of more productive enterprises. On the other hand, shocks and crises could also determine a destructive-destruction process, i.e. market exits by firms would destroy productive resources that would ultimately translate in economic stagnation (Baden-Fuller, 1989). Muzi et al. (2021) carry out a cross-country analysis, finding evidence of a strong negative

Figure 4.2-5: Share of zombie firms[(1)] in the EU, 2002-2017



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on CompNet 7th Vintage, accessed in October 2021

Note: [(1)]Zombie firms are identified as those entities with interest payments exceeding operational profit for three years, and presenting a lack of high labour growth.

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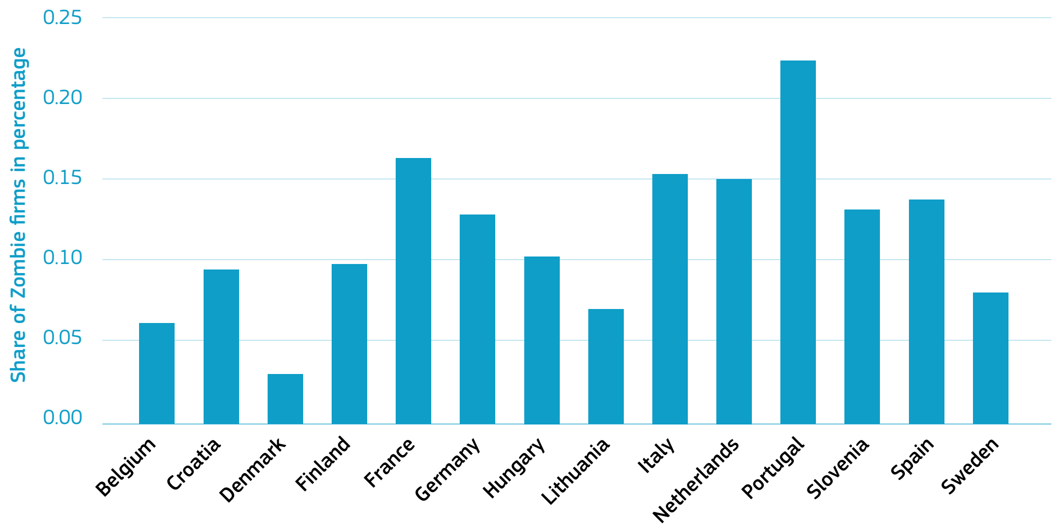
Figure 4.2-6: Share of zombie firms[1] for selected Member States, 2016



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on CompNet 7th Vintage, accessed in October 2021

Note: [1]Zombie firms are identified as those entities with interest payments exceeding operational profit for three years, and presenting a lack of high labour growth.

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-4-2-6.xlsx

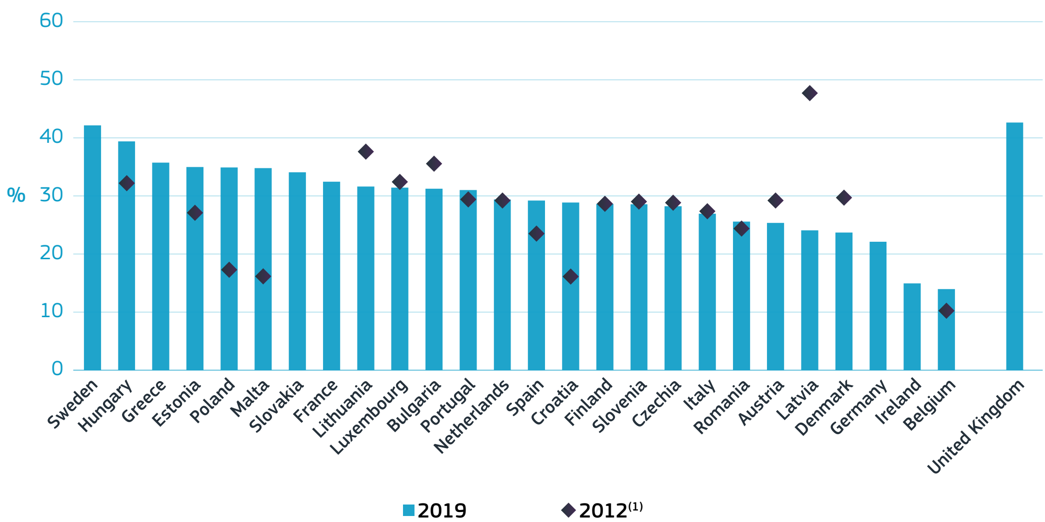
relationship between productivity and firm exit rates during the COVID-19 crisis. Nevertheless, these findings do not allow researchers to clearly discern whether there is a process of cleansing out of unproductive firms at play, or if the crisis is also forcing productive firms to exit the market (Muzi et al., 2021).

Firm exit rates are concentrated in particular industries. Crane et al. (2020) found that firm exit rates were relatively higher for small firms operating in those industries that were affected the most by the lockdown measures. Muzi et al. (2021) also report interesting results concerning other determinants of firm exit rates. First, they found that innovative firms are less likely to leave the market. This result confirms that **innovation, and especially the ability to innovate as market conditions change, represents a key determinant of a firm's survival.** Second, they found evidence of a negative correlation between digital presence and the probability of permanently exiting the market (Muzi et al., 2021). This finding is in line with recent evidence showing a massive increase in the adoption of digital technologies following the outbreak of the COVID-19 crisis (see Chapter 5.3 – ICT sector and digitalisation), and confirms how technology and innovation have helped firms to cushion the negative impact from the pandemic.

3. The EU scale-up gap

Start-ups and scale-ups[5] represent a key driver of economic growth and job creation, playing a critical role in fostering innovation. Start-ups and scale-ups foster aggregate investment activities, in particular those in intangible assets (EIB, 2019). Start-ups and scale-ups companies[6] report significantly higher investment levels per employee than older firms. Furthermore, **they are also catalysts for innovation.** More than 70% of start-ups and scale-ups companies interviewed in the survey indicate the main innovative aspects of their business as the offering new products or services, as well as new delivery modes. However, start-ups and scale-ups also carry new ideas when it comes to developing new ways of generating revenues from products and services sold, and to branding and advertisement strategies implemented on the market (EIB, 2019).

Figure 4.2-7: **Share of start-ups up to 5 years old in total employer enterprises by country, 2012 and 2019**



Science, Research and Innovation Performance of the EU 2022

Source: Eurostat (online data code: bd_9fh_sz_cl_r2)

Note: (1)Data in 2012 not available for FR, DE, EL, IE, SK, SE, UK. (2)Data for CY is not available.

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-4-2-7.xlsx

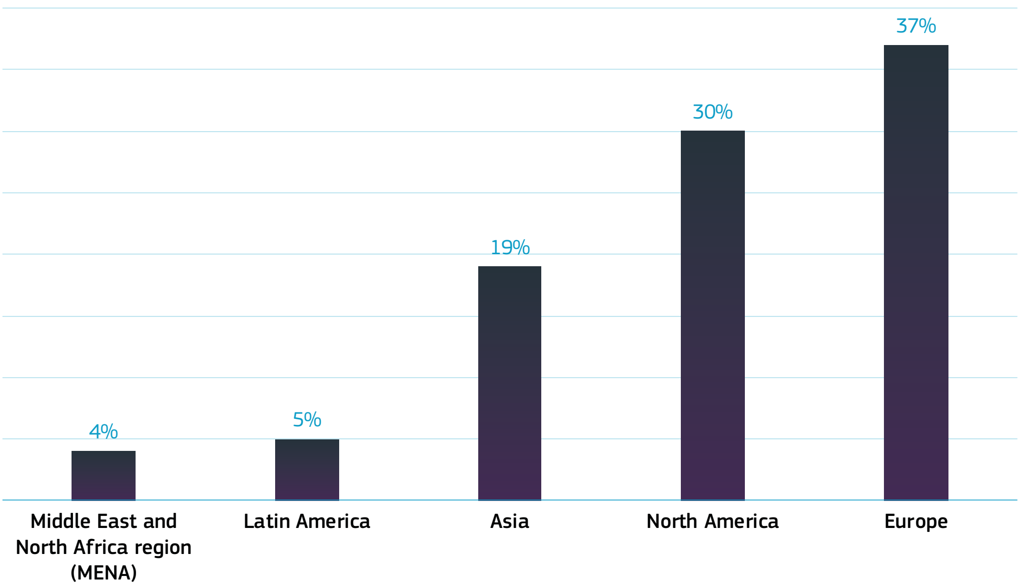
5 Please note that diverging data and definitions (as well as a number of different methodologies) are typically adopted to define start-up and scale-up companies. As such, it is extremely challenging to provide a comprehensive overview of the European landscape, using a unique definition.

6 Here, defined as firms younger than 10 years old and with high growth potential. The definition excludes, for instance, young businesses that do not intend to grow beyond their solo founder or that already reach a wide geographical market (EIB, 2019).

In 2019, the share of start-ups[7] in EU ranged between about 14% (Belgium) to about 42% (Sweden). Compared to 2012, the number of start-ups increased in several countries, notably in Belgium, Croatia, Estonia, Hungary, Malta, Poland, Portugal, Romania and Spain. Croatia and Poland are the Member States that experienced the largest increase over the period considered, with the share of start-ups almost doubling compared to 2012. On the contrary, Latvia experienced a significant contraction in the number of young enterprises, reporting almost 50% less start-ups than in 2012, followed by Denmark with a fall of 20%.

The EU aims at creating a fertile innovation ecosystem so as to play a key role in both the green and digital transition. Innovative start-ups play a pivotal role in addressing the challenges of the twin transition. Andrews et al. (2014) found strong evidence of resource reallocation towards patenting firms. Additionally, both the EU's industrial strategy and SME strategy[8] for a sustainable and digital Europe acknowledge the importance of supporting innovative start-ups as key drivers of economic growth.

Figure 4.2-8: Share of emerging start-up ecosystems by world region, 2020

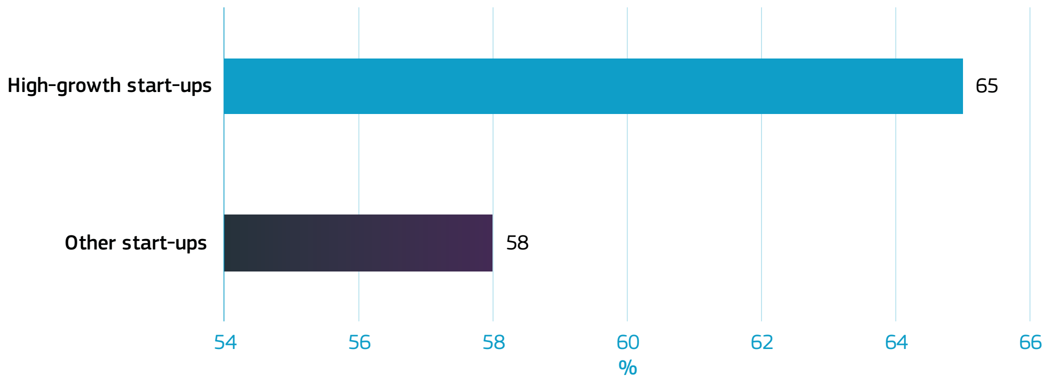


Science, Research and Innovation Performance of the EU 2022

Source: Startup Genome, 2021
Note: Emerging ecosystems are defined as ecosystems at the early-stage of their growth
Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-4-2-8.xlsx

7 Here defined as enterprises up to 5 years old
8 communication-industrial-strategy-update-2020_en.pdf (europa.eu)

Figure 4.2-9: Share of new-to-the-world innovators in EU-28



Science, Research and Innovation Performance of the EU 2022

Source: EIB (2020) based on EIBIS Start-up and Scale-up Survey 2019, firms sampled from Crunchbase.

Note: Baseline is all start-ups that stated an innovative aspect in EU + UK.

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-4-2-9.xlsx

The EU keeps lagging behind its main international competitors in terms of start-up ecosystems[9]. The main objective of a start-up ecosystem is to support companies in their launch and growth phases. When looking at the global start-up ecosystem ranking, North America keeps dominating the international scene, hosting 50% of Top 30 ecosystems in the world. Asia follows with 27%, after having outranked Europe between 2019 and 2021.

Nevertheless, the EU's performance is improving and the EU is performing relatively well in creating emerging start-up ecosystems[10]. In 2020, the EU was in the lead in terms of emerging ecosystems, accounting for 37% of global emerging start-up ecosystems, followed by North America and Asia, with a share of 30% and 19%, respectively (Figure 4.2-8).

Building effective ecosystems for innovative start-ups to grow and scale remains a high priority of the EU's agenda. A distinctive feature of high-growth start-ups is their ability to innovate. According to data collected by the EIB, 65% of high-growth start-ups[11] in Europe report that the most innovative aspect of their business was the creation of innovations previously unknown to the market (against 58% of lower-growth start-ups) (EIB, 2020) (Figure 4.2-9). **The latter aspect makes innovative start-ups essential players for the EU's economic growth**. As carriers of disruptive ideas, high-growth start-ups have the potential to introduce game-changing innovations to the market, thereby creating new economic opportunities that increase EU competitiveness at the global level (EIB, 2020).

9 A start-up ecosystem is defined as a cluster of start-ups (and related entities) which pool together resources and reside within a 100-kilometre radius from a central point (Startup Genome, 2021).

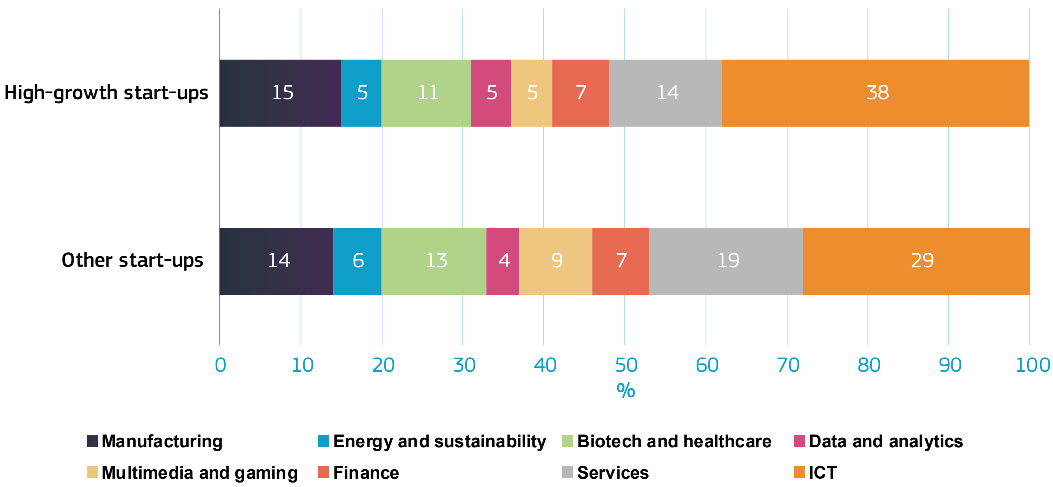
10 Emerging ecosystems are defined as ecosystems at the early-stage of their growth (Startup Genome, 2021).

11 High-growth start-ups are defined as firms less than 10 years old reporting an average turnover growth higher than 60% over the last three years in the EIB Start-up and Scale-up Survey 2019.

High-growth start-ups typically operate in highly innovative sectors. The largest share of high-growth start-ups is registered in innovation-enabling sectors (EIB, 2020): 58% of high-growth start-ups in Europe operate in the ICT sector, against 29% of start-ups with lower growth rates. Other sectors in which there is a good presence of high-growth innovative start-ups are the manufacturing and services sectors, with 15% and 14% of active innovative enterprises (Figure 4.2-10). Furthermore, the share of high-growth start-ups adopting innovative technologies is typically higher than that of other start-ups and SMEs in general (EIB, 2020): 53% of high-growth start-ups adopt cognitive technologies (such as big data or artificial intelligence), compared to 40% of start-ups with lower growth and 11% of SMEs (see Chapter 5.3 - ICT sector and digitalisation).

The number of EU scale-ups has increased in recent years, but the gap with the US remains. On average, there are three times more tech scale-ups in the US than in Europe (Mind the Bridge, 2019). Despite the contraction experienced with the outbreak of the coronavirus, European fast-growing companies showed a good degree of resilience to the COVID-19 shock[12]: after a 20% contraction in the level of scale-up investment, in 2021 the European scale-up landscape has been able to almost double the investment value reported in 2019 (European Scaleup Monitor, 2021).

Figure 4.2-10: Share of high-growth and other start-ups per economic sector



Science, Research and Innovation Performance of the EU 2022

Source: EIB (2020) based on EIBIS Start-up and Scale-up Survey 2019, firms sampled from Crunchbase.

Note: Baseline is all start-ups that stated an innovative aspect in EU + UK. Sector classification based on EIBIS Start-up and Scale-up Survey 2019

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-4-2-10.xlsx

12 See also, Coad et al. (2022) for a discussion on the COVID-19 effects on high-growth enterprises in Europe. Additionally, Coad et al. (2022b) find evidence that R&D investors are more likely to be pessimistic about investment plans as a consequence of the COVID shock.

European scale-ups[13] are strongly concentrated in few countries, notably UK, France which account for about 50 % of total scale-ups in Europe (European Scaleup Monitor, 2021). In 2021, UK remained the leading country in terms of scale-up performance, counting around 33 % of the European scale-up force. London maintained its record as Europe's scale up capital, with 145 scale-up companies. Paris followed with 50 fast-growing firms, accounting for 17 % of total scale-ups in France. Berlin ranked third, with 25 scale-ups (Figure 4.2-11).

The European scale-up landscape is dominated by companies operating in digital and tech industries. Around 57 % of European scale-ups is active in the computer software-industry (57.1 %). Banking, insurance and financial services sector ranks second with 12 %, while 7.5 % of European scale-ups firms operate in the field of biotechnology and life-sciences (European Scaleup Monitor, 2021).

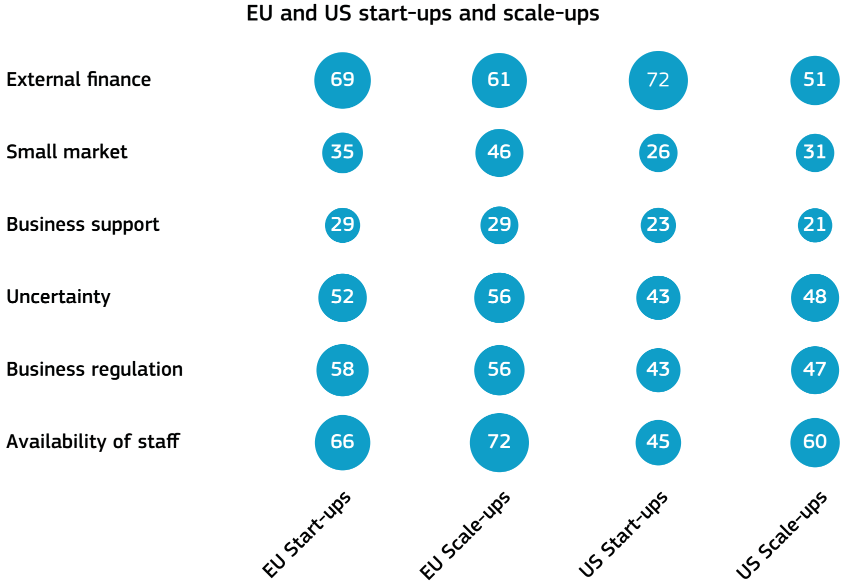
Availability of staff is one of the main barriers identified by innovative start-ups. Difficulties in hiring staff with the appropriate skills is reported as one of the main constraints to start-ups' growth (EIB, 2020). This is particularly relevant for high-growth start-ups, which indicate the lack of skilled personnel as a main barrier to success in 34 % of the cases, against 24 % of start-ups with lower growth rates (Figure 4.2-13). In particular, high-growth start-ups appear to experience particular difficulties in recruiting staff with appropriate technical skills (43 %), while 20 % do not find personnel with the right qualifications or experience (EIB, 2020). The scarce availability of skilled personnel is reported as a major issue by 66 % of EU start-ups, against 45 % of American ones. The gap is striking also when looking at EU scale-ups (72 % against 60 %) (Figure 4.2-13) (see Chapter 4.3. – Skills in the digital era).

Figure 4.2-11: Top Scale-up countries and cities in Europe, 2021

Source: European Scaleup Monitor, 2021
Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-4-2-11.xlsx

13 Here defined as young fast-growing companies (10 years old or younger) that have received at least EUR 1 million within the past 10 years (January 2011 - December 2020) (European Scaleup Monitor, 2021).

Figure 4.2-12: Start-ups and scale-ups obstacles to success – EU vs US



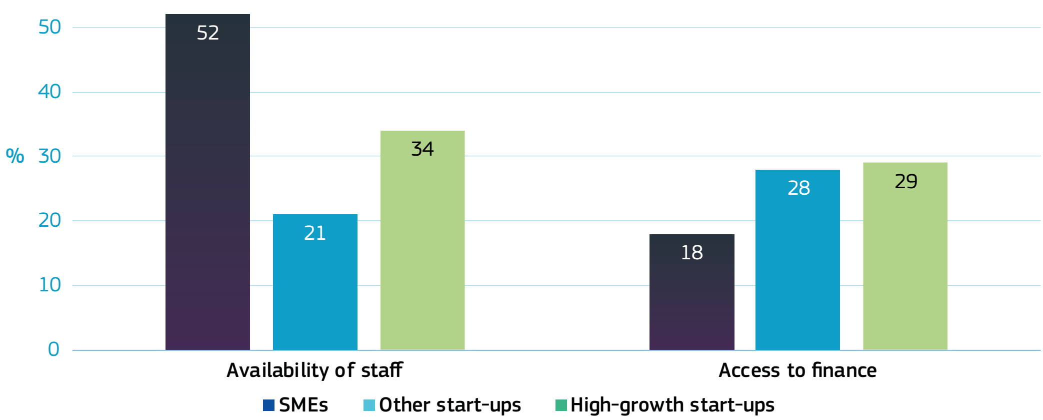
Science, Research and Innovation Performance of the EU 2022

Source: Ambrosio et al. (2021) based on EIB Investment Report 2019/2020, authors' calculations

Note: Data refers to the question 'To what extent is each of the following an obstacle to the success of your business?'. Relative difference is calculated by: $(scale\_up_{\_EU} - start\_up_{\_EU}) - (scale\_up_{\_US} - start\_up_{\_US})$

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-4-2-12.xlsx

Figure 4.2-13: Share of enterprises experiencing 'availability of staff' and 'access to finance' as a main barrier to growth



Science, Research and Innovation Performance of the EU 2022

Source: EIB (2020) based on EIBIS Start-up and Scale-up Survey 2019, firms sampled from Crunchbase.

Note: Baseline is all in EU + UK

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About one in three start-ups indicates limited access to finance as the main constraint to growth (EIB, 2020). This applies equally to high-growth and low-growth start-ups (29% and 28%, respectively), while 18% of European SMEs report barriers to external financing as a major issue (Figure 4.2-13). The lack of external finance contributes to explain the significant scale-up gap between the EU and the US. Europe significantly lags behind the US in terms of venture capital investment, and the gap increases as start-ups get older (EIB, 2020) (see Chapter 7.1 - Financing innovation: access to finance).

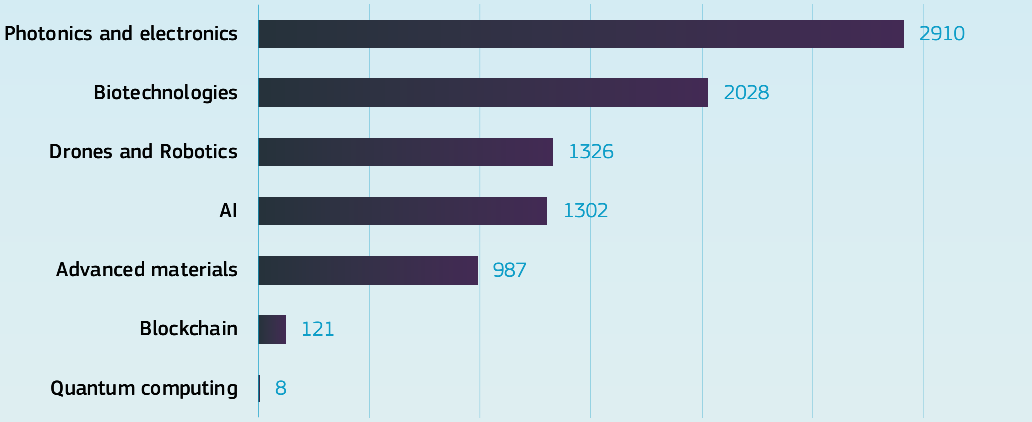
Other structural barriers potentially hindering EU companies' scale-up process include **a still fragmented EU internal market**, which could potentially explain why many start-ups and scale-ups in the EU typically operate only in their home country, and a **heterogeneous business regulation** across Member States (EIB, 2019). In the EU 56% of scale-ups mention business regulation as one of the main obstacles to success, against 47% in the US (Figure 4.2-12). This would call for a more homogeneous legal framework, able to promptly adapt to the pace of technological developments (DigitalEurope, 2021).

Box 4.2-1: Deep technologies

According to Boston Consulting Group (BCG) and Hello tomorrow (2021), **deep technologies are defined as novel technologies offering significant advances over those currently in use**. Deep technologies are typically identified along three dimensions: impact, time, and capital needed. In a study carried out in 2019, BCG and Hello tomorrow identified almost 8700 deep-tech start-ups worldwide. These companies are anticipated to a have a significant impact on different UN Sustainable Development Goals (SDGs). In particular, 51% of the deep-tech start-ups surveyed in the study predict they will impact the goal related to good health and well-being, 50% on the goal related to industry, innovation and infrastructure, and 28% consider their businesses will likely significantly contribute to mitigating the environmental spillovers of human activities. **Nevertheless, deep technologies typically take time to be fully deployable on the market**. The time to develop a commercially viable application varies across sectors (for instance, an average of 4 years is needed to develop deep technologies in the biotech industry, and 2.4 years for a start-up based on blockchain technologies) (BCG and Hello tomorrow, 2021). Furthermore, given the complexity of the products and services produced by these types of firms, significant financing resources are necessary for them to develop and scale.

Deep-tech start-ups mainly operate in seven fields worldwide. About 33.5% of the deep-tech start-ups identified are active in the field of photonics and electronics (2910 start-ups) (Figure 4.2-14). Biotechnologies and drones and robotics follow with 2028 and 1326 firms, respectively. AI ranks fourth, accounting for about 15% of the deep-tech start-ups identified (BCG and Hello tomorrow, 2019)

Figure 4.2-14: Number of Deep-tech start-ups worldwide per technological field



Science, Research and Innovation Performance of the EU 2022

Source: BCG Center for Innovation Analytics; BCG and Hello Tomorrow analysis (2019)

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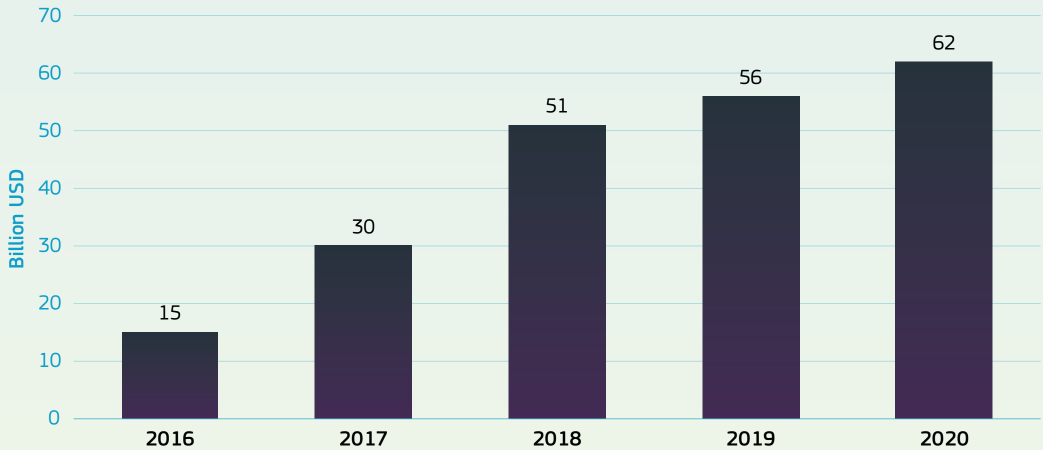
Deep-tech investments world-wide increased significantly over 2016-2020. In 2020, the level of global investments in deep-tech stood at over USD 60 billion (Figure 4.2-15). Funding needs differ considerably depending on the type of technology. Developing a first prototype in biotech is estimated to cost on average USD 1.3 million, while the costs of developing a first prototype in blockchain is about USD 200 000 (BCG and Hello tomorrow, 2021). Additionally, deep-tech investment is unevenly distributed across sectors. In 2020, about two-thirds of deep tech investments was raised by ventures in AI and synthetic biology (BCG and Hello tomorrow, 2021b).

Figure 4.2-15: Deep-tech investments worldwide, 2016-2020



Science, Research and Innovation Performance of the EU 2022

Source: Capital IQ; Crunchbase; Quid; BCG Center for Growth and Innovation Analytics; BCG and Hello Tomorrow analysis

Note: investments include private investments, minority stakes, initial public offerings and M&A

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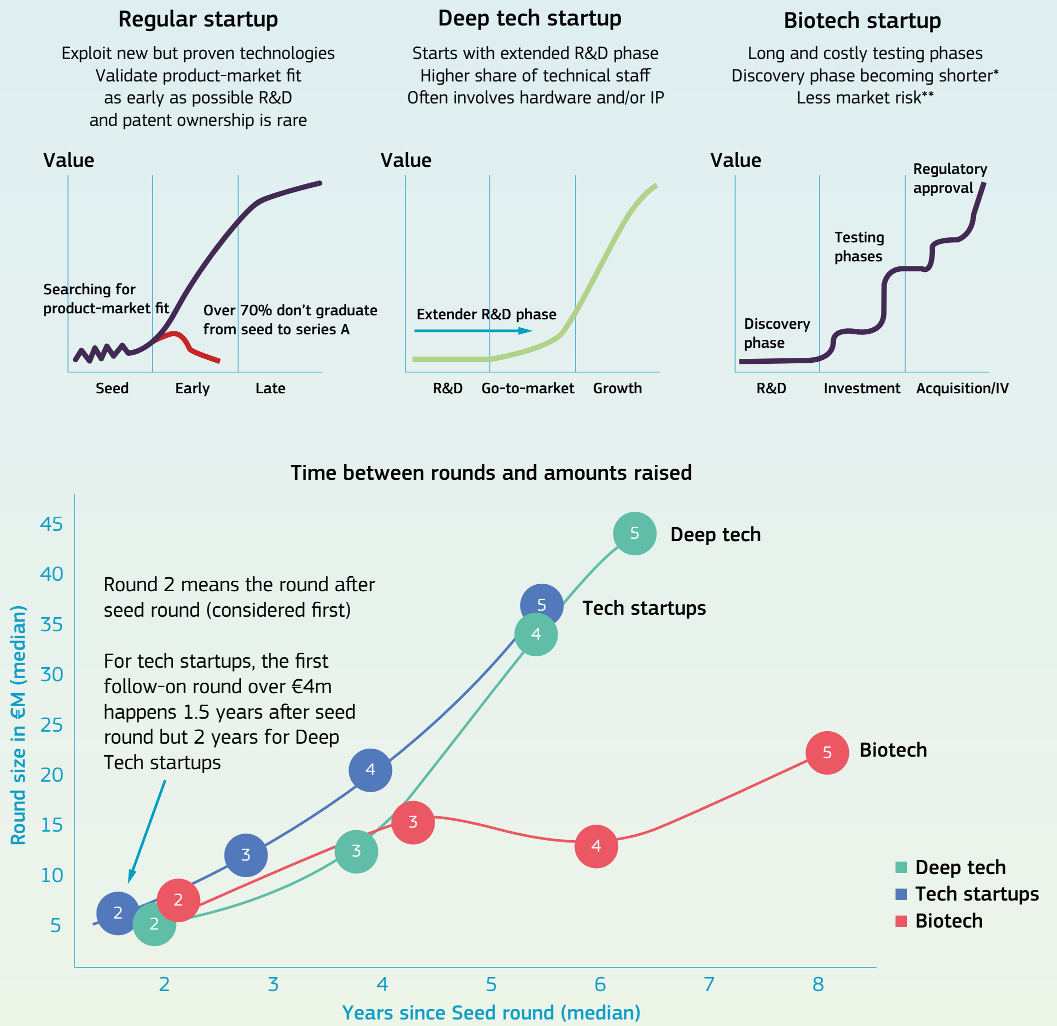
Private investment in deep-tech from corporate investors is on the rise. Between 2016 and 2020, deep-tech private investments coming from corporate investors increased from USD 5.1 billion to USD 18.3 billion. Furthermore, private investment in Europe has experienced a faster growth than China and US, reporting a CARG of 49 %, against the 34 % and 28 %, respectively (BCG and Hello tomorrow, 2021b).

A deep-tech start-up typically takes more time to become fully operational on the market. As shown in Figure 4.2-16, for regular tech start-ups it typically takes 1.5 years after the seed round to raise follow-on capital. This takes longer for deep-tech firms, typically needing about two years (Dealroom, 2021).

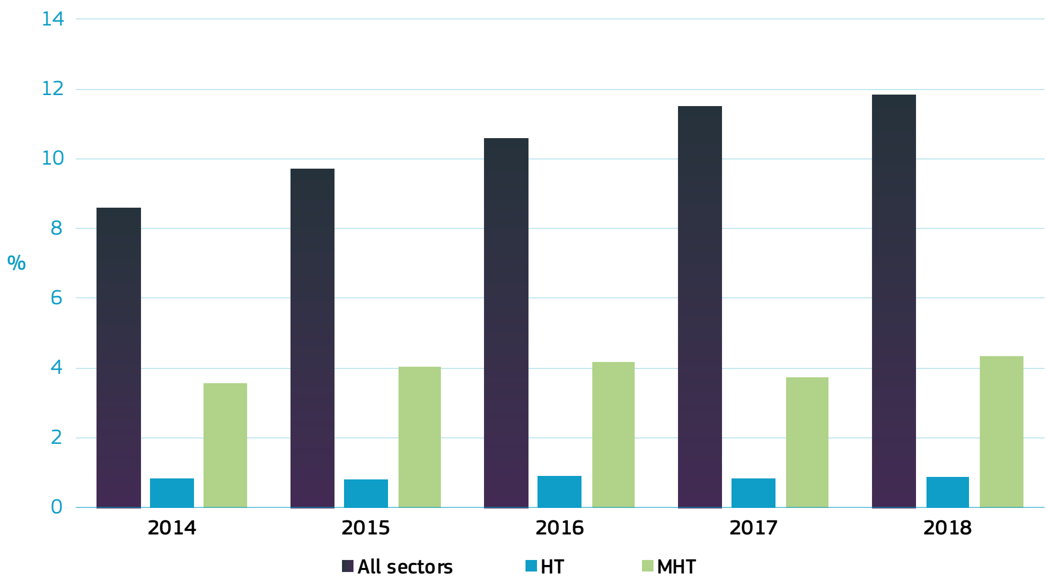
Figure 4.2-16: Differences and time between rounds and amount raised for tech start-ups, deep-tech start-ups and biotech-start-ups



Source: Dealroom - 2021: the year of Deep Tech (2021)
Note: Data refer to 1 700 qualified European start-ups that raised a seed round > EUR 200 000 between 2010 and 2015 and closed a 2nd round of at least EUR 4 million.
Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-4-2-16.xlsx

The untapped potential of European deep-tech is still significant. As noted by Dealroom (2021), many European deep-tech companies are strongly interlinked with academia and heavily rely on public support. An important step to unlock the European growth potential is to foster the entrepreneurial culture within European universities, strengthening the link between academia and the business sector. Europe hosts world-class universities and research centres. In order to reduce the commercial and technological divide between Europe and frontier runners (such as China and US), it is essential to strengthen the relationship between academic production and commercialisation. Furthermore, successes like BioNTech demonstrate the importance of providing promising companies with significant support at early stage. In this regard, government intervention is needed to mobilise financing, which is a pre-condition to keep attracting top talents in Europe and from the rest of the world (Dealroom, 2021).

Figure 4.2-17: Share of high-growth enterprises[1] in EU per sector, 2014-2018



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Eurostat [online data code : bd_9pm_r2_1]

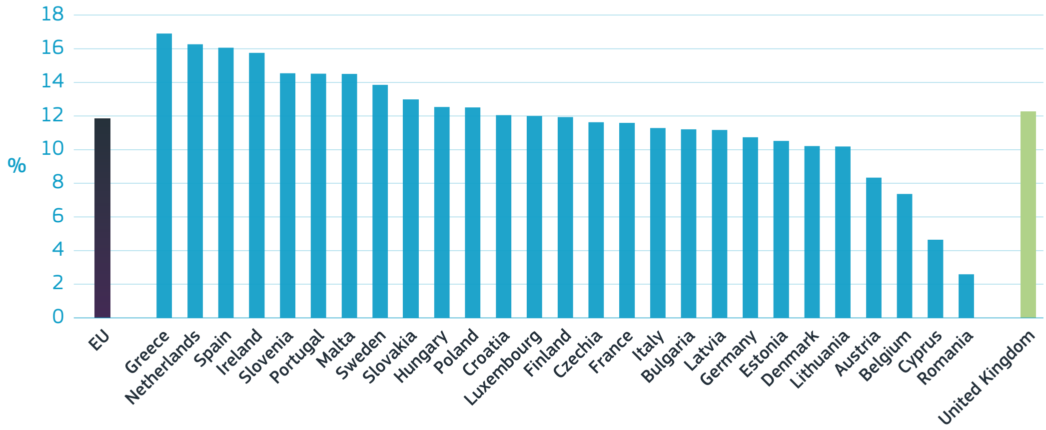
Note: [1]High growth enterprises measured in employment (growth by 10 % or more).

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-4-2-17.xlsx

On average, slightly less than 12 % of companies in EU are high-growth enterprises. The number of high-growth enterprises[14] in the EU has steadily increased over the period 2014-2018 (Figure 4.2-17), but only slightly more than 5% of these enterprises operate in high-tech[15], and medium-high tech[16] sectors.

There exist inter-country differences across the EU in terms of high-growth enterprises. Some EU Member States perform well above the EU average (with a share of around 12 %): Greece, Ireland, the Netherlands, Portugal and Spain report a share of high-growth enterprises of around 16 %. On the contrary, for Austria, Belgium, Denmark, Estonia, Germany and Lithuania we observe a share around 10 %, while Cyprus and Romania perform significantly below the EU average with respectively 4.6 % and 2.5 % of active high-growth enterprises (Figure 4.2-18).

Figure 4.2-18: **Share of high-growth enterprises[(1)] in EU Member States, 2018**



Science, Research and Innovation Performance of the EU 2022

Source: Eurostat [online data code : bd_9pm_r2_1]
Note: [(1)]High growth enterprises measured in employment (growth by 10 % per year or more).
Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-4-2-18.xlsx

14 All enterprises with average annualised growth greater than 20 % per annum, over a three year period should be considered as high-growth enterprises. Growth can be measured by the number of employees or by turnover.

15 High-technology sectors include: firms involved in the manufacture of basic pharmaceutical products and pharmaceutical preparations (C21); manufacture of computer, electronic and optical products (C26); manufacture of air and spacecraft and related machinery (C30.3)

16 Medium-high-technology sectors include: firms involved in the manufacture of chemicals and chemical products (C20); manufacture of weapons and ammunition (C25.4); manufacture of electrical equipment (C27); manufacture of machinery and equipment n.e.c. (C28); manufacture of motor vehicles, trailers and semi-trailers (C29); manufacture of other transport equipment (C30) excluding the building of ships and boats (C30.1) and excluding manufacture of air and spacecraft and related machinery (C30.3); manufacture of medical and dental instruments and supplies (C32.5).

Box 4.2-2: The fully-fledged European Innovation Council (EIC) – Investing in Sustainable Start-ups and Scale-ups, Women Innovators and Business Leaders and European Deep Tech

Prior to the launch of the fully-fledged EIC in March 2021, the EIC pilot and its enhanced version were designed to prepare the ground for the full integration of the predecessor instruments and services, such as the SME instrument, FET Open & Proactive, to arrive at the three main funding instruments that now constitute this unique European initiative. As part of Horizon Europe, the EIC Pathfinder, EIC Transition and the EIC Accelerator funding schemes will ensure Europe's competitiveness when it comes to deep-tech start-ups as well as building an investment pipeline of sustainable scale-ups made in Europe. Furthermore, the EIC is taking action on its ambition to invest in a balanced and diverse European innovation ecosystem by fostering female entrepreneurship and business leaders from all over the EIC community.

The 2021 EIC's Impact Report[17] showed the first successes of the EIC and included 5500 pilot Accelerator projects (including those from SME Instrument) and 408 pilot Pathfinder projects (including those from FET).

EIC Accelerator companies already attracted EUR 9.6 billion in follow on investments, primarily from venture capital, but also from corporates, national promotional banks and others.[18] Overall, they reached a valuation of around EUR 50 billion, including 91 centaurs (with a company valuation of over EUR 100 million) and four unicorns (with a company valuation of over EUR 1 billion).

Figure 4.2-19: The three EIC funding instruments

1. EIC PATHFINDER

For a advanced high-risk research on breakthrough technologies

2. EIC TRANSITION

For transforming the most promising research results into innovation opportunities

3. EIC ACCELERATOR

For ambitious and innovative companies to develop and scale uo cutting-edge innovations

Science, Research and Innovation Performance of the EU 2022

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-4-2-19.xlsx

17 https://eic.ec.europa.eu/news/european-innovation-council-impact-report-2021-key-numbers-eic-performance-2021-11-24_en

18 Investment data in cooperation with Dealroom

Figure 4.2-20: The EIC unicorns

4 Unicorns

CELLINK A BICO COMPANY

BIOARCTIC

SWORD HEALTH

infarm

Science, Research and Innovation Performance of the EU 2022

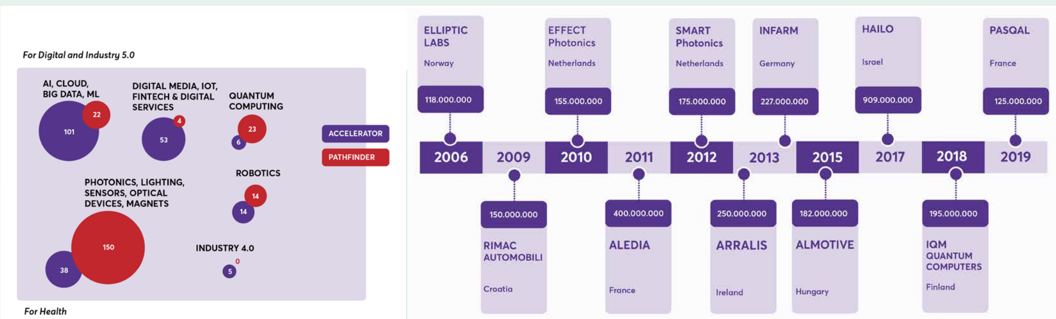
Source: Dealroom

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-4-2-20.xlsx

The EIC's Impact Report 2021 also revealed that EIC companies are well positioned to feed into current investor appetites for digital, green and health investment opportunities:

Figure 4.2-21 below shows the EIC's digital portfolio for both Accelerator and Pathfinder, and includes trending areas such as cloud computing, magnets, fintech and quantum computing. Digital centaurs also contributed to a significant rise in value of the overall EIC portfolio of companies.

Figure 4.2-21: EIC digital portfolio and EIC digital centaurs

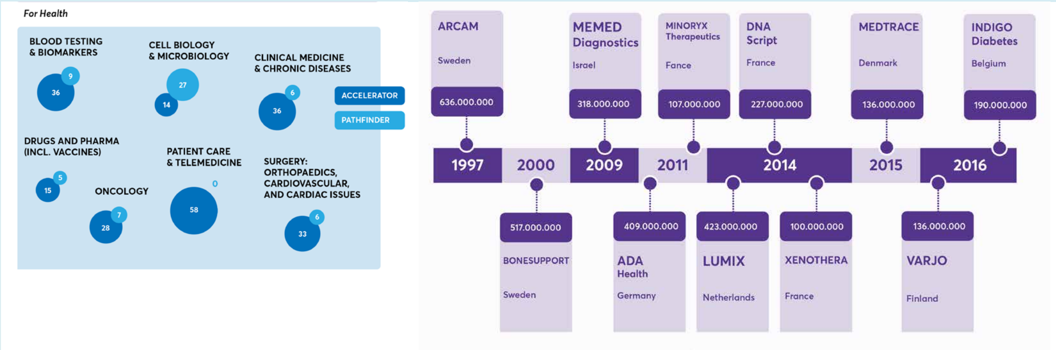


Science, Research and Innovation Performance of the EU 2022

Source: EIC 2021

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-4-2-21.xlsx

Figure 4.2-22: EIC health portfolio and EIC health centaurs



Science, Research and Innovation Performance of the EU 2022

Source: EIC 2021

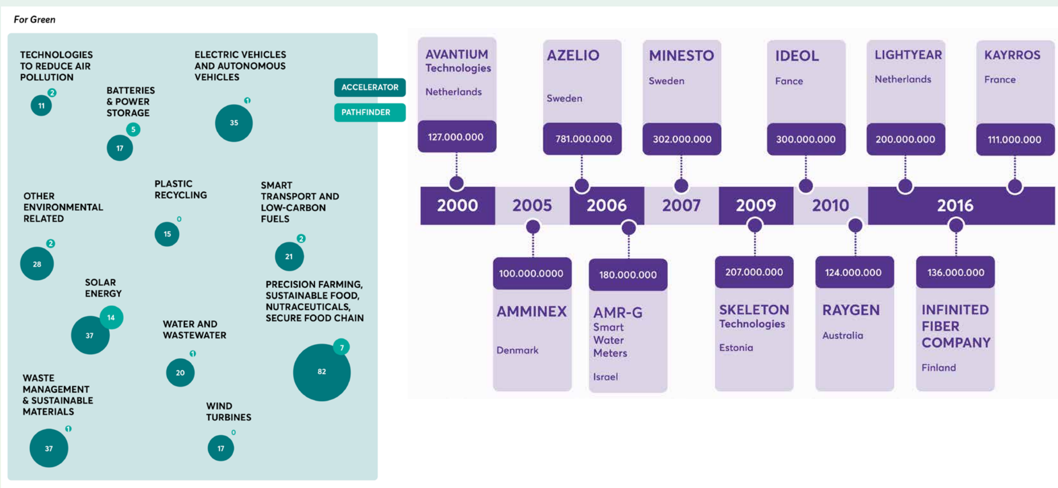
Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-4-2-22.xlsx

The EIC's health portfolio and its associated centaurs are also positioned in promising areas, albeit the pandemic is likely to change its entire composition in the years to come.

The EIC's green portfolio is one of its kind and combines some of the most pioneering companies and projects to target and reach the market for sustainable investing. The portfolio is diverse and wide ranging and includes sustainable food companies as well as sustainable materials innovators.

For 2022, EIC Accelerator funding of EUR 1.16 billion is earmarked for start-ups and SMEs to develop and scale up high-impact

Figure 4.2-23: EIC green portfolio and EIC green centaurs



Science, Research and Innovation Performance of the EU 2022

Source: EIC 2021

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-4-2-23.xlsx

and disruptive innovations. Its blended finance option provides equity (or quasi-equity such as convertible loans) between EUR 0.5 million and EUR 15 million through the EIC fund, with grants of up to EUR 2.5 million. Moreover, about EUR 537 million in Accelerator funding will go towards breakthrough innovations as part of a call dedicated to Open Strategic Autonomy and technologies in line with the Fit for 55 strategy.

EIC Pathfinder is committed to investing in European deep techs with a high risk and high potential for scientific and technological breakthroughs. Pathfinder multi-disciplinary research teams, worth EUR 350 million in 2022, are working towards the future basis for innovations and the investment opportunities of tomorrow. Research teams can apply for up to EUR 3 million or EUR 4 million in grants.[19] According to the EIC's 2021 Impact report, EIC pilot Pathfinder projects have generated over 800 innovations so far (tracked by Innovation Radar). The majority of pilot Pathfinder projects include SMEs or other commercial partners that are also more likely to generate patents as part of their business plans. Moreover, the Pathfinder has led to a large number of scientific impacts (high impact publications). Together with the EIC's Programme Managers, who pro-actively support the innovation potential of their portfolio projects, the EIC strives to bring these breakthroughs closer to the market.

The new EIC Transition Instrument is investing EUR 131 million in 2022[20] to turn research results into innovation opportunities. This will be implemented in cooperation with the European Research Council (ERC), who will contribute with proof-of-concept projects, and the European Institute of Innovation and Technology (EIT). Together the EIC, EIT and the ERC will build business cases for mature technologies and for specific applications.[21] Furthermore, the EIC will continue its commitment towards increasing the number of women-led start-ups in 2022 and the years to come and can already report its first success: Of those awarded funding in 2020, over 20 % have a female CEO, a doubling of the previous level.

19 The bulk of the funding is awarded through open calls with no predefined thematic priorities, while EUR 167 million is allocated to tackle six challenges: carbon dioxide and nitrogen management and valorisation; mid-long term, systems-integrated energy storage; cardiogenomics; healthcare continuum technologies; DNA-based digital data storage and alternative quantum information processing, communication, and sensing.

20 EUR60.5 million for three Transition Challenges: green digital devices for the future; process and system integration of clean energy technologies; and RNA-based therapies and diagnostics for complex or rare genetic diseases.

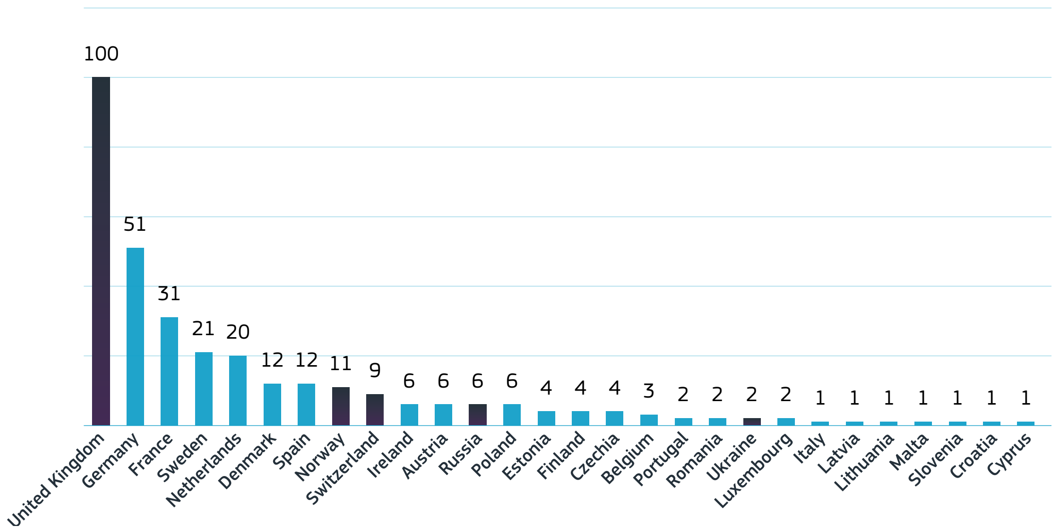
21 Consortia can apply for EUR 2.5 million grants (or more if justified).

4. In need of unicorns ?

Unicorn companies[22] are typically fast-growing start-ups operating at the edge of the innovation frontier. Besides playing an important role in boosting aggregate economic productivity and job creation, unicorns also act as catalyst for innovation. One of the key characteristics of a unicorn company is a quickly adaptable business model, which allows the company to promptly react to changes in market and innovation trends (Casnici, 2021). In monitoring unicorns it is thus useful to investigate emerging trends in the innovation landscape, as this type of company typically swiftly adopts and are themselves carriers of cutting-edge technologies.

The number of European unicorns grew significantly in 2021. According to the latest available data, the number of unicorns founded in Europe increased by almost 44% in 2021, jumping from 223 at the end of 2020 to 321 by November 2021. Between November 2021 and now, 98 new unicorns were founded in Europe (Atomico, 2021). This trend confirms that the European entrepreneurial landscape is strengthening, significantly improving its ability to create new and fast-growing innovative actors. **Nevertheless, many of the unicorns founded in Europe tend to move their headquarters elsewhere.**

Figure 4.2-24: **Geographic distribution of unicorns in Europe, up to 2021**



Science, Research and Innovation Performance of the EU 2022

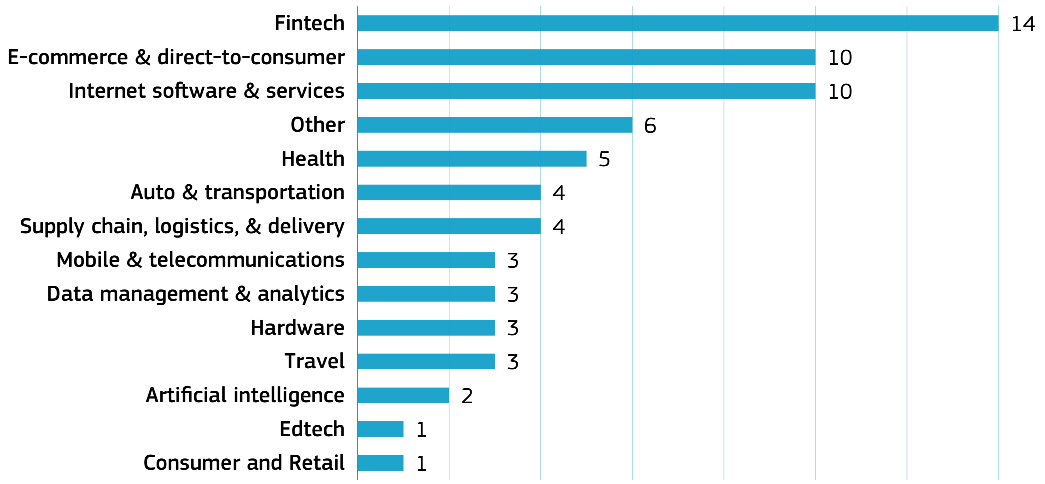
Source: Atomico (2021) based on Dealroom data
Note: Data refers to the number of unicorns founded in each country
Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-4-2-24.xlsx

22 A unicorn start up is a privately owned company which manages to reach a valuation of $ 1 billion (currently about EUR 867.14 million) or more.

There exist considerable differences in the distribution of unicorns across European countries. The UK keeps leading the European landscape in terms of founded unicorn companies, with a total of 100. When looking at the EU Member States, Germany accounts for the largest share of unicorns founded in the EU (51). France has the second highest number of founded unicorns (31), followed by Sweden (21) and the Netherlands (20). Latvia and Cyprus both saw the creation of one unicorn in 2021, with Printful (Latvia) and Nexters Group (Cyprus) reaching unicorn status in May 2021 (Atomico, 2021).

EU unicorns are mostly active in the financial and digital sector. The Fintech sector accounts for about 20% (14) of the EU-headquartered unicorns (Figure 4.2-25), as a result of the large investments injected in this sector over the past ten years (Testa et al., 2022). The ICT-software sector reports 20 unicorn firms (10 unicorns active in the e-commerce industry, and internet software and services, respectively). The health and transportation industries follow with 5 and 4 unicorns, respectively.

Figure 4.2-25: **Sectorial distribution of EU unicorn firms, up to November 2021**



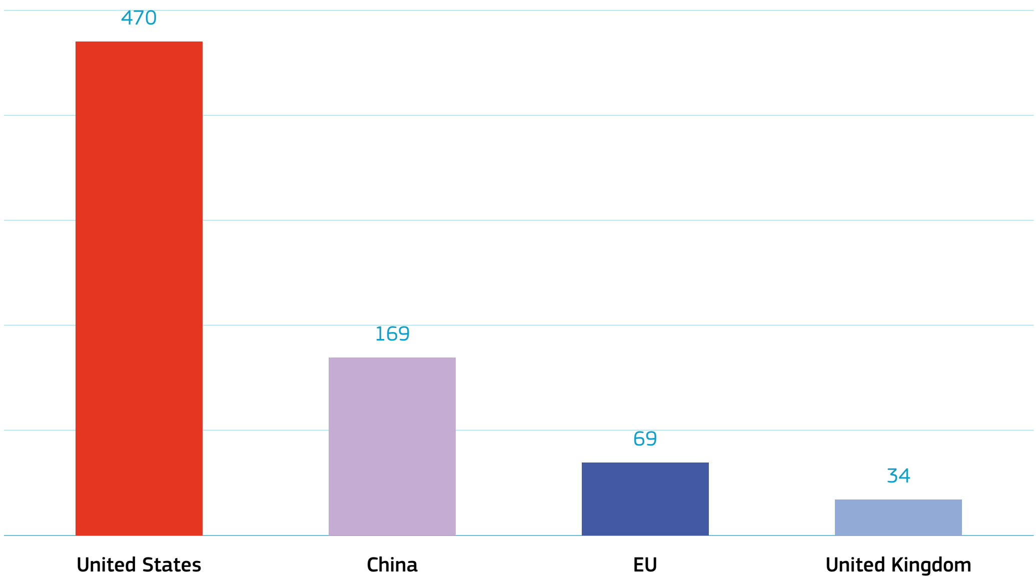
Science, Research and Innovation Performance of the EU 2022

Source: CBInsights, updated up to Nov 2021
Note: Data refers to unicorn companies headquartered in the EU.
Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-4-2-25.xlsx

Despite the rapid increase in the number of European unicorns, the EU still underperforms as compared to other major economies. The EU's limited ability to scale start-ups into major companies is also reflected by the lower number of unicorn firms compared to our main competitors.

In 2021, the US reported almost seven times more unicorns than Europe, while China outperformed the EU by a factor more than two (Figure 4.2-25). By the end of 2021, there were 742 companies worldwide with unicorn status. Of those, more than 60 % (470) are based in the United States, more than one fifth in China (or 169), and about 9 % (69) are in the EU. Furthermore, EU unicorns are typically older than US and Chinese ones. On average, it takes about 10 years for an EU unicorn to reach the USD 1 billion valuation, against the eight and five years reported by US and China (Testa et al., 2022). One of the main reasons behind the differences between the EU and the US is the significant difference in capital markets between the two economies, which calls for the creation of a more efficient capital ecosystem able to raise the necessary funding for EU firms to scale-up (see Chapter 7.1 - Access to finance: the importance of equity and venture capital).

Figure 4.2-26: Number of unicorns across world regions per headquarter, up to August 2021



Science, Research and Innovation Performance of the EU 2022

Source: CBInsights, updated up to Nov 2021

Note: Figure 4.2-26 reports the number of unicorns headquartered in the different geographical regions.

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5. Entrepreneurial ecosystems in the digital age

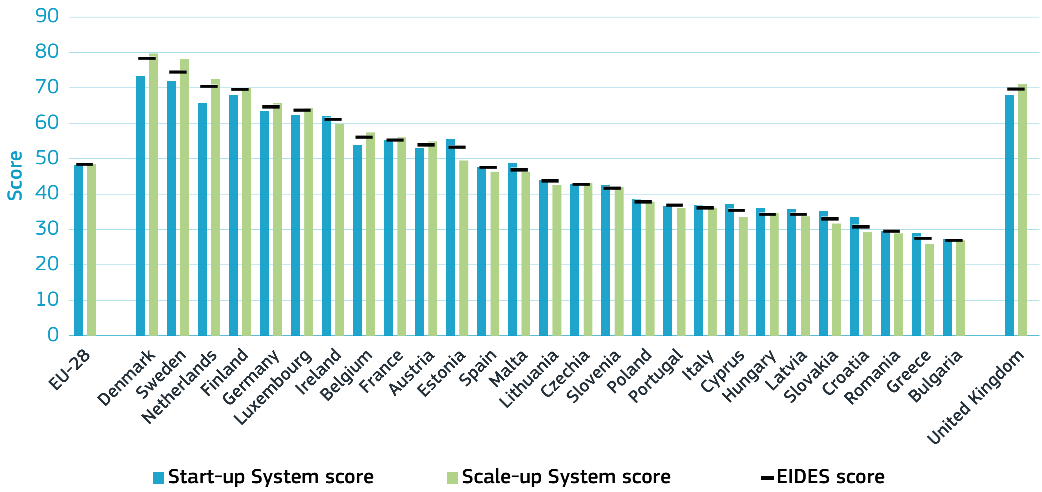
Entrepreneurship is essential for creating jobs, boosting innovation and increasing growth. Along with the concept of creative destruction, Schumpeterian growth theory outlays the idea that innovation and, thus, long-term growth is generated by entrepreneurial investment (e.g., R&D, training, equipment purchases) (Aghion and Howitt, 1992). There exists a large body of economic literature linking entrepreneurial activity to economic growth. Central to this literature is the consideration that economic growth cannot be explained only by looking at the inputted factors of production, but also strongly hinges on the profit opportunities created by the entrepreneurial process (Prieger et al., 2016). In this regard, the literature coined the term 'productive entrepreneurship' to indicate any entrepreneurial activity that contributes to producing additional output (Baumol 1993; Bosma et al., 2018). Although there is a large consensus on the positive relationship between entrepreneurship and growth, the channels through which this relationship works are still debated. Wennekers and Thurik (1999) identified **three main channels through which entrepreneurship can drive economic growth, namely innovation creation, innovation diffusion and competition**. Nevertheless, the link between entrepreneurial activities and economic performance also depends on the institutional environment. An increasing number of studies have attempted to uncover such a complex system of interlinkages, broadly referred to as the 'entrepreneurial ecosystem' (Bosma et al., 2018; Aution and Cao, 2019; Content et al., 2020).

Today entrepreneurial ecosystems are critical for the digital transition. The reorganisation of our societies and the changes in the way of doing business following the harnessing of digital technologies create new opportunities for entrepreneurs, and calls for the adoption of innovative business models and practices (Autio and Cao, 2019). In this context, entrepreneurial ecosystems can play a prominent role in unlocking the opportunities coming from the digital transition (Autio et al., 2020). Furthermore, according to Autio et al. (2019), entrepreneurial ecosystems specialise in fostering digital start-ups, thereby making entrepreneurial ventures a driver for the digital transition (Autio et al., 2020).

EU countries perform very differently in terms of having a digitalised framework conditions for entrepreneurship. The European Index of Digital Entrepreneurship Systems (EIDES) measures both physical and digital conditions for stand-up, start-up and scale-up ventures in the EU Member States, plus the UK. The average performance of EU countries has improved in the last three years (Autio et al., 2020). Figure 4.2-27 reports the result of the 2020 EIDES scores. Denmark, Sweden, the Netherlands, Finland, Germany, Luxembourg and Ireland are leading in terms of their digitalised framework conditions for entrepreneurship.[23] Denmark and Sweden appear as leaders also when sub-indices (stand-up, start-up and scale-up indices) are considered, while the Netherlands ranks as third for the stand-up and scale-up systems, and fifth in terms of start-up systems.

23 Countries can be divided into four groups according to their EIDES score: 1) leaders, with a score above 60; 2) followers, with an score between 60 and 45; 3) catchers-up, with a score ranging between 45 and 35; and 4) laggards, with a score lower than 35.

Figure 4.2-27: EIDES score by country, 2020[1]



Science, Research and Innovation Performance of the EU 2022

Source: Autio et al., 2020 based on EIDES 2020

Note: [1]Countries can be divided into four groups according to their EIDES score: 1) leaders, with a score above 60; 2) followers, with an score between 60 and 45; 3) catchers-up, with a score ranging between 45 and 35; and 4) laggards, with a score lower than 35.

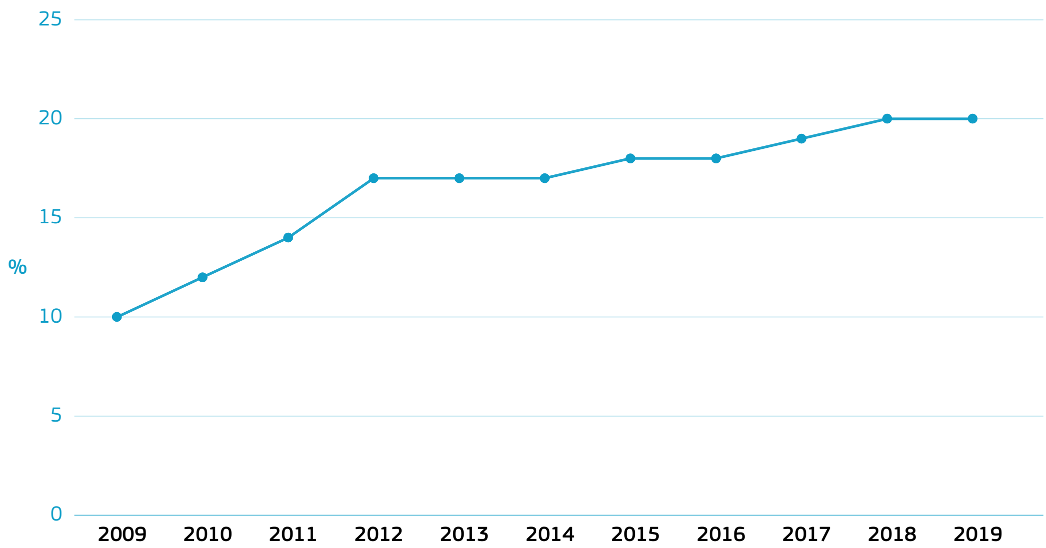
Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-4-2-27.xlsx

Germany and Luxembourg score respectively sixth and seventh in the three sub-indices, whereas Ireland ranks eighth. A second group, with an average score 16 points lower than the leader group identified as followers, comprises of Belgium, France, Austria, Estonia, Spain and Malta. Lithuania, Czechia, Slovenia, Poland, Portugal, Italy, and Cyprus follow as catching-up countries, while Hungary, Latvia, Slovakia, Croatia, Romania, Greece and Bulgaria are lagging behind, with an EIDES score ranging between 26.9 (Bulgaria) and 34.4 (Hungary and Latvia) (Autio et al., 2020).

6. The EU entrepreneurial gender gap

The number of women founding start-ups is increasing worldwide, but a gender gap still remains. Inclusiveness is a critical feature for entrepreneurship. Excluding one or more societal groups from the entrepreneurial ecosystem would result in untapped growth opportunities in terms of job creation, innovation and productivity. Figure 4.2-28 reports the evolution of the share of global start-ups with a female founder over the period 2009-2019. The data shows an increasing trend over time: overall the share of female funded start-ups almost doubled, increasing from 10% in 2009 to 20% in 2019.

Figure 4.2-28: Share of start-ups with a female founder, 2009-2019

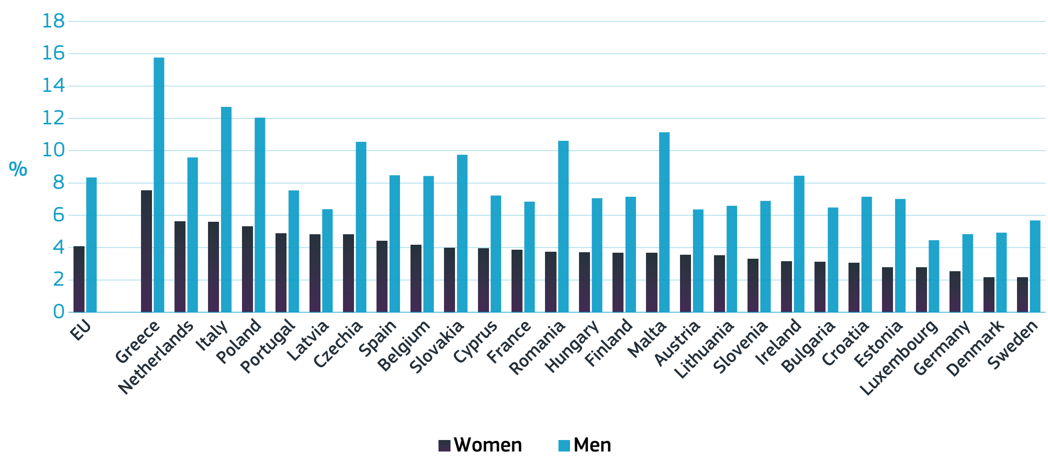


Source: Crunchbase (2019)
Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-4-2-28.xlsx

Europe shows lower female entrepreneurial activities compared to other regions in the world. The rate of early-stage women entrepreneurial activity (i.e. the share of women aged between 18 to 64 years old who are either nascent entrepreneurs, or are owners of a business[24]) in Europe is 5.7%, against a world average of 11% (GEM, 2021). European women perform poorly when compared to men across the different stages of the business creation process.

The entrepreneurial gender gap persists also within EU Member States. When looking at entrepreneurial intentions (i.e., intentions of starting a business), the gender gap is particularly striking in Norway (4.9% for women vs. 10.3% for men) and Poland (2.8% vs. 7%), whereas in Luxembourg (10.7% vs. 11.5%) and Latvia (15.9% vs. 19%) the divergences are less pronounced (GEM, 2021). As regards female entrepreneurial activity in businesses less than 3.5 years old, Italy (0.9% vs. 2.9%), Luxembourg (5% vs. 10.9%) and Slovakia (8.9% vs. 18.8%) report the highest divergences, followed by Spain (4.8% vs. 5.6%) and Germany (4.3% vs. 5.1%) (GEM, 2021). The gap is even more pronounced when considering established businesses (more than 3.5 years old), with most countries showing differences close to or exceeding 100% (GEM, 2021). An alternative way to look at the entrepreneurial gender gap is to focus on female and male self-employment rates[25] (Figure 4.2-29). In 2020, the number of female entrepreneurs were half that of men (4% against 8%). Sweden, Slovakia, Romania, Poland and Malta present the highest gender gaps in terms of

Figure 4.2-29: Female entrepreneurship rates across EU Member States, 2020



Source: Labour Force Survey (2020), [online data code: lfsa_esgan2_1]

Note: The entrepreneurship rate is measured as the number of self-employed women as a proportion of total active population aged 15 to 64.

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24 I.e. entrepreneurs in the process of starting a business but have not paid wages for more than three months, and owners of businesses that are older than three months but younger than 42 months (GEM, 2021).

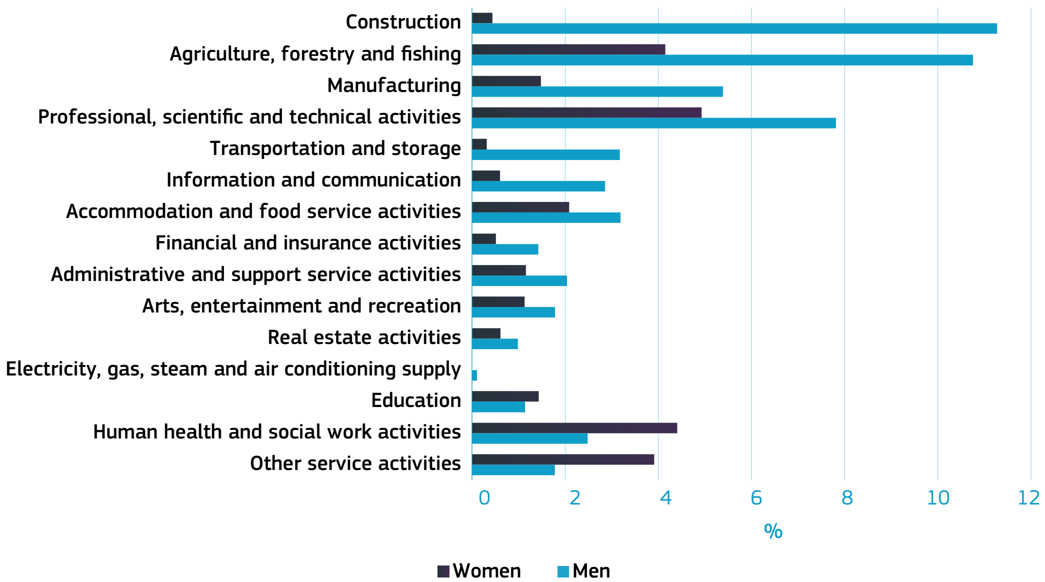
25 Self-employment is one of the most common proxies used to measure entrepreneurial activities.

self-employed women and men, whereas Luxembourg, Latvia, and Germany show the smallest discrepancies.

A potential reason for the EU entrepreneurial gender gap is the presence of a sectorial gender segregation. Female entrepreneurs in the EU are mostly found in economic sectors typically characterised by a lower level of entrepreneurial activities. Typically fast-growing sectors (such as construction, manufacturing, professional, scientific and technical activities, as well as information and communication) are dominated by male entrepreneurs. Such a gap is particularly striking for the construction and manufacturing industries, with a share of male entrepreneurs of respectively 10% and 5%, against less than 1% and 1.5% of female entrepreneurs, respectively. On the contrary, self-employed women mostly operate in the health and social work sector (4.4% women against 2.5% men), and in other service sectors including washing and cleaning textile products, hairdressers, as well as well-being services[26] where the proportion of female entrepreneurs is twice that of males (4% against 2%).

Furthermore, the EU still struggles to improve its performance in terms of female patent applications, and falls behind its main international competitors. The share of female patent applications filed under the Patent Cooperation Treaty (PCT) to the European Patent Office (EPO) did not increase much over 2008 to 2018 (Figure 4.2-31). Furthermore, the EU's performance remains significantly below that of other international economies. China and South Korea are at the top of the ranking, with 31.6% and 30.6% respectively of female patent applicants in 2018.

Figure 4.2-30: Distribution of female entrepreneurs by industry, 2020



Science, Research and Innovation Performance of the EU 2022

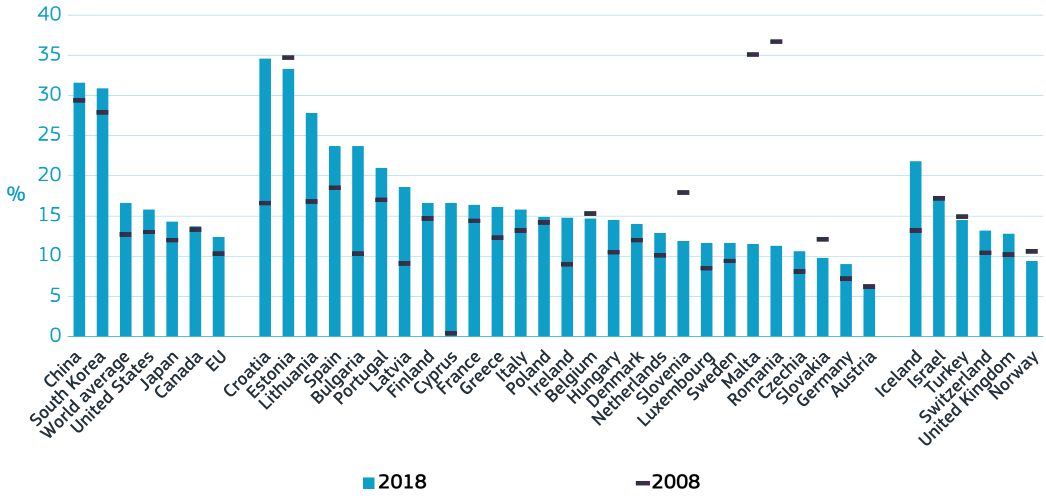
Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit, based on Labour Force Survey (2020), [online data code: lfsa_esgan2_1]]

Note: The entrepreneurship rate is measured as number of self-employed women as proportion of total active population aged 15 to 64.

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-4-2-30.xlsx

26 E.g. medical massage and therapy, and activities related to health, fitness and body-building clubs and facilities.

Figure 4.2-31: **Share of female applicants on patent applications filed under PCT to the EPO, 2008 and 2018**



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Science-Metrix using data from EPO PATSTAT database.

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-4-2-31.xlsx

The US follows with 15.8%, which is slightly below the world average (16.6%). The EU is significantly behind, reporting only a 12.4% share (Figure 4.2-31). In addition, the EU also shows significantly inter-country differences. In 2018, Croatia reported the highest share of female patent applicants (34.6%), followed by Estonia and Lithuania (33.3% and 27.8%, respectively). Croatia was also among the Member States showing the highest increase over 2008 to 2018 (Figure 4.2-31). Similarly, most of the Member States improved their performance over the same time span, ending up above the EU average. The important exceptions were Slovenia, Malta and Romania, which experienced a significant reduction in the share of female patent applications, dropping below 12% (Figure 4.2-31).

7. Conclusions: fuelling business dynamism in EU

In order to reverse the sluggish trend in productivity growth, the EU has to accelerate the development and diffusion of innovative ideas and inventions in support of EU enterprises with high-growth potential. The EU can count on a vibrant start-up ecosystem, and needs to increase its efforts to create a fertile innovation landscape for firms to scale-up and grow. Although still lagging significantly behind US, the European scale-up landscape shows considerable potential and has proved to be able to quickly react to the challenges posed by COVID-19. **Innovative enterprises showed better adaptation capacities to the shock, confirming the role of innovation as key ingredient for economic resilience**. Furthermore, since November 2021 European unicorns have increased by more than 40%, confirming that the role of Europe as global tech player is increasing.

The improved EU performance in terms of fast-growing companies is of key relevance in the aftermath of the COVID-19 pandemic. High-growth firms not only have the potential to speed-up the recovery, but are also essential for progress in the green and digital transition. Nevertheless, challenges remain (notably, the presence of skill bias, limited access to finance and fragmented regulatory framework), which call for continuous actions to improve the EU framework conditions for innovation.

Empowering women entrepreneurs remains a top priority. The EU has always promoted diversity as a key ingredient for a thriving economy. The European challenge to unleash its growth potential also needs solutions to ensure better female representation within the EU entrepreneurial landscape. Currently, the EU suffers from a significant entrepreneurial gender gap, which results in missed opportunities in terms of innovation, employment and growth. In renovating its commitment to reverse this trend, the European Commission presented the *EU Gender Equality Strategy 2020-2025* in March 2020, setting out EU policy objectives to create a gender-equal Europe. This includes actions to strengthen European women's economic empowerment, e.g. the creation of an enabling environment for women's economic activities, facilitating access to finance through innovative investment schemes targeting women entrepreneurs and female-led businesses.

References

Adalet McGowan, M., D. Andrews and V. Millot (2017), *The Walking Dead?: Zombie Firms and Productivity Performance in OECD Countries*, OECD Economics Department Working Papers, No. 1372, OECD Publishing, Paris. http://dx.doi.org/10.1787/180d80ad-en.

Aghion, P., and Howitt, P. (1992), 'A model of growth through creative destruction', *Econometrica*, 60(2), pp. 323–351.

Akgit, U. and S. T. Ates, (2021), 'Ten Facts on Declining Business Dynamism and Lessons from Endogenous Growth Theory', *American Economic Journal: Macroeconomics*, 13, pp. 257-298.

Andrews, D., and F. Petroulakis (2019), *Breaking the shackles: Zombie firms, weak banks and depressed restructuring in Europe*, Working Paper Series 2240, European Central Bank.

Andrews, D., M. Adalet McGowan and V. Millot (2017), *Confronting the zombies: Policies for productivity revival*, OECD Economic Policy Papers, No. 21, OECD Publishing, Paris, https://doi.org/10.1787/f14fd801-en.

Archanskaia L., Canton E., Hobza A., Nikolov P., Simons W. (2022), *The sectoral nature of the COVID-19 shock: a novel approach to quantifying its economic impact*, European Commission, Directorate-General for Economic and Financial Affairs (ECFIN), Discussion Paper, https://ec.europa.eu/info/publications/sectoral-nature-covid-19-shock-novel-approach-quantifying-its-economic-impact_en.

Autio, E. and Zhe Cao (2019), *Fostering Digital Start-ups: Structural Model of Entrepreneurial Ecosystems*, Proceedings of the 52nd Hawaii International Conference on System Sciences.

Autio, E., L. Szerb, E. Komlósi, and M. Tiszberger (2020), *EIDES 2020 - The European Index of Digital Entrepreneurship Systems*, Nepelski, D. (editor), EUR 30250 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-76-19444-6, doi:10.2760/150797, JRC120727.

Autor, D., D. Dorn, L. F. Katz, C. Patterson, and J. Van Reenen (2017), 'Concentrating on the Fall of the Labor Share', *American Economic Review*, 107(5), pp. 180-85.

Baden-Fuller, C. W. (1989), 'Exit from declining industries and the case of steel castings', *The Economic Journal*, 99(398), pp. 949-961.

Banerjee, R. and B. Hofmann (2018), *The rise of zombie firms: causes and consequences*, BIS Quarterly Review, September.

Baumol, W. J. (1993), *Entrepreneurship, management and the structure of payoffs*, London: MIT Press. https://doi.org/10.1080/08109029508629199.

Bijnens, G., & Konings, J. (2020), 'Declining business dynamism in Belgium', *Small Business Economics*, 54(4), pp. 1201-1239.

Blanchard, O, T Philippon and J Pisani-Ferry (2020), *A new policy toolkit is needed as countries exit COVID-19 lockdowns*, Policy Contribution 12/2020, Bruegel.

Bloom, N., C. I. Jones, J. Van Reenen, and M. Webb (2017), *Are Ideas Getting Harder to Find?*, National Bureau Economic Research Working Paper 23782.

Bosma, N., M. Sanders, and E. Stam (2018), 'Institutions, entrepreneurship, and economic growth in Europe', *Small Business Economics*, 51(2), pp. 483-499.

Boston Consulting Group (BCG) and Hello Tomorrow (2019), *The Dawn of the Deep Tech Ecosystem.*

Boston Consulting Group (BCG) and Hello tomorrow (2021), *Deep Tech: The Great Wave of Innovation.*

Boston Consulting Group (BCG) and Hello tomorrow (2021b), *The Deep Tech Investment Paradox: a call to redesign the investor model.*

Bravo-Biosca, A., C. Criscuolo, and C. Menon (2016), 'What drives the dynamics of business growth?', *Economic Policy*, 31(8), pp. 703–742, DOI: https://doi.org/10.1093/ epolic/eiw013.

Caballero, R. and M. L. Hammour (1996), 'On the Timing and Efficiency of Creative Destruction', *Quarterly Journal of Economics*, 111(3), pp. 805-852.

Caballero, R., T. Hoshi and A.K. Kashyap (2008), 'Zombie Lending and Depressed Restructuring in Japan', *American Economic Review*, 98(5), pp. 1943-1977.

Calvino, F., C. Criscuolo and R. Verlhac (2020), *Declining business dynamism: Structural and policy determinants*, OECD Science, Technology and Industry Policy Papers, No. 94, OECD Publishing, Paris, https://doi.org/10.1787/77b92072-en.

Casnici, C. V. C. (2021), *The Rise of Unicorn Companies: A Magical Growth?*, In The Palgrave Handbook of Corporate Sustainability in the Digital Era, pp. 581-593, Palgrave Macmillan, Cham.

Coad, A., Amaral-Garcia, S., Bauer, P., Domnick, C., Harasztosi, P., Pál, R. and Teruel M. (2022), *High-Growth Enterprises in times of COVID-19: an overview*, JRC Working Papers on Corporate R&D and Innovation No 01.

Coad, A., Amaral-Garcia, S., Bauer, P., Domnick, C., Harasztosi, P., Pál, R. and Teruel M. (2022b), *Investment expectations by vulnerable European firms in times of COVID: a difference-in-difference approach*, EIB Working Papers, No. 2022/04, ISBN 978-92-861-5235-1, European Investment Bank (EIB), Luxembourg, https://doi.org/10.2867/19683.

Content, J., N. Bosma, J. Jordaan and M. Sanders (2020), 'Entrepreneurial ecosystems, entrepreneurial activity and economic growth: new evidence from European regions', *Regional Studies*, 54(8), 1007-1019, DOI: 10.1080/00343404.2019.1680827.

Crane, L. D., R. A Decker, A. Flaaen, A. Hamins-Puertolas, and C. Kurz (2020), *Business Exit During the COVID-19 Pandemic: Non-Traditional Measures in Historical Context*, Finance and Economics Discussion Series 2020-089, Washington: Board of Governors of the Federal Reserve System.

Criscuolo, C., P. N. Gal, and C. Menon (2014), *The Dynamics of Employment Growth: New Evidence from 18 Countries*, OECD Science, Technology and Industry Policy Papers No. 14, OECD Publishing, Paris, https://doi.org/10.1787/5jz417hj6hg6-en.

Cros, M, A Epaulard and P Martin (2021), *Will Schumpeter Catch COVID-19?*, CEPR Discussion Paper 15834.

Crunchbase (2019), *Funding to Female Founders*, Funding-To-Female-Founders_Report.pdf (crunchbase.com).

Davis, Steven J. and John C. Haltiwanger (1992), 'Gross Job Creation, Gross Job Destruction and Employment Reallocation', *Quarterly Journal of Economics*, 107(3), pp. 819–63.

De Loecker, J. Eeckhout, and S. Mongey (2021), *Quantifying Market Power and Business Dynamism in the Macroeconomy*, NBER Working paper 28761.

De Loecker, J., J. Eeckhout, and G. Unger (2020), 'The Rise of Market Power and the Macroeconomic Implications', *Quarterly Journal of Economics*, 135, pp. 561–644.

Dealroom (2021), *2021: the year of Deep Tech*.

Decker, R. A., J C. Haltiwanger, R. S. Jarmin, and J. Miranda (2018), *Changing Business Dynamism and Productivity: Shocks vs. Responsiveness*, National Bureau Economic Research Working Paper 24236.

Decker, R. A., J C. Haltiwanger, R. S. Jarmin, and J. Miranda (2016), 'Declining Business Dynamism: What We Know and the Way Forward', *American Economic Review: Papers & Proceedings*, 106(5), pp. 203–07.

Digital Europe (2021), *Scaling in Europe Report*.

EIB (2019), *Investment Report 2019/2020*.

EIB (2020), *From starting to scaling: How to foster startup growth in Europe*.

European Scaleup Monitor (2021), *European scaleups got knocked down, but are up again*.

GEM (2021), *Global Entrepreneurship Monitor - Women's Entrepreneurship 2020/21 Thriving Through Crisis*, GEM Global Entrepreneurship Monitor (gemconsortium.org).

Gordon, R. J. (2016), *The Rise and Fall of American Growth: The U.S. Standard of Living since the Civil War,* Princeton University Press.

Hall, R. (1995), *Lost Jobs*, Brookings Papers on Economic Activity, 26(1), pp. 221–273.

Haltiwanger, J., I. Hathaway, and J. Miranda (2014), *Declining business dynamism in the US high-technology sector*, Ewing Marion Kauffman Foundation.

Haltiwanger, J., R. Decker, and R. Jarmin (2015), *Top ten signs of declining business dynamism and entrepreneurship* in the US, in: Kauffman Foundation New Entrepreneurial Growth Conference, Citeseer.

Haltiwanger, J., R. Jarmin, and J. Miranda (2013), 'Who Creates Jobs? Small versus Large versus Young', *The Review of Economics and Statistics*, 95(2), pp. 347–361.

Haltiwanger, J., S. Scarpetta, and H. Schweiger (2014), 'Cross Country Differences in Job Reallocation: The Role of Industry, Firm Size and Regulations', *Labour Economics*, 26, pp. 11–25.

Hopenhayn, H. A. (1992), 'Entry, exit, and firm dynamics in long run equilibrium', *Econometrica: Journal of the Econometric Society*, pp. 1127–1150.

Karahan, F., B. Pugsley, and A. Sahin (2016), *Demographic Origins of the Startup Deficit*, New York Fed, mimeo.

Mind the Bridge (2019), *Tech Scale ups EU*.

Muzi, S., F. Jolevski, K. Ueda, and D. Viganola (2021), *Productivity and Firm Exit during the COVID-19 Crisis Cross-Country Evidence*, World Bank, Policy Research Working Paper 9671.

Prieger, J. E., C. Bampoky, L. R. Blanco, and A. Liu (2016), 'Economic growth and the optimal level of entrepreneurship', *World Development*, 82, pp. 95–109. https://doi.org/10.1016/j. worlddev.2016.01.013.

Rose, N. L. (2020), *Will Competition Be Another COVID-19 Casualty? Policy Proposal 2020-13*, The Hamilton Project.

Startup Genome (2021), *The Global Startup Ecosystem Report 2021*.

Testa, G., Compano, R., Correia, A. and Rückert, E. (2022), *In search of EU unicorns -What do we know about them*, EUR 30978 EN, Publications Office of the European Union, Luxembourg, 2022, ISBN 978-92-76-47058-8, doi:10.2760/843368, JRC127712.

Wennekers, S., and R. Thurik (1999), 'Linking entrepreneurship and economic growth', *Small Business Economics*, 13(1), pp. 27–56. https://doi.org/10.1023/A:1008063200484.

CHAPTER
4.3

SKILLS IN THE DIGITAL ERA

KEY FIGURES

56 %
of the EU population has basic or above-basic digital skills

23 %
of EU enterprises have provided ICT training to their personnel

34 %
of online job postings in the EU mention communication, collaboration and creativity skills

20 %
increase in the share of high-skilled jobs in the EU from 2002 to 2020

12 %
decrease in the share of middle-skilled jobs in the EU from 2002 to 2020

KEY QUESTIONS WE ARE ADDRESSING

- How is technological change and digitalisation affecting the job market?
- What skills are required in the digital era?
- How does the European population perform in terms of digital skills?

KEY MESSAGES

What did we learn?

- Skill-biased technological change is driving structural changes in skills requirements in both the EU and the US. The share of highly skilled jobs has risen, that of middle-skilled jobs has diminished, and that of low-skilled jobs remained steady.
- In the digital era, the job market presents more jobs requiring non-routine, abstract, analytical and social skills. Skills in high demand are, in addition to technical and ICT skills, the ability to communicate, to work in teams, collaborate and be creative, and the capacity to work effectively with computers.
- In the EU, there is a strong heterogeneity of skills levels across countries, urban and rural areas, and age groups.

What does it mean for policy?

- Reskilling policies for low- and middle-skilled workers will be crucial for sustainable and inclusive economic growth.
- Lifelong learning activities will become increasingly important to keep workers' skills aligned with evolving job market demands and to support longer working lives.
- In the digital era, education and training policies should increase their emphasis on developing non-cognitive skills that complement digital skills, such as social intelligence, collaboration, creativity and adaptability.

1. Skills in a digital world and global trends

The digital transformation is changing the skills requested and rewarded by the labour market. Research confirms that some jobs are being displaced by automation and the nature and tasks of others is changing, while new jobs are emerging as the digital revolution unfolds (e.g. Acemoglu and Restrepo, 2019). To ensure an inclusive digital transition, it is important to understand what types of skills and tasks will be best rewarded in the digital economy, while at the same time identifying the distributional changes that the labour market may face, and which workers risk being displaced by technological change.

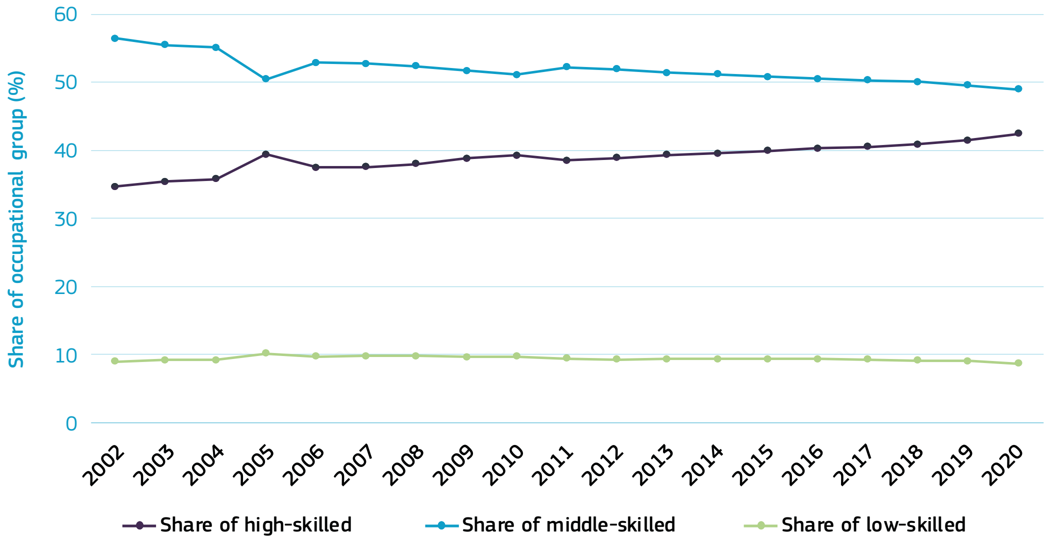
Technology is often described as substituting for less-skilled workers and complementing high-skilled workers, generating skill-biased shifts in labour demand. Technological change is rarely neutral towards the different production factors: it typically changes the proportions in which production factors such as capital, less-skilled labour and high-skilled labour are demanded. Many new technologies increase the complexity of tasks and jobs and therefore raise the skill requirements of jobs. If the increase in demand for higher-skilled individuals outpaces the growth in their supply through the education system, this may put upward pressure on the skills wage premium (Tinbergen, 1974, 1975). As a result, imbalances in the demand and supply of different groups of workers, exacerbated by technological change, can cause a rise in wage inequality[1]. So far, nevertheless, there is little evidence of a structural rise in wage inequality in Europe over the last two decades, possibly as a result of policies and other factors counteracting the rise in inequality[2].

In the EU and the US, the proportion of high-skilled occupations has increased, the proportion of middle-skilled occupations decreased, and the proportion of low-skilled occupations remained steady over the last two decades (see Figures 4-3-1 and 4-3-2). In the EU, the share of high-skilled occupations (out of total employment) increased by 7 percentage points between 2002 and 2020, growing from 35 % to 42 %, especially in market services. The share of low-skilled occupations remained steady at around 10 %. In contrast, the share of middle-skilled occupations plummeted by around 7 percentage points, from 56 % in 2002 to 49 % in 2020. Sector-wise, these job losses were particularly concentrated in agriculture and manufacturing (OECD, 2021). The US presents a similar picture, with the share of high-skilled occupations increasing by 4 percentage points from 2002 to 2020, the share or low-skilled occupations staying almost steady and the share of middle-skilled occupations decreasing by 5 percentage points.

1 See Katz and Murphy (1992), Card and Lemieux (1994), Acemoglu (1998), Autor, Katz and Krueger (1998), Chennells and Van Reenen (1998), Machin and Van Reenen (1998), Card and DiNardo (2002), Goldin and Katz (2010), Acemoglu and Restrepo (2020).

2 See e.g. Filauro and Fischer (2021) and Vandeplas (2021)

Figure 4.3-1: Structural changes in skills requirements[1] in the EU, 2002-2020



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit based on Eurostat data. Online data code: LFSA_EGISED

Note: [1]Following the International Labour Organization (ILO) (2007) methodology, high-skilled occupations include jobs classified under the ISCO-08 1-digit codes 1, 2 and 3. Middle-skilled occupations include jobs classified under the major groups 4, 5, 6, 7 and 8. Low-skilled occupations include jobs classified under group 9.

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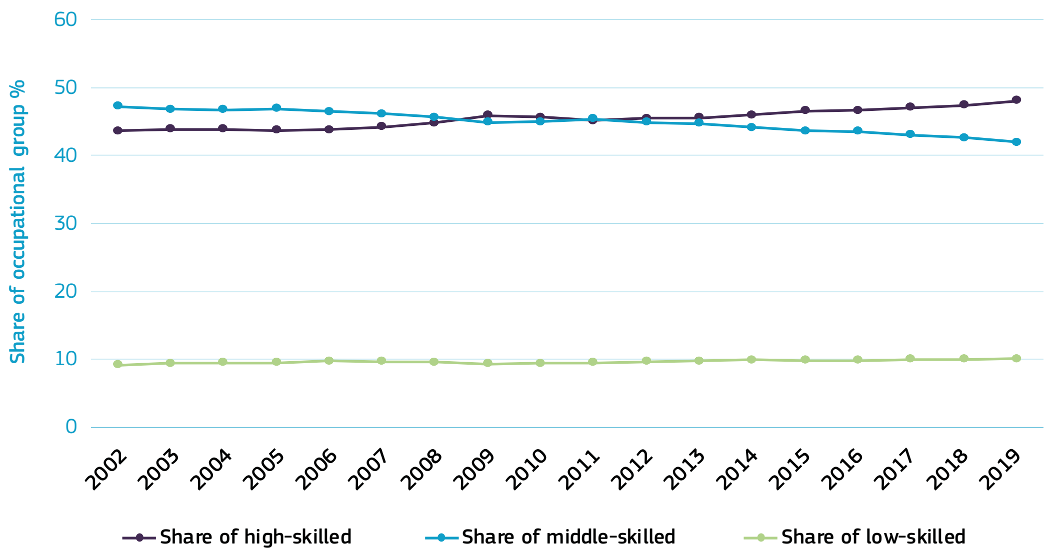
Figure 4.3-2: Structural changes in skills requirements[1] in the United States, 2002-2019



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation Common R&I Strategy and Foresight Service – Chief Economist Unit based on ILO data

Note: [1]High-skilled occupations include jobs classified under the ISCO-08 1-digit codes 1, 2 and 3. Middle-skilled occupations include jobs classified under the major groups 4, 5, 7 and 8. Low-skilled occupations include jobs classified under group 9. In the ILO-USA classification, ISCO code 6 is not presented separately but is merged with ISCO code 9. Data refer to the US.

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A major driver of these observations, as proposed by the literature, has been routine-biased technical change. A commonly used classification of job tasks discerns three major types of tasks:

- *Non-routine abstract tasks*. Activities that require problem solving, intuition, persuasion and creativity. Such tasks are complementary to digital technologies and are mostly performed in professional and managerial jobs.
- *Non-routine manual tasks*. Activities that require situational adaptability, in-person interaction, yet few formal education requirements. Such tasks are harder to automatise; a non-exhaustive list of them may be food preparation and serving, cleaning and janitorial work, maintenance, security and driving.
- *Routine tasks*. Activities that can be easily codified into a series of instructions to be executed by a machine.

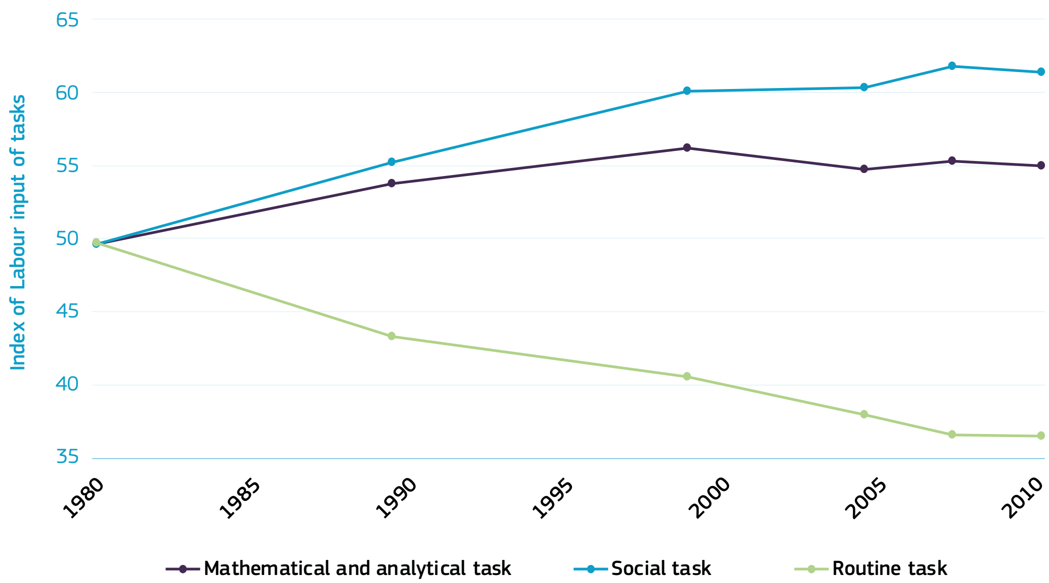
Routine-based tasks that take place in structured environments and require little social interaction are more likely to be automated (or outsourced) (Acemoglu and Autor, 2011; Acemoglu, 2012; Autor, 2015). Acemoglu and Autor (2011) hypothesise that non-routine abstract tasks most often require skills at the high end of the skills distribution, that non-routine manual tasks are usually situated at the low end of the skills distribution, and that routine tasks are characteristic of many middle-skilled jobs, such as clerical and production jobs. Empirical studies nevertheless suggest that the routine content of jobs is highest in occupations in ISCO 1-digit categories 8 (plant and machine operators) and 9 (elementary occupations), in other words the occupations with the lowest skill requirements (see e.g. Marcolin et al., 2019; Cirillo et al., 2021). Work by Graetz and Michaels (2018) also suggests that low-skilled workers are more likely to be displaced by automation than middle- and high-skilled workers. The routine task content and hence the risk of automation is lowest for high-skilled occupations, and these have seen the strongest expansion over the last two decades. Interestingly, even though occupation structures are de-routinising, the task content within jobs may not follow the same trend. Indeed, Bisello et al. (2019) found that (in the EU) jobs with more social-task content are expanding relative to the rest, but that this is in contrast with a decline in the number of social tasks people actually do in those (and other) jobs. Freeman et al. (2020) find that (in the US) social skills go up on aggregate, and that most of this is due to internal changes. Automation has been found to raise labour productivity, raise total factor productivity (TFP) and lower output prices, while redistributing labour away from lower-skilled to higher-skilled workers (Graetz and Michaels, 2018).

These observations highlight the fact that technological change does not happen in a vacuum. As Fernández-Macías and Hurley (2017) argue, economic factors (e.g. business cycle-related developments), policy decisions and institutional variables (e.g. wage-setting systems) have contributed to dynamics in skills demand over recent decades. Oesch and Piccitto (2019) also point to the large impact of wage-setting institutions and trends in skills supply (through changes in educational attainment and migration) on changes in skills demand. Acemoglu and Restrepo (2022) argue that changes in labour supply are driving automation and therefore skills demand. Notably, they found that automation and robot adoption has been particularly widespread in industries most affected by a scarcity of manual workers as a result of demographic ageing.

Non-cognitive skills are increasingly important in the digital economy, as tasks requiring social skills are less easily performed by technology (Morandini et al., 2020). Deming (2017) and Deming and Kahn (2017) find a growing complementarity between cognitive skills and social skills in the labour market, including in STEM jobs. US-based data suggest that when jobs are decomposed into the skills they require, with a distinction between non-routine analytical tasks, social skills, routine skills and high/low maths-intensive skills, routine tasks are on a declining trend, while non-routine analytical and social tasks are on an increasing trend (see Figure 4.3-3).

Adaptability is also set to be a major determinant of worker resilience. Cedefop's European skills and jobs survey (ESJS) in 2014 surveyed about 49 000 adult employees in the European Union, revealing that around 43% of EU employees experienced a recent change in the technologies they use at work, and that 26% thought that their skills would be outdated by 2019 (Cedefop, 2018). The ESJS also underlined that skills requirements are swiftly evolving in highly skilled jobs such as ICT, health, business and engineering related occupations. Even if these are less likely to see displacement by technology, continued participation in adult learning to update skills will also be key for workers in these occupations.

Figure 4.3-3: Task polarisation in the United States, 1980-2012



Science, Research and Innovation Performance of the EU 2022

Source: Deming (2017), Replication data for 'The Growing Importance of Social Skills in the Labor Market' on Harvard Dataverse

Note: The index of labour input of tasks is constructed using O*NET task measures and a method developed by Autor, Levy and Murnane (2003).

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-4-3-3.xlsx

The growing importance of non-cognitive skills is also underlined by recent OECD work identifying which skills are most in demand. The OECD analysis identifies shortages and surpluses for specific types of knowledge, skills and abilities[3] by combining information on employment and wage dynamics by occupation from 2004 to 2013/14 with information on the skills requirements within that occupation (OECD, 2017). The analysis of skills needs suggests that abstract reasoning and soft skills (e.g. active listening, active learning, critical thinking, judgment and decision making) are in high demand in the EU as well as in the US, while manual and routine skills (e.g. operation and control, equipment maintenance, repairing and monitoring) seem to be in surplus already (see Figure 4.3-4). Based on the OECD analysis, shortages of qualified/skilled personnel seem more pressing for the EU than for the US. In the knowledge domain, not surprisingly, IT comes out as a domain in high demand, as do education and psychology, while demand for mechanics and building and construction seems to have declined. In the abilities domain, verbal, reasoning and quantitative abilities are most in demand, while endurance, physical strength and balance/coordination have become less important.

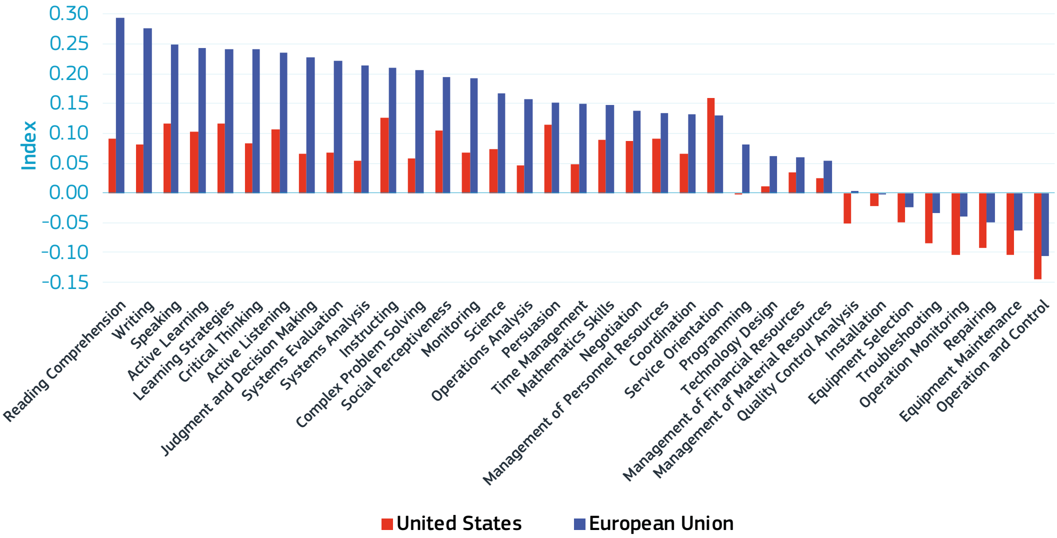
In the aftermath of the COVID-19 pandemic, skills shortages in the EU are at an all-time high and risk creating a drag on recovery. According to the European Business and Consumer Survey, more companies than ever report in 2022 that their growth or investment is held back by labour shortages. In the European Investment Bank's most recent Group Survey on Investment and Investment Finance (EIBIS survey), a lack of skills is the barrier to investment most often reported by firms (EIB 2021). In particular, 79 % of firms in Europe report being held back by the scarcity of workers with the right skills. The figure is higher for more innovative firms, digital and climate-focused firms and SMEs. Through the Network of Eurofound Correspondents, labour shortages in sectors linked to the transition to a climate-neutral economy have been reported for 15 Member States (Eurofound 2021). The percentage of enterprises with hard-to-fill vacancies for ICT specialists has been steadily increasing, from 3 % of all enterprises in 2012 to 5 % in 2021, or from 40 % of enterprises that tried to recruit ICT specialists in 2012 to 55 % in 2020[4]. The ManpowerGroup Talent Shortage survey also finds that talent shortages are more pressing than ever, with 69 % of employers reporting difficulties in filling vacancies in 2021, as compared to 58 % in 2019[5]. Shortages are more frequently reported by firms in the EU than in the US and China according to the ManpowerGroup survey. This aligns with findings by Anderson and Wolff (2020), who highlight a more serious shortage of artificial-intelligence skills in the EU when compared to the US and China. They argue that the European Union produces fewer master's and PhD graduates in computer science and artificial intelligence and that it struggles to transform theoretical research into applied research that produces algorithms ready for practical commercial use.

3 While abilities are defined as 'enduring individual attributes that influence performance at work', skills are 'developed capacities that facilitate learning and performance', which include, inter alia, basic and transversal skills. Knowledge types relate to general work domains, such as business, engineering, psychology and so on.

4 Cf. ESTAT's survey on ICT use in enterprises, variable code ISOC_SKE_ITRCRN2

5 ManpowerGroup Talent Shortage survey

Figure 4.3-4: Need for skills in the EU and United States, 2015



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Source: OECD Skills for Jobs database

Note: Positive values indicate skill shortage while negative values point to skill surplus. The larger the absolute value, the larger the imbalance.

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Skills shortages can negatively affect labour productivity by constraining investment and slowing down the process of innovation and diffusion of new technologies (Vandeplas et al., 2019). Studies confirm that company investment in employee training has a positive impact on productivity. The impact on productivity is generally larger in magnitude than the impact on wages[6]. Individuals nevertheless stand to gain significantly from having better skills as it improves employability prospects and access to quality jobs.

For Europe at large, persistent skills shortages come at economic and social costs (Brunello and Wruuck, 2019). The incidence of labour shortages was already on the rise before the pandemic. This was also because of demographic trends: the working-age population has been shrinking all over the EU. The pandemic has exacerbated these shortages at least transitorily as it hampered education and training activities and had different impacts across sectors, and thus influenced the sectoral composition of labour demand.

6 See Konings and Vanormelingen (2015) for a study using Belgian data; Colombo and Stanca (2014) for a study using Italian data; Dearden et al. (2006) for a study using UK data; and Almeida and Carneiro (2009) and Martins (2021) for two studies using Portuguese data.

Sectors with a high proportion of non-essential contact-intensive jobs saw a stronger contraction in demand, while sectors with a high proportion of teleworkable jobs were considerably more resilient. The pandemic is also likely to have temporarily reduced the responsiveness of the labour supply to sectoral changes in demand through policy support measures and by imposing barriers to inward mobility and migration.

Policy can help mitigate skills shortages through adequate investment in education and training by strengthening skills intelligence, making labour markets more inclusive and facilitating migration. Higher skills levels and a stronger capacity to adapt to changing labour market conditions are crucial to equip workers to successfully navigate the digital transition and to ensure inclusive growth going forward. Preparing a highly skilled workforce, without leaving anyone behind, requires adequate and efficient investment in education and training from an early age and throughout life. As the duration of working lives is expanding while the pace of change in the labour market appears to be accelerating, high quality initial education is a precondition but not sufficient to equip workers adequately for the labour market: providing sufficient up- and reskilling opportunities to workers to update their skills and flexibly move into expanding sectors is key (Gratton and Scott, 2016). Education and training programmes and policies should be kept up-to-date by strengthening skills intelligence and gathering insights on emerging labour market needs in close collaboration with stakeholders, not least employers. Labour markets that are more inclusive can draw on a broader labour supply and a wider variety of skills. Facilitating migration already helps to address skills shortages in the short run.

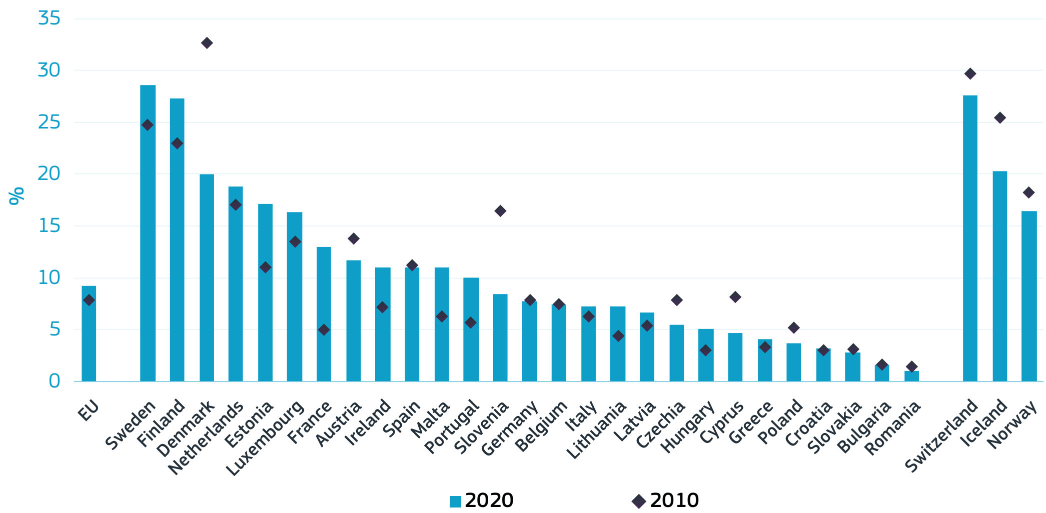
At the EU level, several initiatives have already been taken to address skills shortages, and more are underway. In 2020, the Commission proposed a renewed Skills Agenda, with 12 actions set to expand opportunities for people to train, especially in view of the green and digital transition. The agenda aims to catalyse investment in adult learning by public and private entities[7]. It highlights the need for collective action, mobilising all stakeholders to work together, identify skills needs and invest in the development of skills, including through the Pact for Skills. It interlinks with other policy initiatives such as the European Education Area, which promotes innovative and inclusive education at all levels, and the European Research Area, which promotes upskilling and reskilling, especially in academia. The Digital Europe programme invests particularly in the development of advanced digital skills. More recently, the revised EU Blue Card Directive aims to facilitate attracting high-skilled migrants to the EU. The Commission proposal on individual learning accounts proposes to provide each individual, independent of their working status, with a training entitlement and to reinforce the institutions that enable people to undertake training. The proposal on micro-credentials proposes a European approach to certification of upskilling and reskilling experiences and to support cross-border recognition. The Commission also recently proposed a European strategy for universities to strengthen the EU dimension of higher education and research and to empower universities as key actors of change in the green and digital transition. The Commission proposal on learning for environmental sustainability recommends that Member States support educators to also use new tools and materials to teach for environmental sustainability, including in digital settings.

7 https://ec.europa.eu/social/BlobServlet?docId=22832&langId=en

Adult participation in training increased across most EU countries over 2010-2019, but slid back in 2020. On average, the proportion of adults aged 25-64 participating in learning rose from 8% in 2010 to 11% in 2019, but deteriorated to 9% in 2020 (see Figure 4.3-5). The pandemic is likely to be the main culprit, as training and learning activities were severely hampered by social distancing measures and widespread school closures. In 2020, Sweden topped the EU ranking with 29% of its adult population having engaged in learning in the four weeks preceding the survey, closely followed by Finland and Denmark. Slovakia, Bulgaria and Romania show the lowest figures, with only 1% of the adult population in Romania having engaged in learning activities.

Given the shift toward a digital and learning economy, stronger engagement in lifelong learning would make the workforce more resilient and ready for transformational change. Pronounced cross-country differences in engagement in continuous learning risk exacerbating existing cross-country disparities. Furthermore, even within countries, adults with lower levels of education and skills engage less actively with adult learning activities (OECD, 2019). A key reason for this participation gap is that adults with low skill levels find it more difficult to identify their learning needs and hence are less likely to seek out training opportunities (Windisch, 2015). Participation rates also vary along the spatial dimension: while the participation rate in cities in the EU

Figure 4.3-5: Adult participation in learning[(1)], 2010 and 2020



Source: Eurostat (online data code: SDG_04_60)

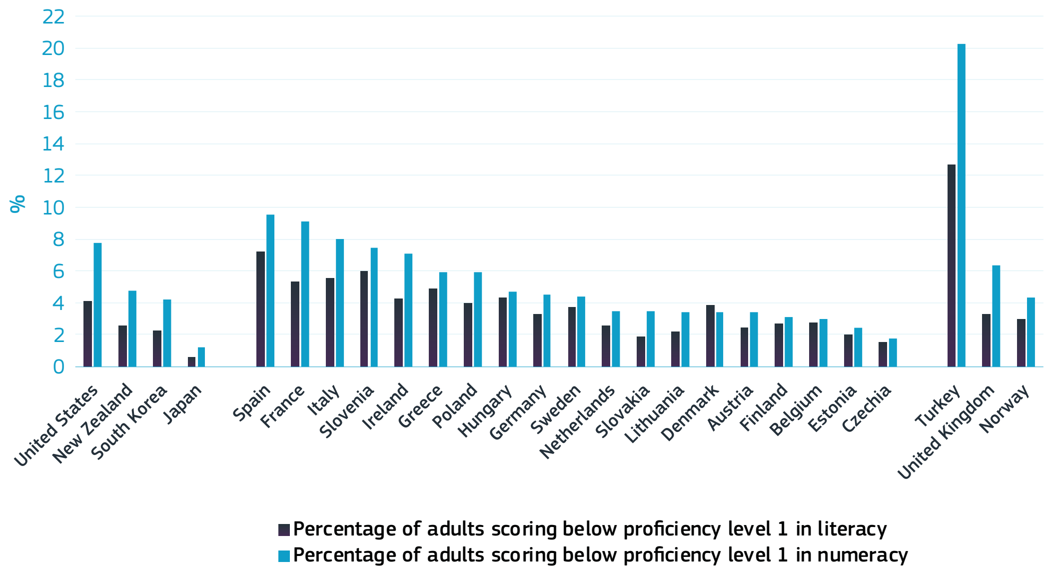
Note: [(1)]Share of people aged 25 to 64 who stated that they received formal or non-formal education and training in the four weeks preceding the survey

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-4-3-5.xlsx

was 11.5 % in 2020, it dropped to 8 % in towns and suburbs, and to 7 % in rural areas. Skill-biased technological change risks widening existing spatial inequalities. Therefore, policies that address disparities, and provide additional support to vulnerable regions and individuals through investments in infrastructure, local economic development and skills development, are necessary to ensure inclusive growth and avoid a deterioration in social tensions, political divide and unrest.

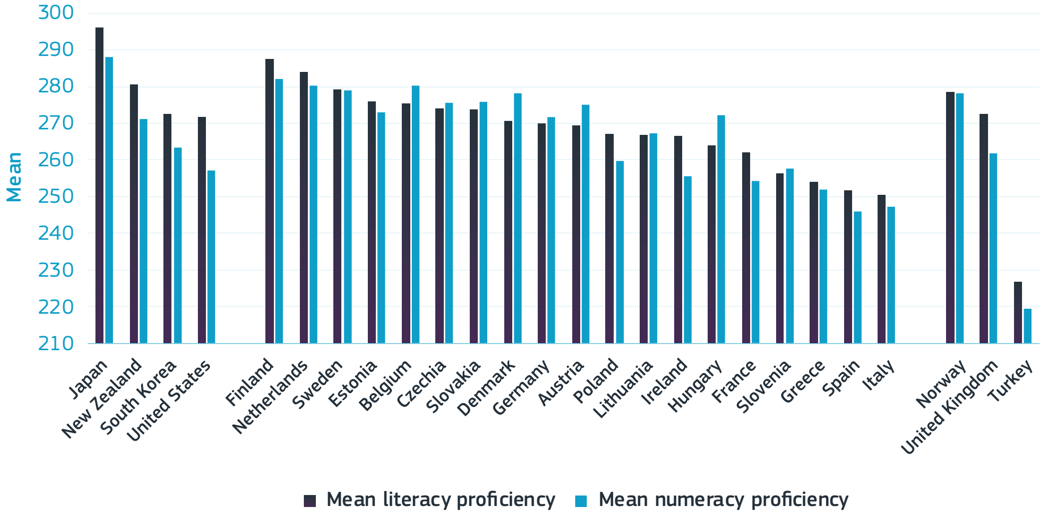
Ensuring a strong foundation of basic and transversal skills for all, while leaving no one behind, is key to enabling adults to engage in up- and re-skilling later in life. These foundational skills (such as literacy and numeracy) are acquired in initial education and training and are indispensable to further learning. Between 2011 and 2017, the OECD surveyed adults aged 15-65 in nearly 40 countries around the world and tested their foundational skills (literacy, numeracy and problem-solving) (Survey of Adult Skills, Programme for the International Assessment of Adult Competencies - PIAAC). Japan is the best-performing country, with only around 1 % of adults having very low literacy and numeracy skills (around 1 % for both). Spain is the EU Member State with the worst performance, having around 10 % of adults with a very low numeracy level, and 7 % of adults with very low literacy performance (see Figure 4.3-6). A similar picture is obtained for average adult population scores on literacy and numeracy. In almost all countries, the level of numerical proficiency is lower than the level of literacy proficiency. Japan and Finland obtain the highest scores, while Turkey and Italy the lowest (see Figure 4.3-7). The UK and the US score above most EU countries in the centre or south, yet below northern European countries.

Figure 4.3-6: Share of adults with very low literacy and numeracy skills, 2011-2015



Source: Survey of Adult Skills (PIAAC), wave1-3 (2011-2015)
Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-4-3-6.xlsx

Figure 4.3-7: Average literacy and numeracy proficiency of adult population, 2011-2015

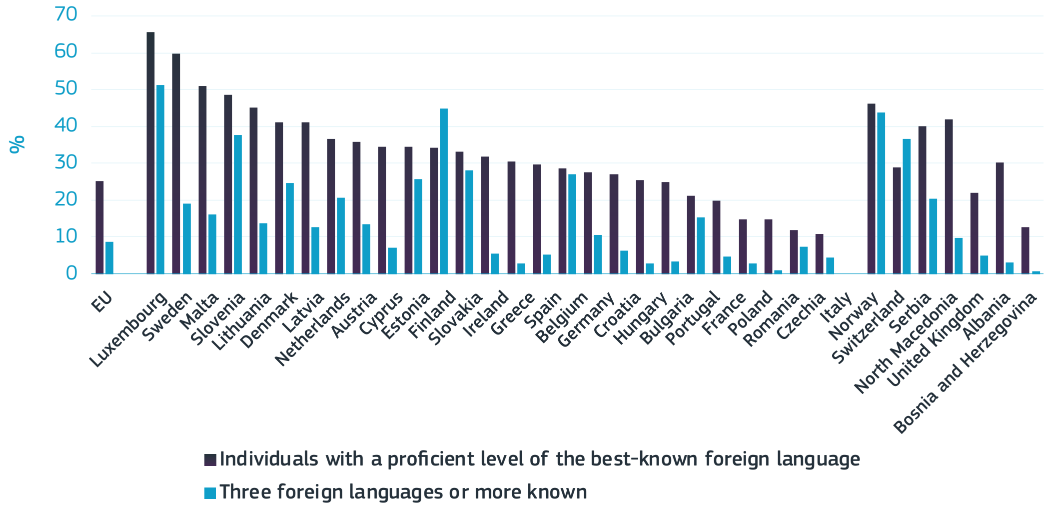


Source: Survey of Adult Skills (PIAAC), wave1-3 (2011-2015)
Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-4-3-7.xlsx

In 2016, on average, 9% of EU individuals knew more than three foreign languages, while 25% define themselves as 'proficient'[8] in the foreign language that they know best (see Figure 4.3-8). Italy, Czechia, Romania and Poland are the countries with fewer individuals speaking at a proficient level their best-known foreign language. In Italy, only 11% of individuals speak proficiently their best-known foreign language, and 12% in Czechia and 15% in Romania. Luxemburg and Sweden are the nations with the highest proportion of individuals fluent in a foreign language. The countries that have the highest percentage of the population speaking more than three foreign languages are Luxemburg, Finland and Norway.

8 Proficient' was the highest level in the list (better than 'good' or 'basic' knowledge) and defined as 'I can understand a wide range of demanding texts and use the language flexibly. I master the language almost completely.'

Figure 4.3-8: Share of individuals with foreign language skills, 2016



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Source: Eurostat. Percentage of individuals (age group 25-64) self-reporting knowing three or more foreign languages in 2016. Online data code: EDAT_AES_L21. Percentage of individuals self-reporting their best-known foreign language to be at a proficient level of knowledge. Online data code: EDAT_AES_L31

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2. Digital skills supply in Europe

In an increasingly digitalised world, digital skills are key to allowing people to take part in the labour market, the economy and society more broadly. On average, only 56 % of the EU population aged 16 to 74 had at least a basic level of digital skills in 2019 (see Figure 4.3-9), up from 54 % in 2015. Skills levels vary across gender, age, qualification level and employment status[9]: among women, 54 % have at least basic skills, versus 58 % of men. Among young people (aged 25-34), 74 % have at least basic skills, versus only 24 % for older individuals (aged 65-74) (see Figure 4.3-10).

Among people with low qualifications, only 32 % have at least basic digital skills, as compared to 54 % with medium qualifications and up to 84 % with tertiary qualifications. Among unemployed people, only 44 % have at least basic digital skills.

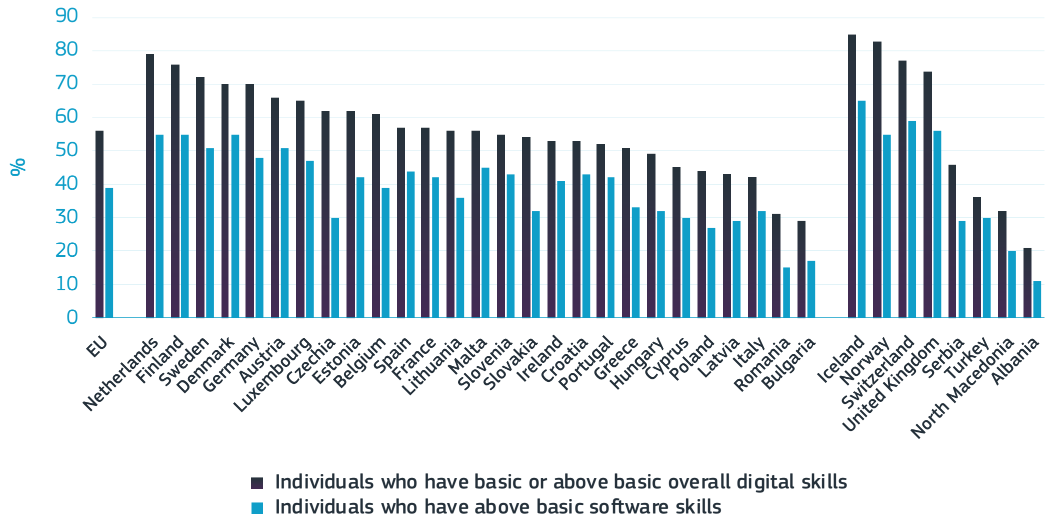
What are digital skills?

The EU digital competence framework 2.2 (DigComp 2.2) distinguishes five areas:

- information and data literacy (e.g. using a search engine and storing information and data);
- communication and collaboration (including teleconferencing and application sharing);
- digital content creation (such as producing text and tables, and multimedia content);
- safety (e.g. using a password and encrypting files, but also being aware of the social and environmental impact of digital technologies);
- problem solving (e.g. finding IT assistance and using software tools to solve problems).
- More details are available in Vuorikari et al. (2022).

9 See ESTAT variable isoc_sk_dskl_i

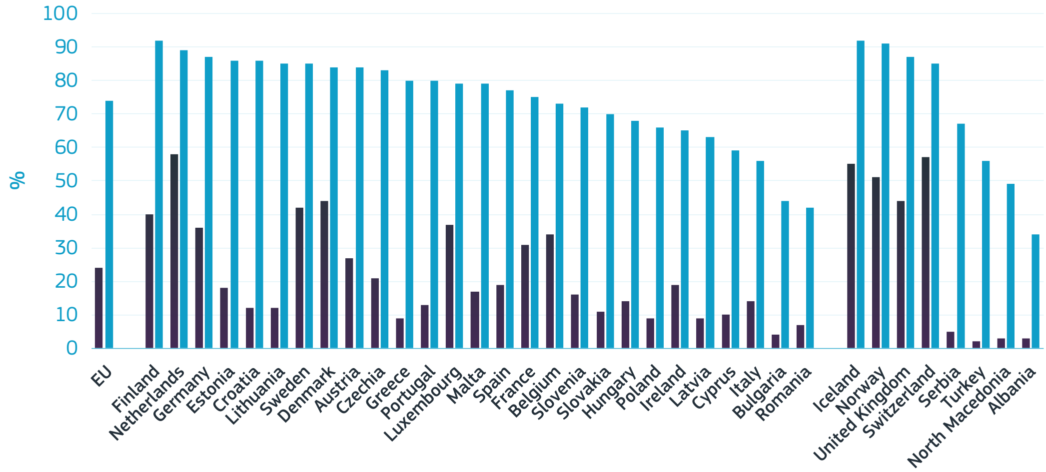
Figure 4.3-9: Share of Individuals with digital skills, 2019



Source: Eurostat (online data code: ISOC_SK_DSKL_I)
Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-4-3-9.xlsx

Northern European countries top the ranking with very high levels of overall digital literacy and software programming skills. In 2019, the proportion of adults with at least basic digital skills ranged from 79% in the Netherlands to 29% in Bulgaria (Figure 4.3-9). Even for young people, the difference remains wide: in the Netherlands, 89% of people aged 25-34 have at least basic digital skills as compared to 44% in Bulgaria (Figure 4.3-10). Furthermore, Dutch individuals in the 65-74 age group have better digital literacy than individuals in the 25-34 age group in Romania, Bulgaria and Italy.

Figure 4.3-10: Individuals who have basic or above-basic overall digital skills by age group (2019)



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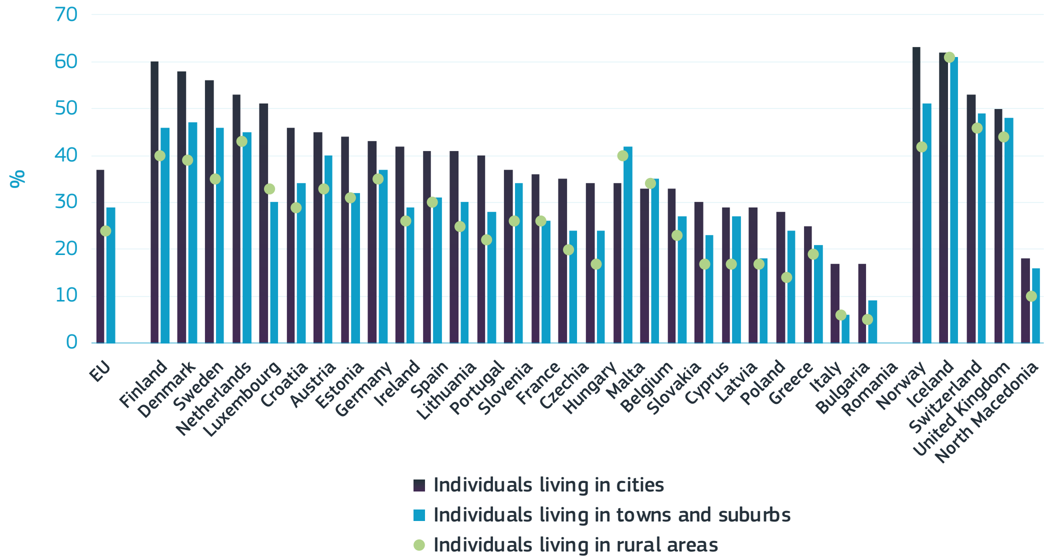
Source: Eurostat (online data code: ISOC_SK_DSKL_I)
Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-4-3-10.xlsx

Individuals living in cities have higher digital literacy than those living in towns, suburbs and rural areas (see Figure 4.3-11). Among individuals living in cities in the EU, 37 % hold above-basic digital skills. The proportion is lower for individuals living in towns and suburbs (29 %) and for individuals living in rural areas (24 %). In some countries, such as Bulgaria and Romania, rural-urban gaps are particularly accentuated, while in other countries, gaps are much smaller. In Belgium, people in rural areas are better equipped with digital skills than people in urban areas. As already mentioned above, these spatial inequalities should be addressed by policymakers to promote inclusive growth and social resilience.

Figure 4.3-11: Share of individuals who have above-basic overall digital skills by urban group, 2019



Science, Research and Innovation Performance of the EU 2022

Source: Eurostat (online data code: ISOC_SK_DSKL_I)
Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-4-3-11.xlsx

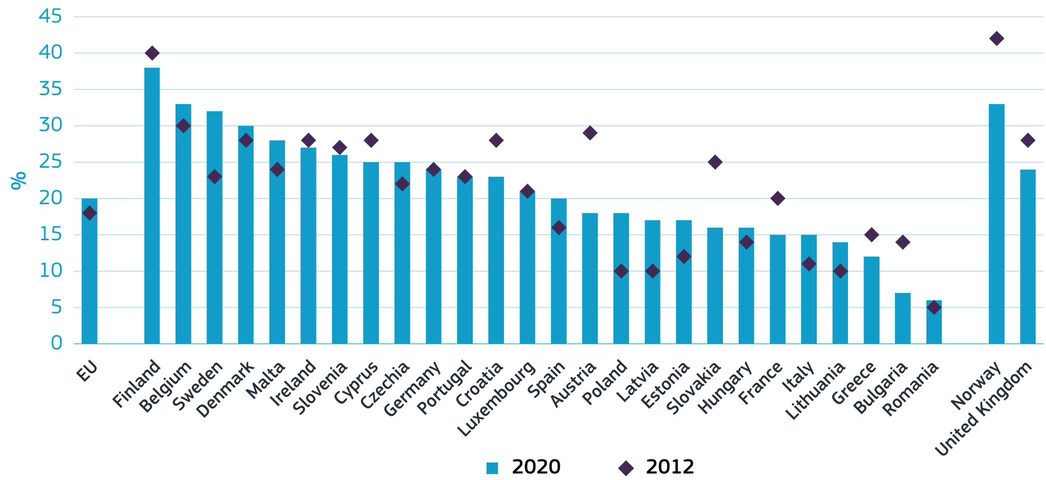
The diffusion of digital technologies drives transformation in the world of work and contributes to the transition towards climate and environmental objectives. New types of jobs are emerging, and routine-based jobs are disappearing. Importantly, digital skills are not employed in ICT sectors only, but are increasingly required in different occupations, and all citizens need at least basic digital skills to participate in society (Carretero et al., 2017). Digital technologies can also be leveraged to drive forward the green transition, for instance to digitalise energy systems, realise sustainable-mobility solutions in urban and rural settings and promote participatory approaches to involving people in shaping the green transition.

Given the rising importance of digital skills in the work environment, more and more firms are training their personnel in ICT skills. Between 2012 and 2019, the percentage of EU firms that provided ICT training to their employees increased by 5 percentage points, growing from 18% to 23%, equivalent to a growth rate of 28 % (see Figure 4.3-12). The country that most trained its workers among the surveyed countries is Norway, with around 44 % of enterprises providing ICT training, followed by Finland, Belgium, Austria and the UK. The country that engaged the least in training provision was Romania with only 6 % of enterprises upgrading workers' ICT skills.

The European Commission has undertaken substantial efforts to support firms and individuals to tackle digital skills gaps. For instance, the Digital Skills and Jobs Coalition was launched by the European Commission in 2016 in tandem with Member States, employers, training providers and other organisations with a view to strengthening digital skills through a multi-stakeholder partnership. As part of the 2020 SME strategy, the European Commission launched a digital volunteers programme, through which skilled mentors from leading companies offer their expertise for the digital transformation of EU SMEs. It has also announced it will roll out digital crash courses for SME employees to become proficient in areas such as AI, cybersecurity or blockchain. Further initiatives are spelled out in the European Commission's Digital Education Action Plan and the Digital Europe programme.

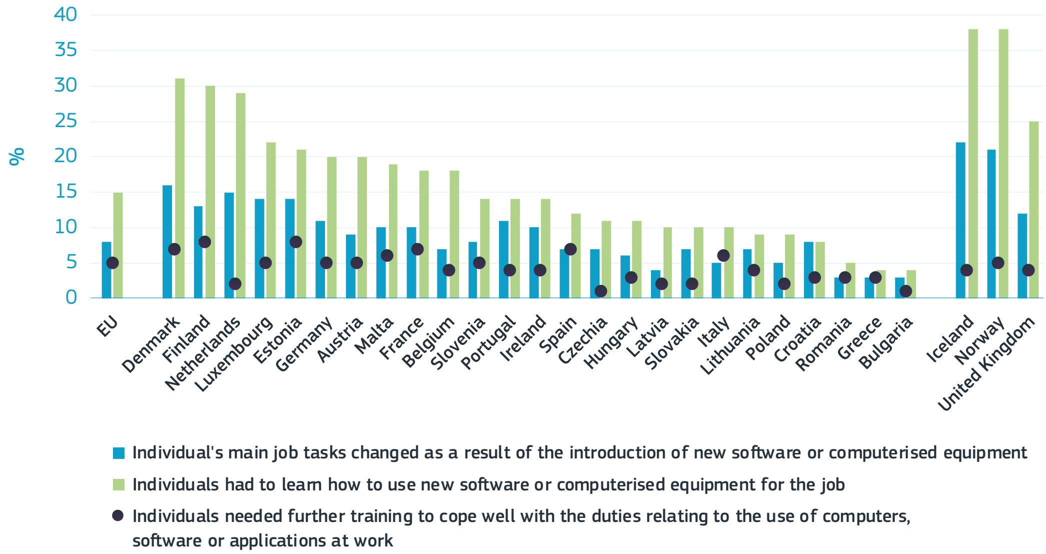
The rise of ICT has not only required workers to reskill, but also changed the tasks performed and number of individuals engaging with computers and software. In the EU, 8 % of individuals reported the content of their job changing because of new software or computer equipment (see Figure 4.3-13). This statistic is very high in countries such as Iceland (22 %), Norway (21 %), the Netherlands (15 %), Denmark (16 %) and Finland (13 %), while very low in countries such as Romania (3 %), Bulgaria (3 %) and Greece (3 %).

Figure 4.3-12: Share of enterprises that provided training to develop/upgrade ICT skills of their personnel, 2012 and 2020



Source: Eurostat (online data code: ISOC_SKE_ITTN2)
Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-4-3-12.xlsx

Figure 4.3-13: Individuals who had their skills impacted by ICT, 2019



Science, Research and Innovation Performance of the EU 2022

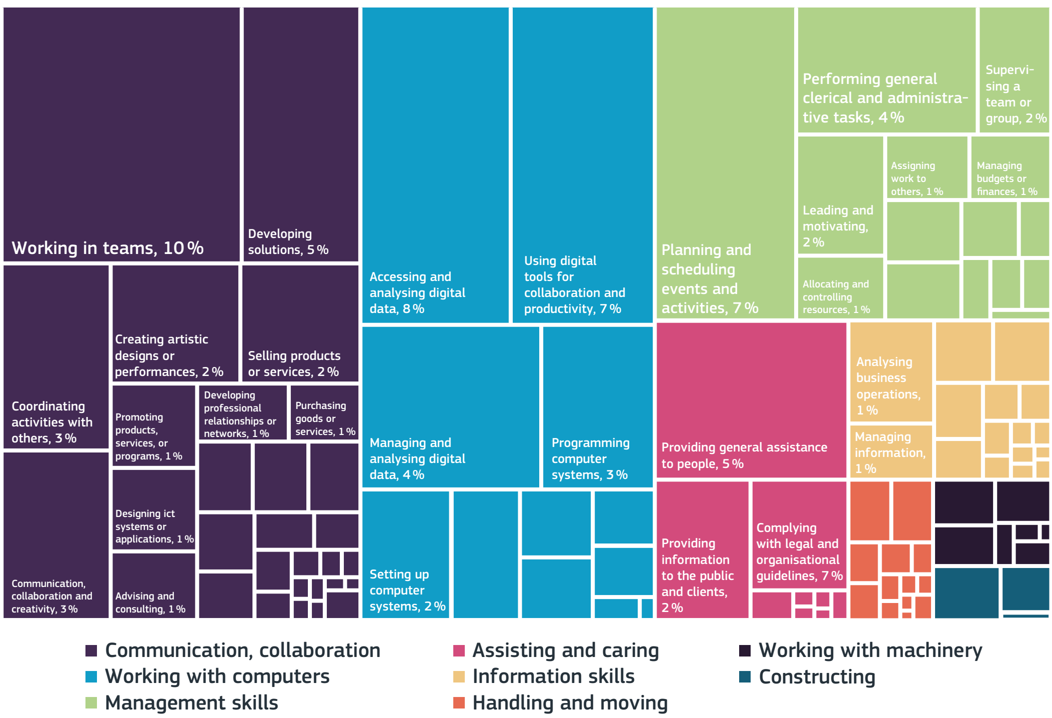
Source: Eurostat (online data code: ISOC_IW_IMP)

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-4-3-13.xlsx

3. Skills demand in Europe

Analysis by Cedefop suggests that social and digital skills, combined with managerial and analytical competences are among the most frequently requested in online job vacancies in the EU. Cedefop collected millions of online job advertisements in EU countries from thousands of sources, including private job portals, public employment service portals, recruitment agencies, online newspapers and corporate websites over Q3 2020-Q2 2021. The collected data were analysed in terms of their references to specific types of skills, knowledge, attitudes and work values, and language-related skills[10]. While around 45 % of online job posts referred to relevant skills and 36 % to requirements in terms of specific competences or knowledge, only 13 % referred to desirable attitudes and work values and 6 % to language-related skills.

Figure 4.3-14: **Percentage of skills type total mention in the EU, Q3 2020-Q2 2021**



Source: Cedefop, Skills-OVATE

Note: The image represents the share of total mentions of skills (skills ranking) in millions of online job advertisements in EU countries, collected from thousands of sources, including private job portals, public employment service portals, recruitment agencies, online newspapers and corporate websites.

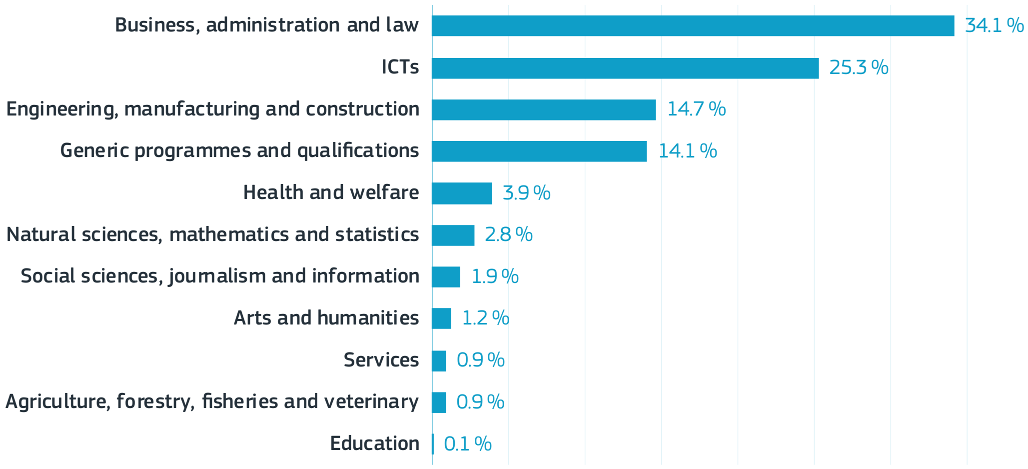
Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-4-3-14.xlsx

10 Online job advertisements tend to relatively over-represent white-collar (mostly professional) occupations and their attendant skills, compared to manual ones, in terms of occupational structure.

The most requested transversal skills are on the one hand, the abilities to communicate, work in teams, collaborate and being creative, and on the other hand, the capacity to work effectively with computers. Around 34 % of online jobs posted in the EU (from 2020 to 2021) mention communication, collaboration and creativity skills, 28 % mention computer skills and 20 % mention management skills (see Figure 4.3-14). Such trends are in line with our above-mentioned findings on structural changes in skills requirements triggered by the digital transformation: the diffusion of digital and automation technologies increases demand not only for digital skills but also for complementary abstract thinking and social skills. The least requested skills are constructing (0.98 %), working with machinery (1.55 %) and handling and moving (1.8 %).

The most requested knowledge domains are business, law and ICT, closely followed by engineering. Around 34% of online job posted in the EU from 2020 to 2021 mention business, administration and law, 25 % mention ICT competences and 15% mention engineering, manufacturing and construction knowledge (see Figure 4.3-15). A relatively high proportion of vacancies (14%) include only generic qualification requirements. The high demand for ICT-related knowledge suggests that ICT skills are not required exclusively in the science and technology sector, but are required across the entire economy.

Figure 4.3-15: **Percentage of knowledge type total mention (EU)**



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Source: Cedefop, Skills-OVATE
Note: The image represents the share of total mentions of knowledge (knowledge ranking) in millions of online job advertisements in EU countries, collected from thousands of sources, including private job portals, public employment service portals, recruitment agencies, online newspapers and corporate websites. Period: Q3 2020-Q2 2021
Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-4-3-15.xlsx

4. Conclusions: skills, labour market and technological change

Digitalisation is affecting the task content of jobs and as a result the skills sought and rewarded in the labour market. Routine tasks have been in decline, while tasks requiring abstract thinking and social skills have expanded. Skills endowments are becoming increasingly linked to stable and high-quality employment outcomes. This risks widening disparities between workers with low and high skills endowments. To ensure an inclusive digital transition, policymakers will need to step up investment in digital skills and infrastructure, particularly for vulnerable workers and regions. Adequate investments should be made in education and skills from an early age, but also, very importantly, for adults. The lengthening of working lives in today's knowledge economy requires a paradigm shift in which individuals dedicate themselves to long-life learning.

In the digital economy, technical and digital skills increasingly need to be complemented by social and communication skills and the capacity to adapt to changing circumstances. Formal and non-formal education and training programmes should cater to digital era needs by considering the complementarities between technical and social skills. The stronger the foundation skills that individuals have, the easier they will find it to upskill and reskill and to adjust to changing circumstances in the labour market.

Digital skills are key for individuals and for employers alike, to support high-quality labour market outcomes and sustainable and inclusive growth, as well as citizens' effective inclusion in a participative and democratic modern society. Nevertheless, skills gaps persist. Employers around the world report that their investments are being hampered by shortages of skilled labour. The demand for ICT specialists has become ever more pressing. But even when it comes to very basic digital skills, skills gaps persist: 44 % of EU adults were found to have not even the most basic digital skills. Unfortunately, countries with the largest skills gaps are typically also the countries with the lowest adult participation in learning. This is likely to perpetuate and exacerbate existing disparities and risks worsening social cohesion in the EU. Policymakers need to step up efforts to address these gaps, with extensive support from the EU, and to tackle observed disparities across age groups, countries and regions to successfully construct a resilient, competitive and fair European society.

References

Acemoglu, D. (1998), 'Why do new technologies complement skills? Directed technical change and wage inequality', *The Quarterly Journal of Economics*, 113(4), pp. 1055-1089.

Acemoglu, D. (2012), 'What does human capital do? A review of Goldin and Katz's The race between education and technology', *Journal of Economic Literature*, 50(2), pp. 426-63.

Acemoglu, D., & Autor, D. (2011), Skills, tasks and technologies: Implications for employment and earnings. In *Handbook of labor economics* (Vol. 4, pp. 1043-1171), Elsevier.

Acemoglu, D., & Restrepo, P. (2019), 'Automation and new tasks: how technology displaces and reinstates labour', *Journal of Economic Perspectives*, 33(2): pp. 3-30.

Acemoglu, D., & Restrepo, P. (2020), 'Unpacking skill bias: Automation and new tasks', In *AEA Papers and Proceedings* (Vol. 110, pp. 356-61).

Acemoglu, D., & Restrepo, P. (2022), 'Demographics and automation', The *Review of Economic Studies*, 89(1): pp. 1–44, https://doi.org/10.1093/restud/rdab031.

Almeida, R., Carneiro, P. (2009), 'The return to firm investments in human capital', *Labour Economics*, 16(1): pp. 97-106.

Anderson, J., Viry, P., & Wolff, G. B. (2020), 'Europe has an artificial-intelligence skills shortage', Bruegel-Blogs.

Autor, D. H., Katz, L. F., & Krueger, A. B. (1998), 'Computing inequality: have computers changed the labor market?', *The Quarterly journal of economics*, 113(4), pp. 1169-1213.

Autor, D. H., Levy, F., & Murnane, R. J. (2003), 'The skill content of recent technological change: An empirical exploration', *The Quarterly Journal of Economics,* 118(4), pp. 1279-1333.

Autor, D.H (2015), 'Why are there still so many jobs? The history and future of workplace automation', *Journal of Economic Perspectives*, 29(3), pp. 3-30.

Bisello, M., Peruffo, E., Fernández-Macías, E., & Rinaldi, R. (2019), *How computerisation is transforming jobs: Evidence from the Eurofound's European Working Conditions Survey* (No. 2019/02). JRC Working Papers Series on Labour, Education and Technology.

Brunello, G., & Wruuck, P. (2019), *Skill shortages and skill mismatch in Europe: a review of the literature*, (No. 12346). IZA Discussion Paper.

Card, D., & DiNardo, J. E. (2002), 'Skill-biased technological change and rising wage inequality: Some problems and puzzles', *Journal of Labor Economics*, 20(4), pp. 733-783.

Card, D., & Lemieux, T. (1994), 'Changing wage structure and black-white wage differentials', *The American Economic Review*, 84(2), pp. 29-33.

Carretero, S., Vuorikari, R., & Punie, Y. (2017), 'The digital competence framework for citizens', *Publications Office of the European Union.*

Cedefop. (2018), *Insights into skill shortages and skill mismatch: Learning from Cedefop's European skills and jobs survey.*

Chennells, L., & Reenen, J. V. (1998), 'Establishment level earnings, technology and the growth of inequality: evidence from Britain', *Economics of Innovation and new technology*, 5(2-4), pp. 139-164.

Cirillo, V., Evangelista, R., Guarascio, D. & Sostero, M., (2021), 'Digitalization, routineness and employment: An exploration on Italian task-based data'. *Research Policy*, 50(7), p.104079.

Colombo, E., & Stanca, L. (2014), 'The impact of training on productivity: evidence from a panel of Italian firms', *International Journal of Manpower*, 35(8): pp. 1140-1158.

Dearden, L., Reed, H., Van Reenen, J. (2006), 'The impact of training on productivity and wages: evidence from British panel data', *Oxford Bulletin of Economics and Statistics*, 68(4): pp. 397-421.

Deming, D. J. (2017), 'The growing importance of social skills in the labor market', *The Quarterly Journal of Economics*, 132(4), 1593-1640.

Deming, D., & Kahn, L. B. (2017), Firm *heterogeneity in skill demands*. National Bureau of Economic Research.

EIB (2021), *EIB Investment Report 2021/2022*. European Investment Bank, Luxembourg.

Eurofound (2021), *Tackling labour shortages in EU Member States*, Publications Office of the European Union, Luxembourg.

Fernández-Macías, E., & Hurley, J. (2017), 'Routine-biased technical change and job polarization in Europe', *Socio-Economic Review*, 15(3), pp. 563-585.

Filauro, S., Fischer, G. (2021), *Income inequality in the EU: General trends and policy implications*, VoxEU, 17 April 2021, https://voxeu.org/article/income-inequality-eu-trends-and-policy-implications.

Freeman, R. B., Ganguli, I., & Handel, M. J. (2020, May), 'Within-occupation changes dominate changes in what workers do: A shift-share decomposition', 2005–2015. In *AEA Papers and Proceedings* (Vol. 110, pp. 394-99).

Goldin, C., & Katz, L. F. (2010), *The race between education and technology*. Harvard university press.

Graetz, G., Michaels, G. (2018), 'Robots at work', *The Review of Economics and Statistics*, 100(5): pp. 753-768.

Gratton, L., & Scott, A. J. (2016), *The 100-year life: Living and working in an age of longevity*. Bloomsbury Publishing.

Katz, L. F., & Murphy, K. M. (1992), 'Changes in relative wages, 1963–1987: supply and demand factors', *The quarterly journal of economics*, 107(1), pp. 35-78.

Konings, J., Vanormelingen, S. (2015), 'The impact of training on productivity and wages: firm-level evidence', *The Review of Economics and Statistics*, 97(2), pp. 485-497.

Machin, S., & Van Reenen, J. (1998), 'Technology and changes in skill structure: evidence from seven OECD countries', *The Quarterly Journal of Economics*, 113(4), pp. 1215-1244.

Marcolin, L., Miroudot, S. and Squicciarini, M. (2019), 'To be (routine) or not to be (routine), that is the question: a cross-country task-based answer', *Industrial and Corporate Change*, 28(3), pp. 477-501.

Martins, P. (2021), 'Employee training and firm performance: evidence from ESF grant applications', *Labour Economics*, 72: 102056. https://doi.org/10.1016/j.labeco.2021.102056.

Morandini, M., Thum-Thysen, A., & Vandeplas, A. (2020), *Facing the digital transformation: are digital skills enough?,* No 054. Directorate General Economic and Financial Affairs (DG ECFIN), European Commission.

OECD (2017), *Getting skills right: Skills for Jobs indicators*. OECD Publishing, Paris.

OECD (2019), *Getting Skills Right: Future-Ready Adult Learning Systems*, Getting Skills Right, OECD Publishing, Paris, https://doi.org/10.1787/9789264311756-en.

OECD (2021), *What happened to jobs at high risk of automation?* Policy Brief on the Future of Work, January 2021. https://www.oecd.org/future-of-work/reports-and-data/what-happened-to-jobs-at-high-risk-of-automation-2021.pdf.

Oesch, D., & Piccitto, G. (2019), 'The polarization myth: Occupational upgrading in Germany, Spain, Sweden, and the UK, 1992–2015', *Work and Occupations*, 46(4), pp. 441-469.

Tinbergen, J. (1974), 'Substitution of graduate by other labour', Kyklos: international review for social sciences.

Tinbergen, J. (1975), *Income Differences: recent research. Books (Jan Tinbergen)*. North-Holland Publishing Company, Amsterdam.

Vandeplas, A., & Thum-Thysen, A. (2019), *Skills mismatch & productivity in the EU*, European Economy Discussion Paper 100. Directorate General Economic and Financial Affairs (DG ECFIN), European Commission. doi:10.2765/954687.

Vandeplas, A. (2021) Education, income, and inequality in the European Union. In: Fischer, G., Strauss, R. (eds.) *Europe's Income, Wealth, Consumption, and Inequality*, Oxford University Press.

Vuorikari, R., Kluzer, S., Punie, Y. (2022) DigComp 2.2: *The Digital Competence Framework for Citizens. With new examples of knowledge, skills, and attitudes*. EUR 31006 EN, Publications Office of the European Union, Luxembourg, 2022, ISBN 978-92-76-48882-8, doi:10.2760/115376, JRC128415.

Windisch, H. (2015), *Adults with low literacy and numeracy skills: A literature review on policy intervention*, OECD Education Working Papers, No. 123, OECD Publishing, Paris, https://doi.org/10.1787/5jrxnjdd3r5k-en.

CHAPTER 5

INVESTMENT: THE CRITICAL ROLE OF INTANGIBLES

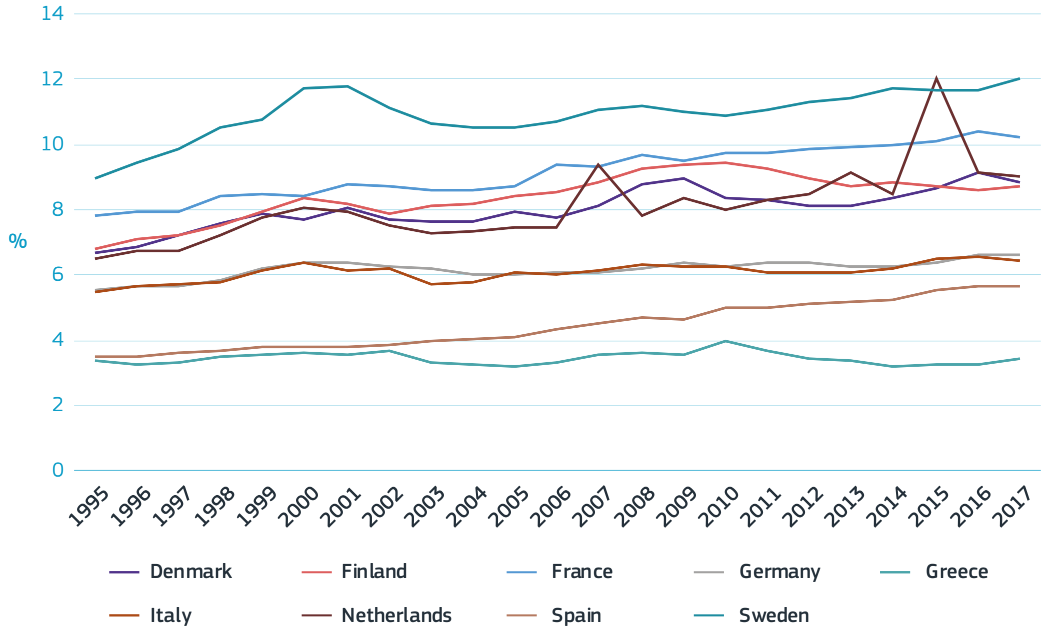
CHAPTER
5.1

INTRODUCTION: TANGIBLE AND INTANGIBLES ASSETS

The processes of production commonly require a combination of different inputs such as machines and buildings, computer hardware and software, and data and workers with digital skills. Such inputs can be classified in different ways, such as 'capital' and 'labour', as well as 'tangible' and 'intangible' assets. Investments in one asset are likely to effect the effectiveness of others, creating a complex network of complementarities and optimal mixes of strategic investments. As an example, hiring highly skilled IT workers is not very effective without the necessary investment in software and IT infrastructure.

Over the past 25 years, the investment mix has shifted towards intangible assets and the COVID-19 pandemic appears to have accelerated this shift toward a dematerialised economy (Haskel and Westlake 2017; Roth 2019, Thum-Thysen 2019). Over the last decades different Member States increased their investments in intangibles (as a share of GDP), yet there is wide heterogeneity across countries (see Figure 5.1). In 2020, the EU share of investment on software, data and IT activities has been 15% of the total investments, training of employees has been 10%, R&D has been 8% (see Figure 5.2). Yet, investments in machinery and equipment still represent a large part of the overall investment planning, with 48%, yet their typology and quantity are increasingly linked to the intangible assets of companies.

Figure 5.1-1: Investments in intangible assets (% of GDP[1]), 1995-2017



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit own elaboration.

Note: [1]data on intangible assets expressed in current prices, million units of national currency, are taken from the INTAN-Invest database. Data on GDP from Eurostat (online data code: NAMA_10_GDP) expressed in current prices, million units of national currency.

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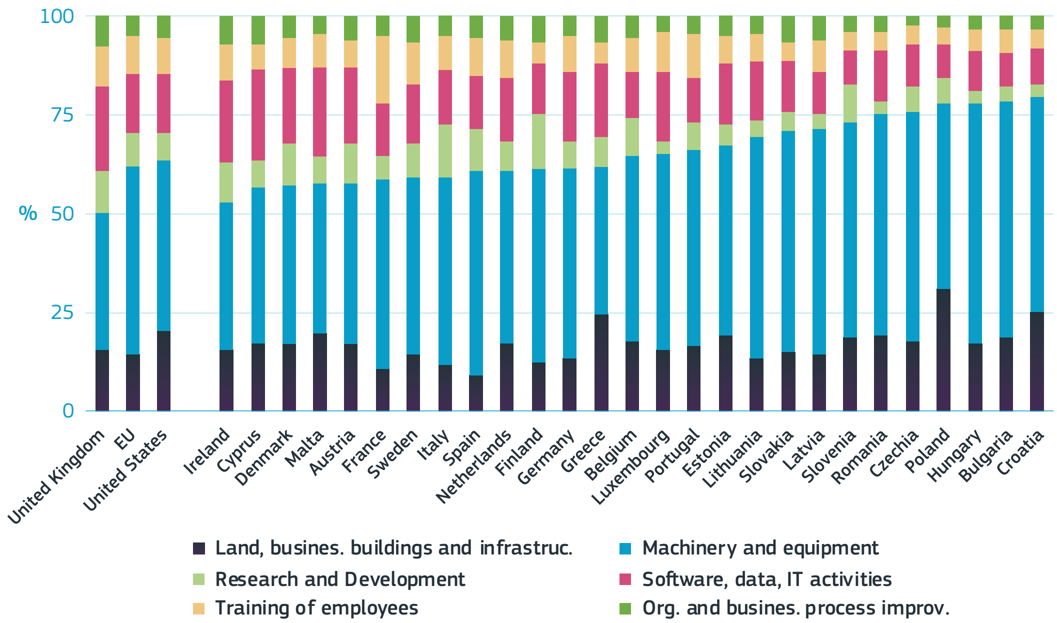
Figure 5.1-2: Average share of investment in different asset types across countries



Science, Research and Innovation Performance of the EU 2022

Source: EIB Investment Survey 2021

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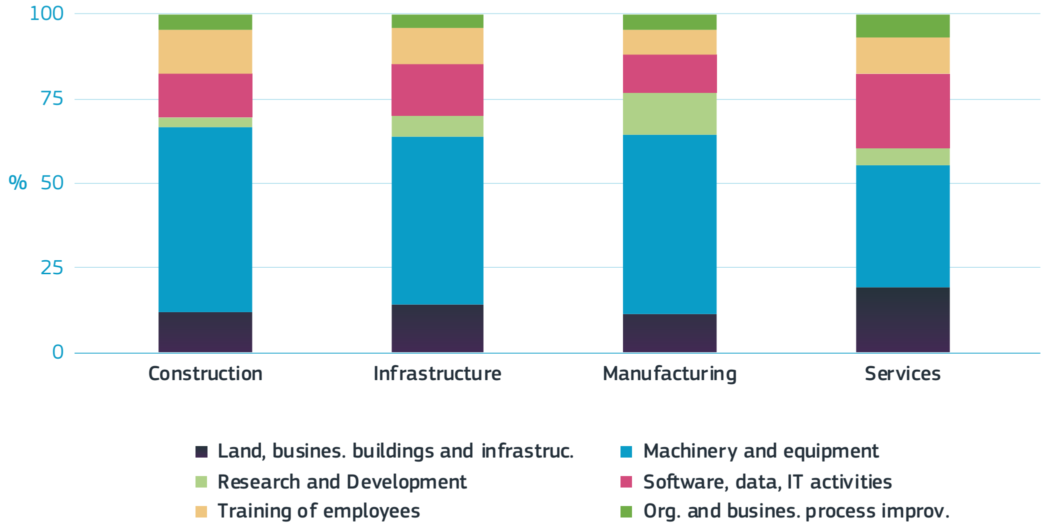
Figure 5.1-3: Average share of investment in different asset types across sectors in the EU



Science, Research and Innovation Performance of the EU 2022

Source: EIB Investment Survey 2021
Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-1-3.xlsx

The use of tangible and intangible assets vary both across countries and across sectors. Countries that invest more (as share of the total) on intangible are Ireland, Cyprus, Denmark and Malta, while countries that spend less are Croatia, Bulgaria, Hungary and Poland. At a sectoral level, the service sector has the highest share of spending on intangibles, with the share of investment in software, data and IT services (22 %), almost doubling the spending on software by other sectors (see Figure 5.3).

Both tangible and intangible assets positively affect firms' productivity and innovative potential. In the EU, software investments contribute to 19 % of productivity growth, followed by economic competencies[1] (16 %) and innovative property[2] (8 %). Total Factor Productivity contributes to 47 % and tangible capital to 10 % of productivity growth (see Chapter 4.1 for more). Furthermore, the returns from investments in tangible and intangible are not unrelated from each other. Complementary between tangible and intangible assets play a relevant role in explaining productivity (Radhakrishnan 2017, Thum-Thysen et al. 2021), competitive advantages and innovations (Stieglitz and Heine 2007). Human capital, in particular, is necessary for firms to capture the productivity enhancing properties of new technologies (see Chapter 5.4 for more).

Regardless of the sectors, companies that invest more in intangibles grow more. Leading firms (companies in the top quartile for growth in gross value added, a measure of economic growth) invest much more in intangibles than low growers, companies in the bottom quartiles[3]. Such a pro-

1 Advertisement, market research and branding, vocational training and organisational capita
2 Research and development and design and other product developments
3 Getting tangible about intangibles: The future of growth and productivity? | McKinsey

ductivity divide is profoundly linked with the relationship between the tangible and intangible assets of the digital economy, with only top-performer companies having the ability to afford the initial non-trivial adjustment costs, organisational changes, new skills and infrastructures required to purposely succeed in the dematerialisation of the economy.

Drivers and barriers to investing in intangible and tangible are different. The regulatory framework seems to be more relevant for investments in intangibles while financial conditions and, in particular, the availability of external funding, appears to be more important for investments in tangibles. In turn, investment in intangibles is funded more from internal resources, which makes such investments arguably less dependent on bank lending rates. In addition, investment in human capital emerges as important for fostering investment in intangible assets, pointing to the need for well-integrated education systems targeting early as well as lifelong learning (Thum-Thysen 2019). Such elements may justify policy interventions, such as higher spending on the education system, R&D public investment and subsidies to firms aimed at stimulating investment in intangible assets and the creation of a knowledge-based economy.

References

Haskel, J. and Westlake, S. (2017), *Capitalism without Capital: The Rise of the Intangible Economy*, Princeton University Press, Princeton, NJ.

Radhakrishnan, S., Wang, H., Wang, K., & Zhu, Z. J. (2017), *R&D Investment and Firm Growth: The Role of Tangible Asset Complementarit*y, Available at SSRN 3096806.

Roth, F. (2019), *Intangible capital and labour productivity growth: A review of the literature*, Hamburg Discussion Papers in International Economics No. 4.

Thum-Thysen, A., Voigt, P., Bilbao-Osorio, B., Maier, C., & Ognyanova, D. (2019), 'Investment dynamics in Europe: Distinct drivers and barriers for investing in intangible versus tangible assets?', *Structural Change and Economic Dynamics*, 51, pp. 77-88.

Thum-Thysen, A., Voigt, P., & Weiss, C. (2021), *Reflections on Complementarities in Capital Formation and Production: Tangible and Intangible Assets across Europe* (No. 152), Directorate General Economic and Financial Affairs (DG ECFIN), European Commission.

CHAPTER
5.2

INVESTMENT IN R&D

KEY FIGURES

2.3 %
of GDP was invested in R&D in the EU in 2020

6 out of 10 euros
invested by governments in R&D was in the form of tax reliefs in the EU in 2019

7
Member States have reached their national 2020 R&D investment targets

€205 bn
was invested in R&D by the business sector in the EU in 2020

€2.73 bn
was invested in public R&D in energy efficiency, renewables, hydrogen and fuel cells, power and storage in the EU in 2020

KEY QUESTIONS WE ARE ADDRESSING

- What is the state of R&D investments and their evolution in Europe, in the Member States and compared to other international players?
- What are the key drivers, sectors and components of R&D investments in Europe?
- What are the main policy tools to support R&D in Europe?

KEY MESSAGES

What did we learn?

- R&D intensity stood at 2.3% of GDP in the EU in 2020. The EU accounts for almost 20 % of global R&D expenditure, though its share is on a declining trend.
- R&D intensity increased over 2000-2019 in 24 Member States, but significant heterogeneity persists across EU countries.
- Against the backdrop of the COVID-19 pandemic, R&D business investments in the EU decreased from EUR 208 billion in 2019 to EUR 205 billion in 2020. Due to a sharp decline in GDP, this translated into a small increase in R&D intensity to 2.32% of GDP in 2020.
- R&D tax support doubled over the past decade to reach 58% of total government support for R&D in 2019.
- The European Commission's R&I funding programmes (including Horizon 2020) were responsible for 7.2% of public funding for R&D in the EU in 2019.

What does it mean for policy?

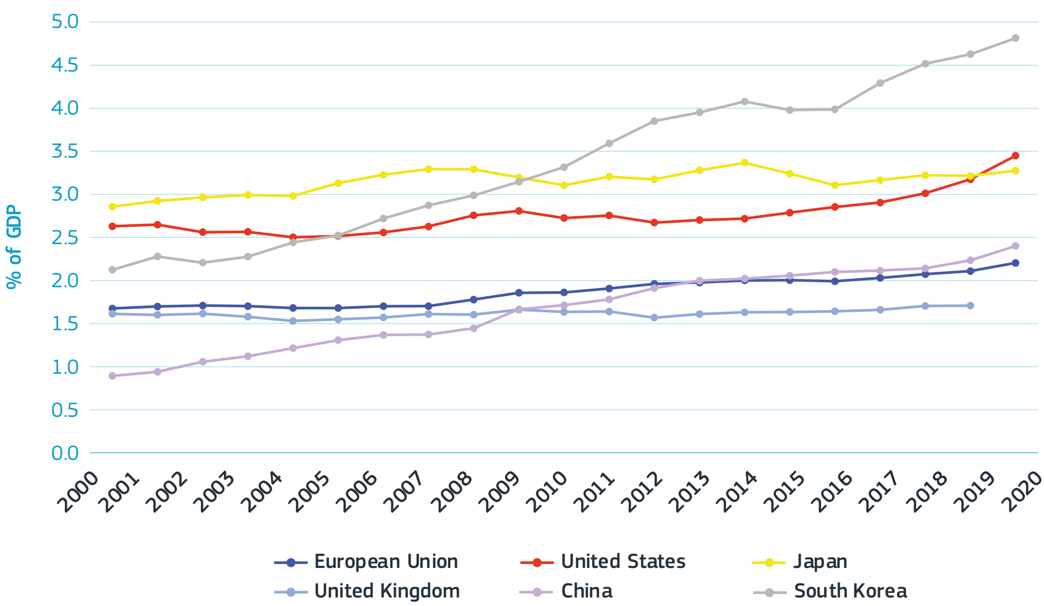
- The EU needs a transformative R&I policy to pursue the green and digital transitions and to enhance resilience against future crises. Such a policy requires directionality in national and EU investments to facilitate and coordinate the alignment of R&I investments with EU priorities.
- This coordinated reform and modernisation effort could aim to improve the effectiveness and efficiency of R&I investments as well as to leverage private investments.
- The revitalised ERA agenda under the New ERA for Research and Innovation includes a set of ambitious political objectives and R&D investment targets. The timeline and intensity of such investments as well as structural reforms of R&I systems could be adapted to the national context and national specificities. This also calls for enhanced national strategies ensuring timely delivery of those key objectives.
- Green innovation policies complement net-zero policies.

1. R&D investments in Europe: state of play

Europe has intensified its R&D investments over the past two decades, but there remains a gap in terms of R&D intensity compared to some of its main competitors. Figure 5.2-2 highlights that the EU R&D intensity increased from 1.81% of GDP to 2.32% of GDP over 2000-2020, but in 2020 still below the US (3,45%), Japan (3,27%), and South Korea (4,81%). China experienced steady growth, reaching the EU level in 2020 (2.32%).

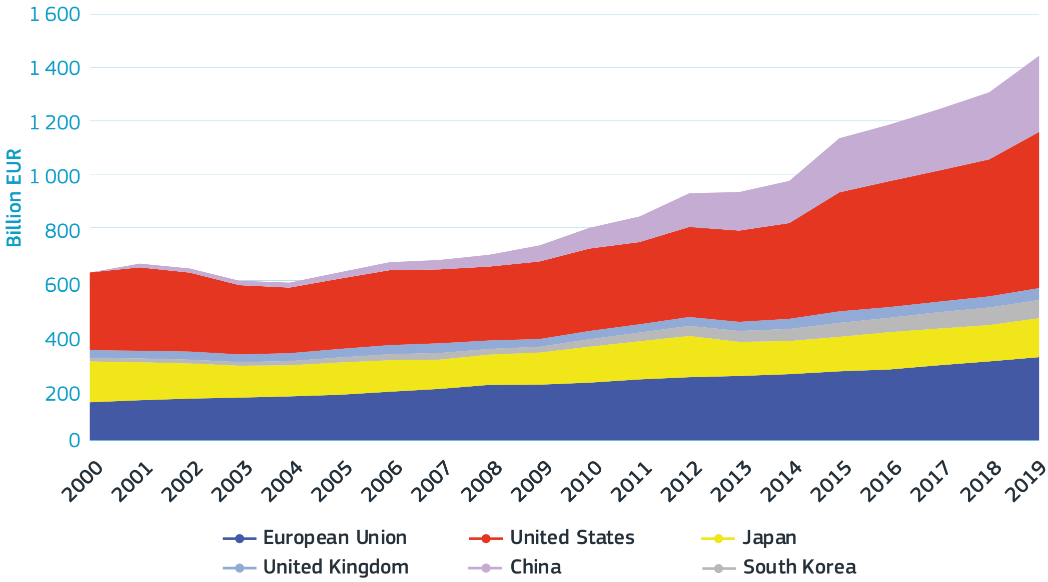
The scientific and technological divide between the more advanced Member States and the rest (i.e. central European and southern countries) is largely the result of lower public R&D investment and of how this funding is allocated. R&D spending is highly concentrated in the EU. In 2020, only three Member States were responsible for 50% of total R&D investments in the EU, and eight for 85% (Figure 5.2-3). The distribution is, however, more dispersed across the EU than a decade ago (the same first three Member States had a share of 61% in 2010). Several Member States have increased their share in EU-wide R&D spending over 2010-2020, but there is still a clear divide between these leading countries and the rest of the EU.

Figure 5.2-1: R&D intensity (R&D expenditure as % of GDP), 2000 - 2020



Source: OECD (Main Science and Technology Indicators)
Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-2-1.xlsx

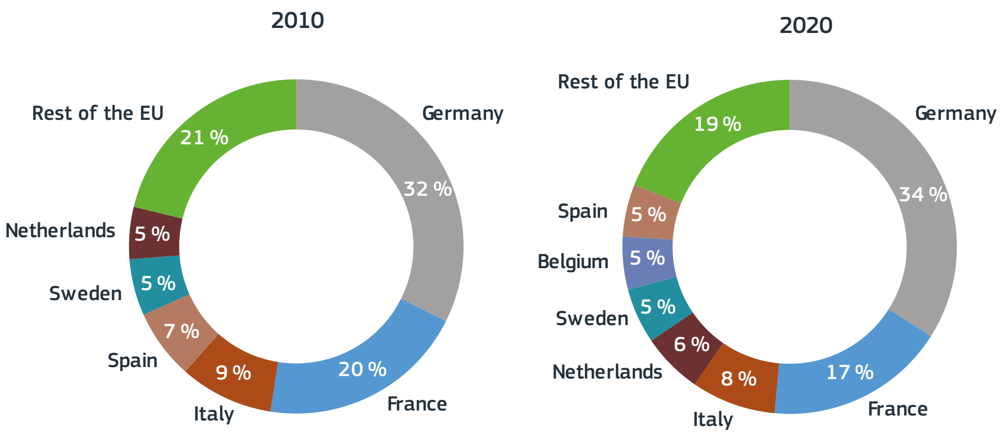
Figure 5.2-2: R&D investments in billion euro, 2000-2019



Science, Research and Innovation Performance of the EU 2022

Source: Eurostat (online data code: rd_e_gerdtot)
Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-2-2.xlsx

Figure 5.2-3: Distribution (%) of gross expenditure in R&D (GERD) within the EU, 2010 and 2020



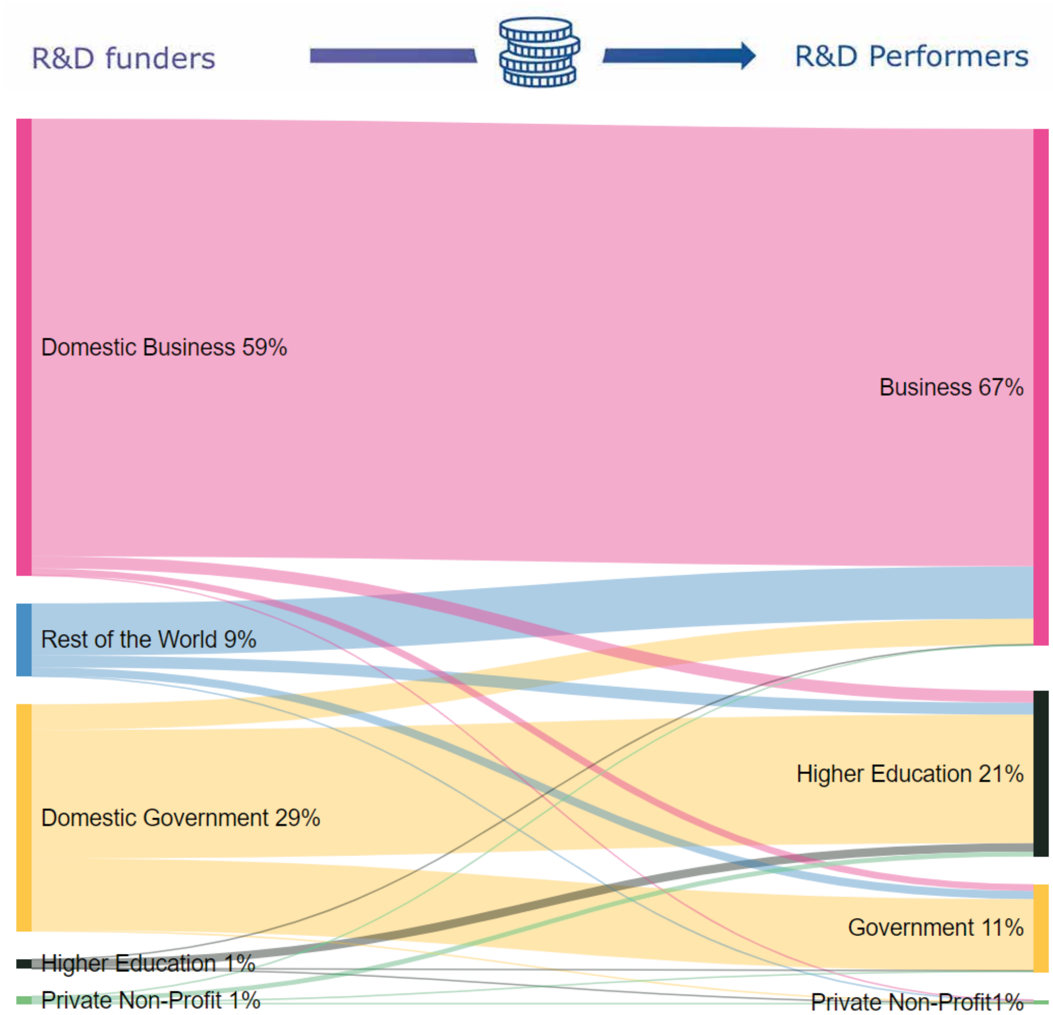
Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation, Chief Economist - R&I Strategy & Foresight Unit based on Eurostat (online data code: rd_e_gerdtot)
Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-2-3.xlsx

Governments finance about 30 % of R&D expenditure in the EU and the private sector slightly less than 60 % (Figure 5.2-4, for 2019). About two-thirds of these investments are carried out by the private sector, about 20 % by universities and higher education institutes, and about 11 % by the government directly. Public R&D investments are primarily directed towards creating an excellent public science base (composed of higher education institutions and other public organisations performing R&I), which will generate the knowledge and talent needed by innovative firms and will leverage and benefit private investments, notably in the more innovative and dynamic industries (Dosi and Stiglitz, 2014; Mazzucato, 2013; Archibugi and Filippetti, 2018). The quality of the public science base of Member States is directly linked to the level of public R&D investments and the effectiveness of the latter. During the recent pandemic, the research community repeatedly advocated stronger public support to ensure the sustainability of long-term research projects, increasing the resilience and the preparedness of societies when facing similar threats in the future.

The EU has a much lower rate of R&D investments from the business sector than its international competitors. Figure 5.2-5 shows that the business sector funds 59 % of R&D investments in the EU, while it funds 63 % in the USA, 76 % in China, 77 % in South Korea and 79 % in Japan. With respective shares of 21 % and 23 % of R&D investments, the higher education sector is much more involved in the EU and in the UK than it is in the USA and Japan (both 12 %) or in China and in South Korea (both 8 %). It is also interesting to note that China has the highest share of R&D investment performed by the government (16 %), followed by the EU with 11 %.

Figure 5.2-4: R&D funders and performers in the EU in 2019



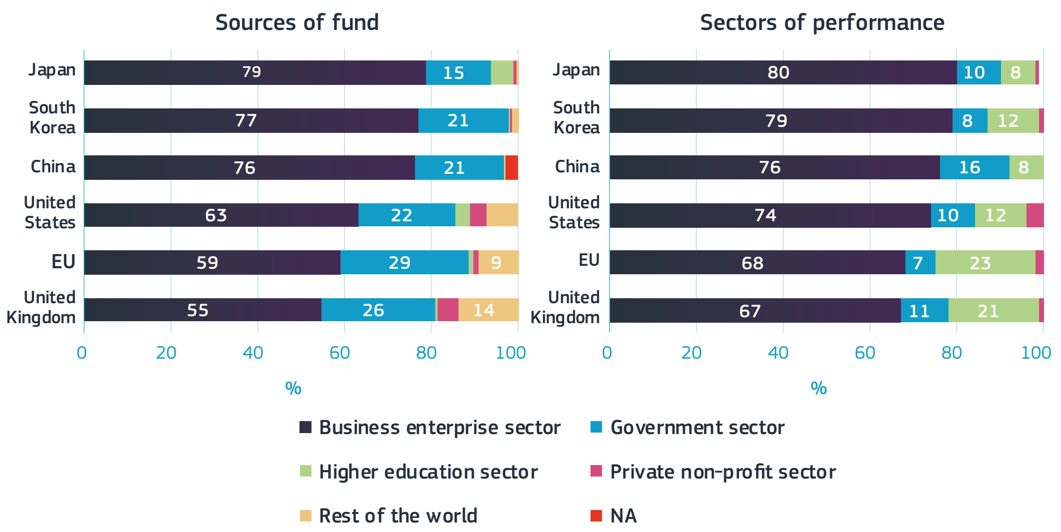
Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation, Chief Economist - R&I Strategy & Foresight Unit based on Eurostat (online data code:rd_e_gerdfund)

Note: In the Rest of the World, 3 of the 9% is funded by the public sector (European Commission and international organisations) and about 1.2% of these go to the higher education sectors.

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-2-4.xlsx

Figure 5.2-5: Gross Expenditure in R&D (GERD) by source of funds and sectors of performance per country/region, 2019



Science, Research and Innovation Performance of the EU 2022
Source: DG Research and Innovation, Chief Economist - R&I Strategy & Foresight Unit based on Eurostat (online data code:rd_e_gerdfund)
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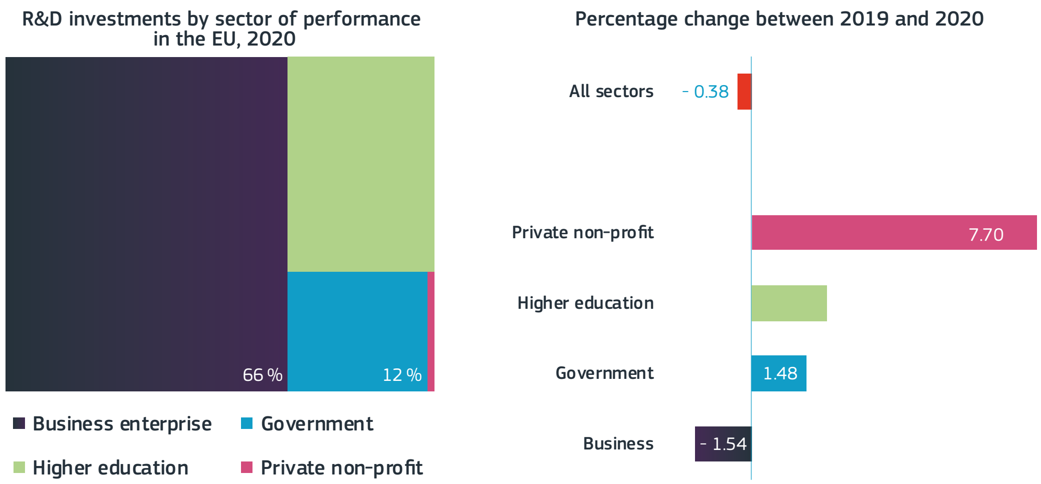
The COVID-19 pandemic has led to a decrease in R&D investments in the EU. In 2020, for the first time since 2010, business R&D investments decreased in the EU from EUR 208 billion in 2019 to EUR 205 billion in 2020 (Figure 5.2-6). In contrast, performance in the public sector has increased, from EUR 102 billion in 2019 to EUR 104 billion in 2020 (the government sector by 2.3% and higher education by 2.04%). The private non-profit sector experienced the highest growth rate, with a 7.7% increase from 2019 to 2020. As the business sector is the main R&D performer, **the overall effect is a decrease in R&D investments in 2020 compared to the 2019 level.** However, it is worth noting that due to the decline in GDP linked to the COVID-19 pandemic, EU total R&D intensity increased to 2.32% of GDP in 2020.

Figure 5.2-6: R&D investments by sector of performance in the EU in 2020 and percentage change between 2019 and 2020



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation, Chief Economist - R&I Strategy & Foresight Unit based on Eurostat (online data code:rd_e_gerdfund)

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Box 5.2-1 Business R&D investment and sectoral composition

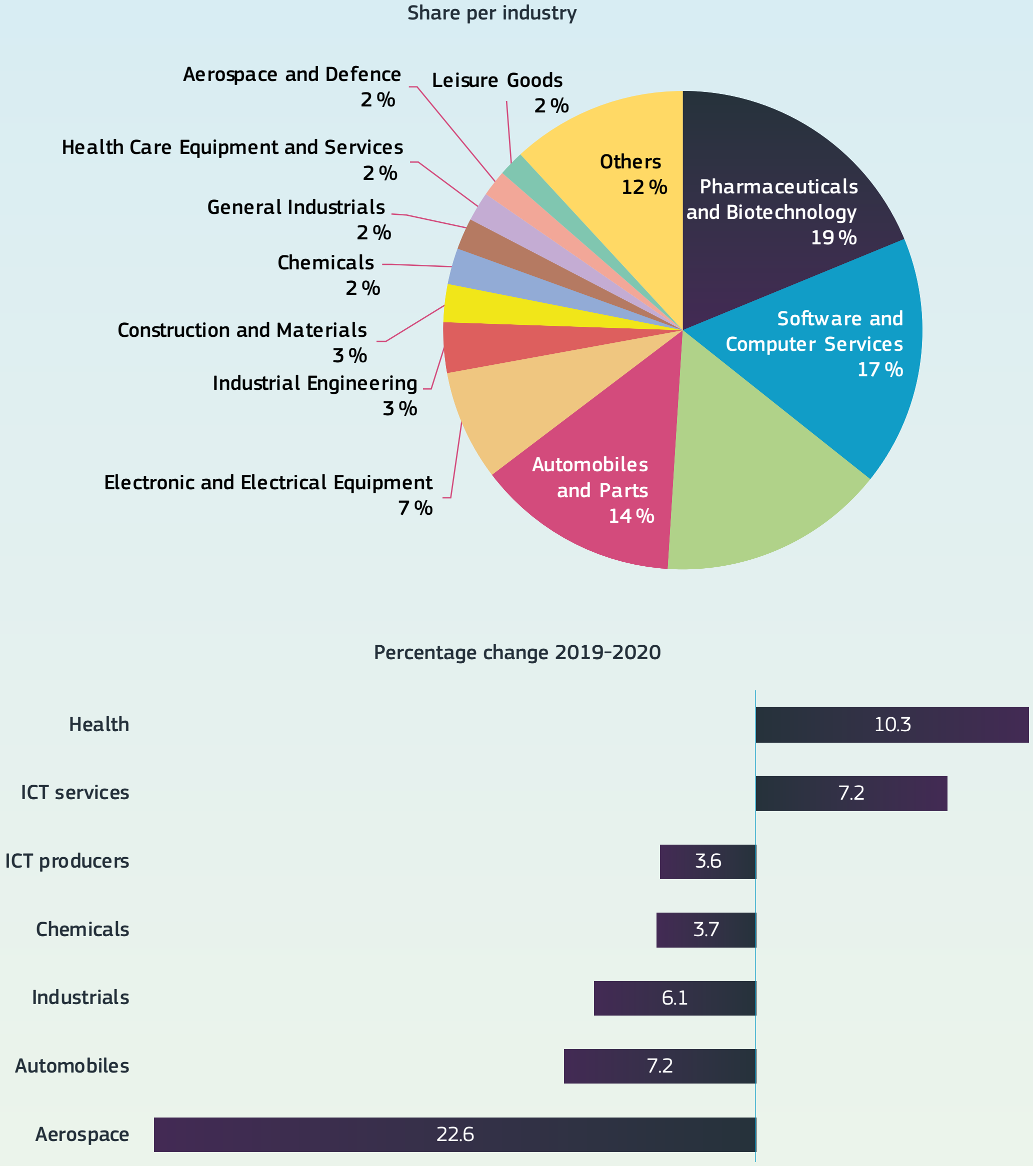
Analysis based on the 2021 EU Industrial R&D Investment Scoreboard (European Commission, 2021d)

Despite the COVID-19 pandemic, worldwide investment in R&D continued to increase significantly in 2020, but at a much slower pace than the year before[1]. In 2019, the world top 2 500 R&D business investors increased their investment by 9.2% compared to 2018, whereas in 2020 they invested EUR 909.8 billion in R&D, 6.0% more than in 2019 (2021 EU Industrial R&D Investment Scoreboard). Still, according to the 2021 EU Industrial R&D Investments Scoreboard, **business R&D investments for the top 2 500 R&D investors proved to be one of the most resilient factors during the crisis**. Most of the other performance indicators were more strongly affected by the pandemic, particularly operating profits, net sales and capital expenditure. R&D investments are less pro-cyclical than other performance indicators for several reasons, one being that it can be cheaper for companies to invest in R&D during a recession (the opportunity-cost effect). It may also underline the important role R&D investment plays in tackling major societal challenges and in maintaining the competitive position of companies in order to reap post-crisis opportunities.

The decrease in R&D investments in Europe is mainly linked to a difference in the sectoral composition of European industry compared to the US and Chinese industrial landscapes. While most major R&D investors in the ICT and health industries across the world, including in Europe, exhibited growth in R&D investments, firms in other industries, especially in transport equipment and industrials, experienced a large reduction in R&D investment (OECD, 2021). As shown in Figure 5.2-7, the largest R&D investors with their headquarters in the EU operate in the automotive, chemicals and industrial sectors, which were severely hit by the crisis. For this reason, business R&D investments by the top R&D investors declined in absolute terms in 2020. These differences in sectoral composition may explain why R&D investments in the EU have declined more than in the USA or in China.

1 This result is based on the EU Industrial R&D Investment Scoreboard, which captures companies' activities regardless of their location (i.e. of the parent companies and their subsidiaries) and not only investments made by companies and subsidiaries based in the EU. At the world level, inward and outward flows in companies compensate each other to a certain extent, which makes this approach coherent.

Figure 5.2-7: R&D private investments by industry in the EU for the top EU R&D investing companies amongst the top 2500 R&D investors worldwide, 2020



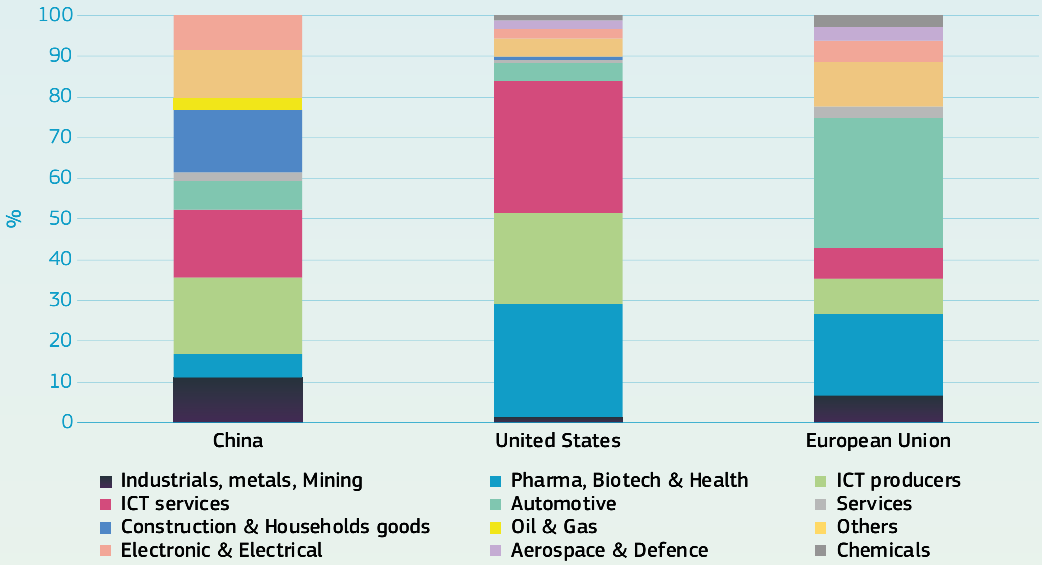
Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on European Investment Scoreboard 2021

Note: The sectoral distributions are calculated using only the R&D investments of the top 401 R&D investors that have their headquarters in the EU.

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-2-7.xlsx

The sectoral composition of the European economy can also explain, to some extent, the lower business R&D intensity in the EU compared to its main competitors. **Figure 5.2-8 shows that less than 50 % of EU corporate R&D expenditures is in the high R&D-intensity sectors** (e.g. ICT producers, ICT services, health industries) and **around 40 % in the medium-high R&D-intensity sectors** (e.g. automobiles and other transport)[2]. Conversely, 80 % of R&D investment by US companies (and more than half of Chinese business R&D investment) is in the high R&D-intensity sectors. Over the past 10 years, the USA and China have increased their specialisation in ICT sectors, and the US increased its proportion in the health sector. In terms of R&D intensity, in 2019, China already caught up to the European level. According to R&D-investment trend for the top investors worldwide, we might expect China to leapfrog the EU in terms of business R&D investment within two to three years (2021 EU Industrial R&D Investment Scoreboard).

Figure 5.2-8: Sectoral distribution of R&D investment by country/region, considering the top 2500 R&D investors worldwide, 2020



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on European Investment Scoreboard 2021

Note: The sectoral distributions are calculated using only the R&D investments of the top 2 500 R&D investing companies worldwide, distributed according to the location of their headquarters (China, USA, EU) and not the country/regions of the world where investments are carried out.

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-2-8.xlsx

2 Based on the 2019 EU Industrial R&D Investment Scoreboard (Hernández et al., 2019) which covers more than 90 % of business spending on R&D (BERD) worldwide.

2. R&D investments dynamics at national level

The headline target of investing 3% of GDP in R&D has provided a stimulus to the EU R&I, growth and competitiveness policy. This target was set at the 2002 Barcelona European Council[3] and subsequently confirmed in the Europe 2020 strategy (European Commission, 2010). Most Member States[4] defined national R&D intensity targets for 2020, taking into consideration their R&I-system maturity and their industrial specialisation. **Although the EU did not fulfil its R&D investment ambition in 2020** (Figure 5.2-9), **the headline target is an essential compass** that can help to accelerate the transition towards an environmentally, socially and economically sustainable Europe. Hence, continuation of the EU-wide 3% R&D investment target and joint reflection with Member States on the performance of R&D systems compared to the national targets[5] is crucial, including in the context of the New ERA for Research and Innovation (Razic et al., 2021). **In 2020, the EU would have needed to invest an additional EUR 91 billion to reach the 3% target,** the equivalent of the budget of an entire European Commission framework programme for R&I. The gap declined from 2019 to 2020, however this was not due to an increase in R&D investments but to the decrease in GDP.[6]

R&D investments by Member States remain uneven, with important differences across countries. R&D intensity at national level varies from 0.5% to 3.5% of GDP, with the highest values observed in the northern and western parts of the EU (Table 5.2-1). R&D activity is concentrated into a limited number of countries. Most R&D is performed in Germany (34%), France (17.5%) and Italy (8.1%) (data refer to 2020). Germany alone still accounts for almost the same amount of R&D spending as 23 Member States combined. Trends in R&D intensity are very diverse between Member States. **R&D intensity increased over 2000-2019 in 24 Member States, but significant heterogeneity persists across European countries** (Table 5.2-1). Only eight Member States stand above the EU average intensity (Sweden, Austria, Germany, Denmark, Belgium, France, Finland and the Netherlands). Besides, **only seven Member States have reached their 2020 targets**. However, it is worth noting that in 2019, only two Member States had already reached their 2020 targets (Germany and Cyprus). The other five may have therefore reached their targets because of the decline in GDP.

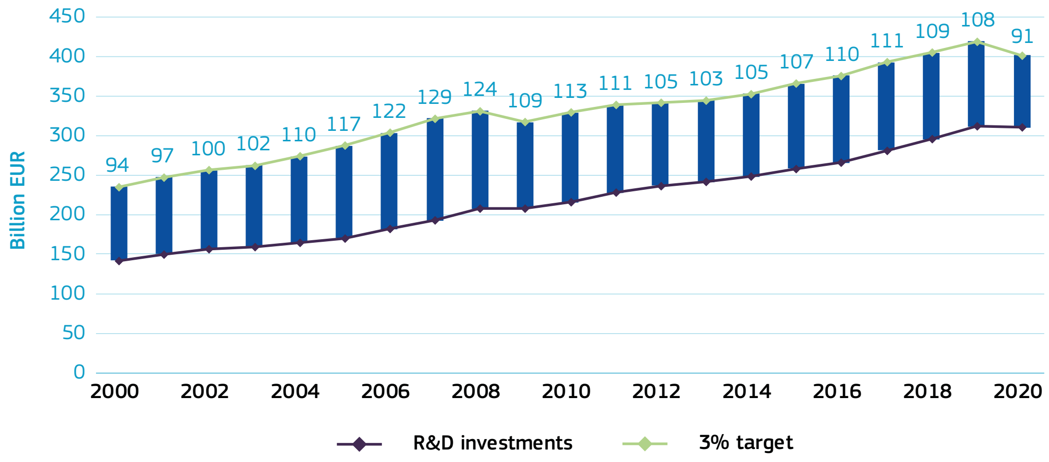
3 Presidency Conclusions, Barcelona 15 and 16 March 2002, SN 100/1/02 REV 1

4 Czechia defined a target for its public R&D intensity only.

5 https://op.europa.eu/en/publication-detail/-/publication/4adfd6f8-b2cf-11eb-8aca-01aa75ed71a1/language-en/format-PDF/source-212299297 R&D investment targets and reforms - Publications Office of the EU (europa.eu)

6 In 2020, the EU recorded a 6.1% decrease in GDP as the initial impact of the COVID-19 crisis was felt. This decrease was considerably larger than the decrease in activity in 2009 during the global financial and economic crisis.

Figure 5.2-9: R&D investment gap in the EU, 2000-2020



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation, Chief Economist - R&I Strategy & Foresight Unit based on Eurostat (online data code:rd_e_gerdfund)

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Table 5.2-1: Situation of each Member State with regard to its national R&D intensity target

	R&D intensity 2020 (% of GDP)	R&D 2020 target (% of GDP)	Compound annual growth 2010-2020 (%) [4]	Gap to reach the target in m euros
Sweden	3.5	4.0	1.01	2 356
Belgium	3.48	3.0	5.37	Target reached in 2020
Austria	3.2	3.76	1.62	2 119
Germany	3.14	3.0[5]	1.39	Target reached in 2019
Denmark	3.03	3.0	0.37	Target reached in 2020
Finland	2.94	4.0	-2.3	2 509
France	2.35	3.0	0.78	14 855
EU	2.32	3.0	1.65	91 000
Netherlands	2.29	2.5	0.89	1 646
Slovenia	2.15	3.0	-1.29	400
Czechia	1.99	(*new 2030 target:* 3.0%)	4.14	
Estonia	1.79	3.0	1.28	324
Hungary	1.61	1.8	2.46	263
Portugal	1.6	2.7-3.3[3]	0.42	2 200
Italy	1.53	1.53	2.36	Target reached in 2020
Greece	1.5	1.3	9.5	Target reached in 2020
Spain	1.41	2.0	0.33	6 671
Poland	1.39	1.7	6.82	1 613
Croatia	1.25	1.4	5.44	76
Ireland	1.23	1.9 (1)	-2.55	2 862
Lithuania	1.16	1.9	3.96	Target reached in 2020
Luxembourg	1.13	2.3-2.6[2]	-0.73	752
Slovakia	0.91	1.2	4.13	266
Bulgaria	0.85	1.5	4.25	397
Cyprus	0.82	0.5	6.35	Target reached in 2019
Latvia	0.69	1.5	1.37	238
Malta	0.65	2.0	1.08	176
Romania	0.47	2.0	-0.65	3 352

Science, Research and Innovation Performance of the EU 2022

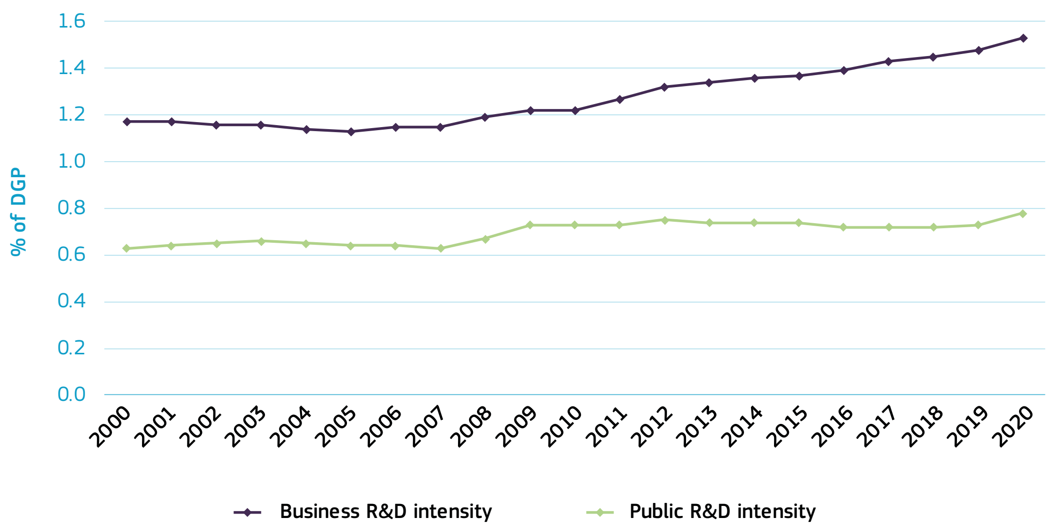
Source: DG Research and Innovation, Chief Economist - R&I Strategy & Foresight Unit based on Eurostat, adapted from Ruzika et al., 2021

Note: [1]IE: The national target of 2.5% of GNP has been estimated to be equal to 2.0% of GDP. [2]LU: A 2020 target of 2.45% was assumed. [3]PT: A 2020 target of 3.0% was assumed. [4]IT, LU, HU, NL, RO, SI: Breaks in series occur between 2010 and 2020; when there is a break in series the growth calculation takes into account annual growth before the break in series and annual growth after the break in series. [5]DE: new 2025 target of 3.5%. CZ: new 2030 target of 3.0%.

Following the COVID-19 pandemic, the decline in business R&D expenditure over 2019-2020 was driven by only six countries: Germany, Czechia, Italy, Luxembourg, Austria and Romania. **The other 21 EU Member States saw their expenditure increase in 2020**, with the highest increases observed in Lithuania, Latvia and Portugal. However, six Member States still recorded a business R&D intensity below 1% of GDP in 2020: Romania, Malta, Latvia, Cyprus, Bulgaria and Slovakia. These differences in investment translate into gaps in scientific excellence and innovation output. For example, indicators for science quality (top cited scientific publications) also demonstrate a persistent innovation gap across the EU (see Chapter 2.2 – Zoom in). In the context of the new ERA, the European Commission has proposed a new 1.25% EU GDP public R&D target, to be achieved by 2030 in a coordinated manner through public national R&D targets. This will leverage and incentivise private investment in R&D.

The public sector is a main source of funding in countries where conditions for business R&D investment are still insufficiently attractive. Conversely, in the most research-intensive countries, the business sector is the predominant source of funding (Figure 5.2-12). Adding up investments from national governments and the EU, we find exceptionally high shares of publicly funded R&D in Latvia, Cyprus and Lithuania. The public sector is also the predominant investor in Greece, Luxembourg, Romania, Portugal, Slovakia and Spain. In the more research-intensive Member States (Germany, Sweden, Belgium, Denmark, Finland

Figure 5.2-10: Evolution of Business R&D and Public[1] R&D as % of GDP in the EU, 2000-2020



Source: DG Research and Innovation, Chief Economist - R&I Strategy & Foresight Unit based on Eurostat (online data code:rd_e_gerdfund)

Note: [1]Public R&D is defined as the sum of Government and Higher Education sectors

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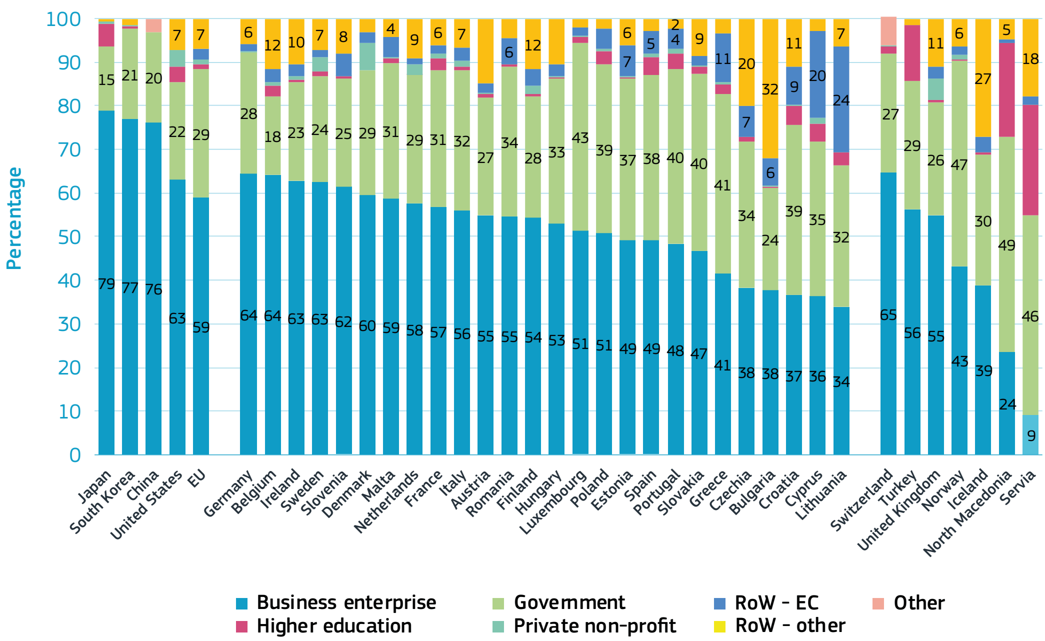
and Slovenia), the business sector is the predominant source of funds. In those countries, the R&I funding from the business sector is comparable to that in the United States (62%), although significantly lower than in South Korea, China and Japan, where businesses finance more than 75% of R&D.

Businesses are more inclined to invest in R&D in countries with a high quality of public administration, sufficient availability of high-skilled workers and solid research infrastructure. Hence how much the private sector invests in a particular country relies largely on the return it can expect and therefore on the framework conditions in place. Figure 5.2-11 shows the sources of R&D funding broken down into business enterprise, domestic government, rest of the world and other sources.

Investments in R&D carried out by the public sector over 2010-2020 increased at an annual growth rate above the EU average (0.7%) in Member States with high levels of public R&D intensity (Belgium, Austria, Germany, Denmark) and in Member States with low public-investment in R&D intensity (Cyprus, Malta, Slovakia, Lithuania, Croatia), (Figure 5.2-12). **For the first group, this improved their position as leaders in the field; for the second this allowed some convergence across the EU.** In contrast, some Member States with strong public R&D intensity (Finland, Sweden, Estonia) witnessed a stabilisation or reduction in public R&D spending over 2010-2020. Persistent weak public R&D investments for countries characterised by a declining annual growth rate between 2010 and 2020 and low levels of R&D

Figure 5.2-11: Source of R&D funds by country, 2019[(1)]



Source: DG Research and Innovation, Chief Economist - R&I Strategy & Foresight Unit based on Eurostat (online data code:rd_e_gerdfund)

Note: [(1)]UK, US: Year 2018.

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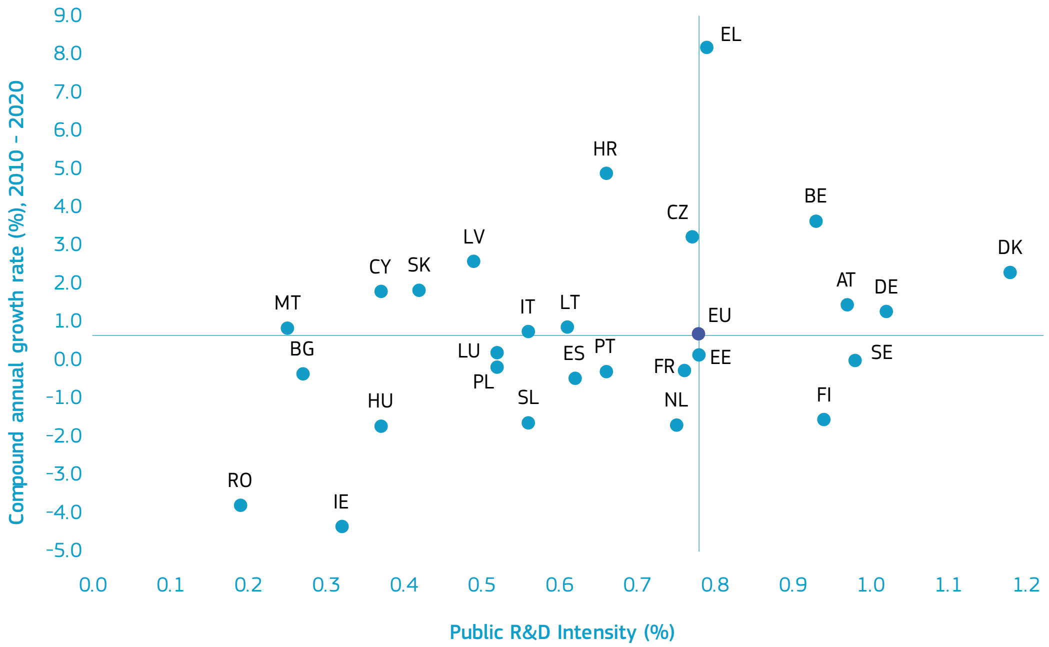
intensities (Bulgaria, Hungary, Romania, Ireland, Poland, Slovenia, Spain, Portugal, France and the Netherlands) may limit their prospects of improving the performance of their public science base. This, in turn, may severally hamper the technological upgrade of their private sector and slow down their catch-up towards countries with higher levels of productivity. For the more advanced Member States, public investment in R&D is critical to being at the technological frontier and generating the knowledge and skills needed to fully reap the benefits of the digital and green transitions. It is worth noting that several Member States that in 2020 had an R&D intensity below the EU average increased their R&D investments between 2010 and 2020 (Croatia, Lithuania, Slovakia, Cyprus, Italy, Greece, Latvia and Cyprus), in particular over 2018-2020, which has likely helped some of them to reach their 2020 targets (Italy, Greece, Latvia and Cyprus). However, this result should also be interpreted in light of the decrease in GDP over 2019-2020.

Even though the EU has one of the highest public R&D intensities worldwide, some countries still need to develop their public science base substantially for this base to play a role in their transition from an economy based on cost competitiveness[7] to an innovation-driven one. This will require not only more public R&D investments, but also

Figure 5.2-12: Public(1) R&D intensity, 2020 and compounded annual growth rate (%), 2010-2020



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation, Chief Economist - R&I Strategy & Foresight Unit based on Eurostat (online data code:rd_e_gerdfund)

Note: (1)Public investments are the sum of government and higher education investments.

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7 competition to reduce unit costs

significant structural reforms in the national and regional R&I systems (e.g. improving the excellence of the science base, and stronger links between business and science) to ensure that these investments are efficient and effective to bring in more private R&D investment.

Over 2010-2020, most Member States characterised by low business R&D investments have experienced a relatively strong increase in private R&D spending (Cyprus, Poland, Greece, Latvia, Bulgaria, Slovakia, Croatia, Romania, Hungary, Czechia and Italy), **allowing some convergence across the EU** (Figure 5.2-13). However, the declining R&D intensity observed over 2010-2020 in many Member States with already low-to-median business R&D spending (Lithuania, Luxembourg, Ireland, Malta, Spain) is particularly worrisome. In contrast, some Member States still have scope to improve private R&D spending, such as Luxembourg, Malta, Lithuania, Spain, Greece and Ireland. Several Member States are characterised by relatively high R&D intensity in their business sector but have decreased their business R&D investments (Slovenia, Denmark, Finland, Germany, Austria and Sweden). **Only Belgium and the Netherlands have intensified their business R&D investments at a relatively high growth rate over 2010-2020**.

Figure 5.2-13: Business R&D intensity, 2020 and compounded annual growth rate (%), 2010-2020

Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation, Chief Economist - R&I Strategy & Foresight Unit based on Eurostat (online data code:rd_e_gerdfund)

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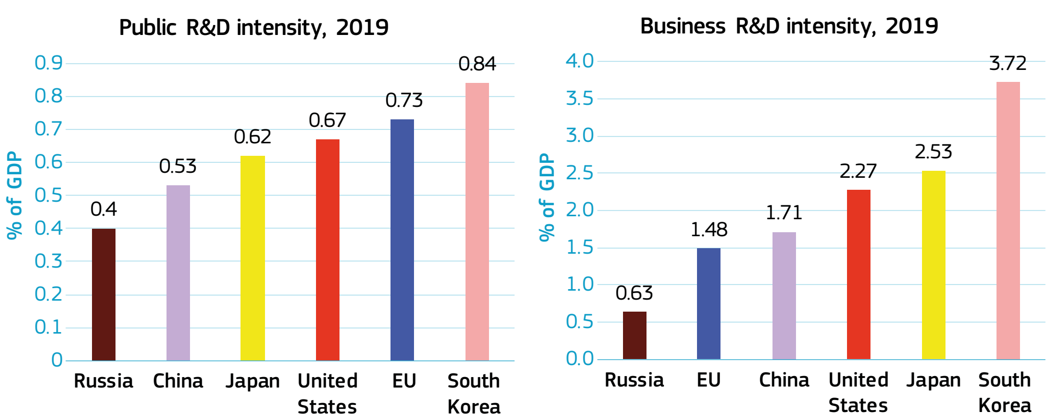
CHAPTER 5.2

Stimulating private R&D investment is critical but remains a challenge. Compared to its main competitors, EU R&D investment is especially low in terms of private investments (Borunsky et al., 2020; Figure 5.2-14). Businesses that intend to invest in R&D typically face various obstacles, possibly resulting in underinvestment. These obstacles are high risks, high sunk costs, market uncertainty, lack of full appropriability of results and financing constraints (European Commission, 2017). Due to positive externalities from R&D investments, the social rate of return on these investments is about two to three times higher than the private return for the company making the investment (Frontier Economics, 2014; Coe and Helpman, 1995; Kao et al., 1999). This discrepancy calls for public support. Furthermore, R&D efforts are increasingly concentrated in a limited number of firms, while innovation expenditure in SMEs is faltering, leading to a productivity gap between technology leaders and other firms.

R&D tax incentives, used to stimulate business R&D investments, surpassed direct funding in the EU. R&D tax support doubled over ten years, from 26% of total government support to business in 2006 to 58% in 2019 (OECD, 2021). The EU level of R&D tax incentives (% of total government budget for R&D investments) is higher than in China, Canada, the United States and South Korea, in which respectively 55%, 53%, 48% and 43% of the total government support to R&D is given through tax incentives, but below the rate of Japan (82%). In the EU, the number of countries offering R&D tax relief increased from 12 in 2000 to 20 in 2019 (Figure 5.2-15).

R&D tax policies, such as tax relief, increase firms' R&D activities (Hall & Van Reenen, 2000; OECD, 2016; Hall, 2019). Direct funding involves discretionary (and potentially costly) choices on the part of governments on which R&D projects and firms to support (Hall, 2020). In contrast, most R&D tax incentives are mar-

Figure 5.2-14: Public and private R&D investments as % of GDP in country/regions, 2019



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation, Chief Economist - R&I Strategy & Foresight Unit based on Eurostat
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ket-based instruments that provide more broad-based support. These comply with state-aid and international competition rules, and promise lower administrative and compliance costs (Appelt et al., 2020). Literature suggests **that R&D tax incentives are effective in raising R&D investment by business**. Its effect on experimental development is almost twice as large as its effect on research (OECD, 2020). However, **even if tax incentives are market-based, they might render tax (incentive) systems overly complex if not designed properly, which ultimately reduces their effectiveness and distorts the business climate. Direct funding usually provides better directionality to R&D** (European Commission, 2021b) and higher social returns, but also brings a high administrative burden for national authorities and therefore greater costs. Finally, direct and indirect governmental support have similar effectiveness (each euro of either direct or tax support leads to around 1.4 euro of R&D on average) but may serve different policy objectives. Therefore it is important to have a balanced policy mix (European Commission, 2021c).

Trends in forgone tax revenues are very diverse among Member States. In some Member States, tax incentives represent over or close to 80 % of total government support for business R&D: 89 % in Malta, 85 % in Ireland, 83 % in Portugal and Lithuania, and 80 % in Italy (2019 or closest-year data, Figure 5.2-15). These high levels reflect a shift in the business R&D support policy mix towards R&D tax incentives that is observable in many EU countries.

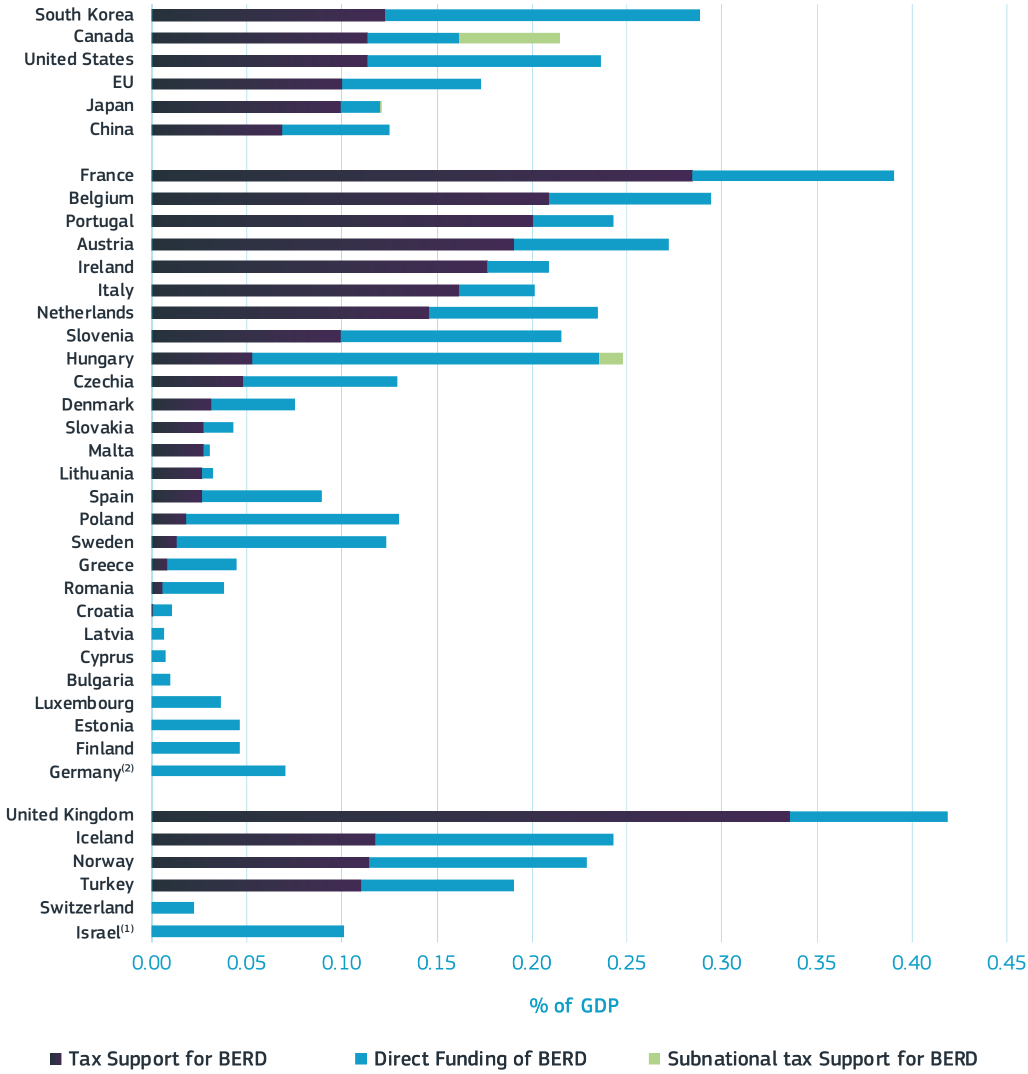
Furthermore, the combined support for R&D (direct and tax) is relatively high in France, Belgium, Austria, Hungary and the Netherlands, ranging between roughly 0.23 % and 0.40 % of GDP. On the other hand, combined support is very low in Bulgaria, Croatia, Cyprus and Latvia (around 0.01 % of GDP) and exclusively through direct support. **The EU average support to R&D is about 0.1 % and 0.07 % of GDP for tax incentives and direct funding, respectively**, in 2019. Other Member States have introduced R&D tax incentives only recently, such as Germany in 2020 and Finland in 2021. Yet another group uses R&D tax incentives only to a limited extent, while still offering relatively high direct support to private R&D investments, such as Hungary (0.18 % of GPD), Poland (0.11 % of GDP) or Sweden (0.11 %).

The increasing importance of R&D tax incentives has translated into a significant increase in the number of firms receiving R&D tax support over the last decade (OECD, 2021). Figure 5.2-16 demonstrates that **SMEs account for most R&D tax relief recipients in the EU**, ranging from around 50 % in Belgium[8] to 98 % in Lithuania. It is noteworthy that self-employed individuals feature among R&D tax relief recipients in Slovakia, Sweden and the Netherlands, though they account for fewer than 10 % of tax relief recipients. **The distribution of R&D tax support is, however, heavily skewed towards large firms, which account for the bulk of R&D in most economies**. Large companies receive high percentages of R&D tax relief, ranging from 12 % in Lithuania to 80 % in Belgium (Figure 5.2-16).

While the support for R&D is essential, giving preferential treatment to SMEs via tax incentives might encourage them to limit their growth to keep the incentives alive (i.e. a harmful tax-avoidance strategy) (Evers et al., 2015; Almunia and Rodriguez, 2018; Sterlacchini and Venturini, 2018).

8 The low percentage for Belgium can be partly explained by the definition of SMEs, which is more restrictive in this country compared to others in the EU. In Belgium, SMEs are defined as enterprises that, in the last two years, have not exceeded an average annual number of employees below 50, revenue under EUR 9 million or a balance sheet under EUR 4.5 million whereas in most EU MS, SMEs are defined as having 1-249 employees.

Figure 5.2-15: Tax support and direct government funding for business R&D (as a % of GDP), 2019



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation, Chief Economist - R&I Strategy & Foresight Unit based on OECD Measuring Tax Support for R&D and Innovation: Indicators - OECD

Note: (1)The percentage represent the percentage of tax incentives over total government support for R&D in the corresponding country. (2)Germany has introduced tax incentives in 2020.

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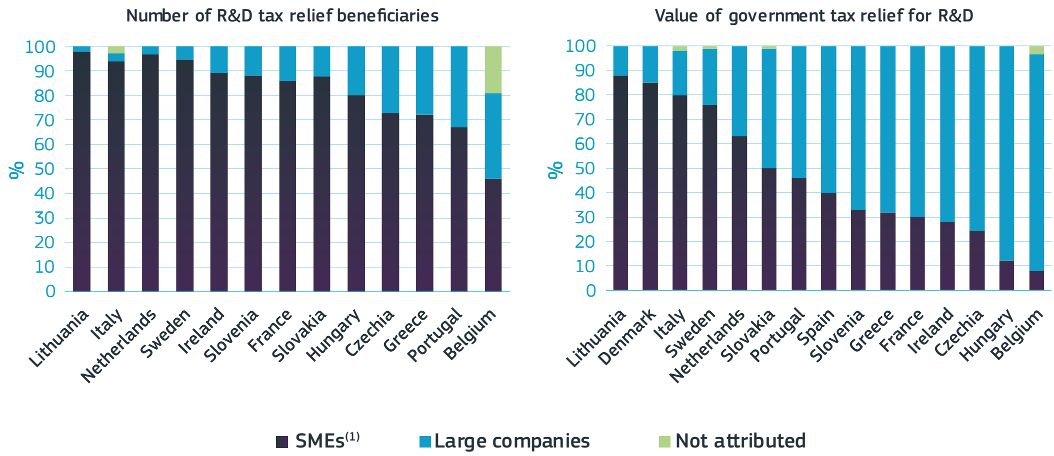
Figure 5.2-16: Number of R&D tax relief beneficiaries and value of government tax relief for R&D in selected EU Member States, 2019



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation, Chief Economist - R&I Strategy & Foresight Unit based on OECD Measuring Tax Support for R&D and Innovation: Indicators - OECD

Note: [(1)]SMEs are defined as companies with number of employees between 1-249, except for HU, LI, NL, ES where SMEs are defined as firms with less than 250 employees and an annual turnover that does not exceed EUR 50 million or an annual balance sheet that does not exceed EUR 43 million; BE where they are defined as enterprises that, in the last two years, do not exceed an average annual number of employees below 50 or a revenue under EUR 9 million or a balance sheet under EUR 4.5 million; SI where they are defined as firms with 1-249 employees, a balance sheet total less than EUR 20 000 000 and a net turnover less than EUR 40 000 000; and SE where SMEs are defined as firms with 10-249 employees.

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Box 5.2-2: The OECD R&D tax incentives database, selected extracts from the 2021 edition

Since 2007, the OECD has continuously worked to collect international evidence on R&D tax incentives and has developed experimental methodologies and data infrastructure that have received considerable interest and become widely used in the policy, statistical and academic arenas. This progress in the measurement of expenditure-based R&D tax incentives is the result of 10 years of close collaboration with a network of official experts from OECD countries and partner economies. In recent years, such efforts have been intensified with support from the EU's Horizon 2020 programme, which has contributed to an increased frequency of data collection and extended coverage and analysis. This work has been supported by the OECD R&D tax incentives network, which comprises delegates from the OECD Working Party of National Experts on Science, Technology and Innovation (NESTI) and Working Party No. 2 on Tax Policy and Statistics (WP2), among other national experts on R&D tax incentives.

The annual OECD R&D tax incentives data collection has been collecting information on R&D tax relief beneficiaries since 2016 and further extended its scope in 2020 to additionally collect information on the amount of qualifying R&D expenditures. At the same time, the number of countries reporting beneficiary figures has increased steadily over the last years, reaching 36 in 2021. We present below some selected parts of the 2021 OECD R&D tax incentives database report, drawing on the 2021 OECD R&D tax incentives data collection.

R&D and eligible activities

Definitions of R&D or other types of expenditures eligible for tax relief differ across jurisdictions and with respect to the OECD Frascati Manual definition (OECD, 2015a), but most countries attempt to be consistent with the manual. Only a few countries extend tax relief beyond R&D to other innovation activities, and when they do, it is typically under much stricter and less generous terms. R&D in the social sciences are sometimes excluded, possibly because of the difficulty in distinguishing these from market research and related activities. The tax relief is often more closely targeted at the financial cost of R&D to the firm (expense), regardless of who carries out the R&D, than the cost of the R&D activity incurred within the firm (i.e. intramural R&D, regardless of who funds the work).

Some R&D tax incentive schemes explicitly target specific types of R&D costs. Overall, there is a general preference for considering costs relating to labour and other current expenditures as within the scope of eligible R&D costs. R&D personnel costs account for the largest share of intramural R&D costs. In principle, the focus on R&D personnel incentivises investment in human resources based in the domestic economy. Acquisition of capital assets to be used for R&D is less typically supported as assets may be subsequently disposed of or used for other purposes.

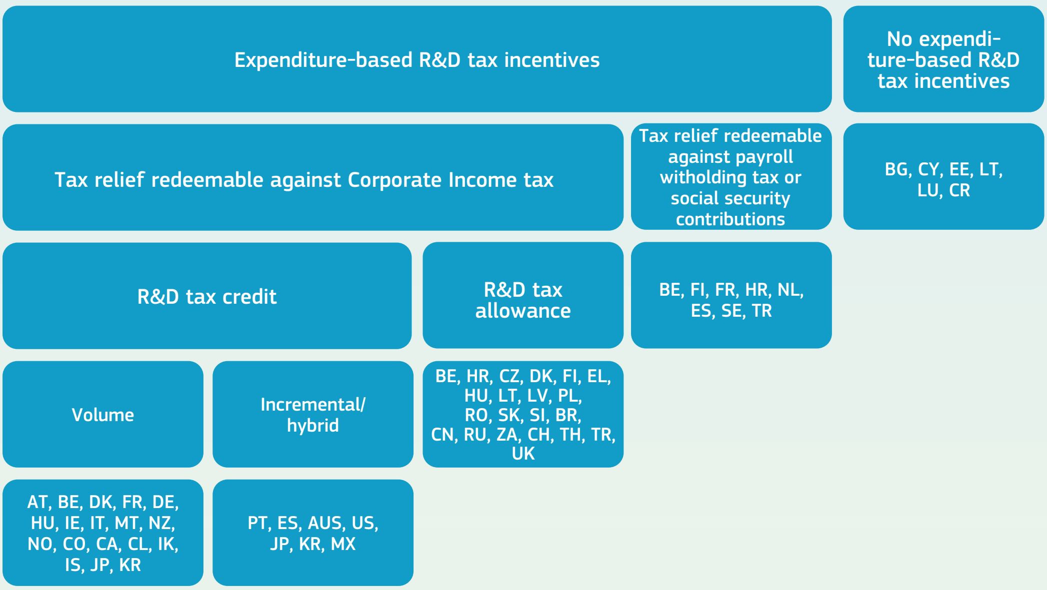
Types of tax instrument

Any form of tax relief can be provided as an allowance, exemption, deduction or credit.

- Tax allowances, exemptions and deductions effectively subtract from the tax base before the tax liability is computed, reducing the taxable amount before assessing the tax.
- A tax credit is an amount subtracted directly from the tax liability due from the beneficiary unit after the liability has been computed.

The choice between credits and allowances is largely a formal one, as they can be converted into each other to be made equivalent. However, the value of the tax benefit will react differently to changes in the tax rate, as the value of R&D tax allowances is directly linked to the level of the corporate income tax rate.

Figure 5.2-17: Different types of R&D tax relief



Source: Adapted from the OECD (2021), "OECD R&D tax incentives database report, 2021 edition", December 2021, https://www.oecd.org/sti/rd-tax-stats-database.pdf

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Directionality and R&D tax reliefs

Although tax incentives are generally seen as a more market-based, non-discretionary alternative to direct support for R&D, a number of countries target R&D tax incentives to particular types of firms, industries or activities. Targeted relief measures may be motivated by evidence or the belief that some groups of firms with observable characteristics, e.g. firm size or age, can be more responsive to a given unit of financial support. Tax provisions may give more favourable treatment to SMEs and young firms in the form of more generous rates of tax support or refund provisions that are exclusively available to these firms. Likewise, in the 2021 OECD R&D tax incentives data collection, a few countries reported having special, temporary or emergency tax relief provision for R&D in specific priority areas such as green or energy related R&D. These include:

- Italy. A higher tax credit rate is available for technological innovation for 4.0 innovation (national strategy) or the ecological transition.
- Portugal. Expenses related to making eco-design products are increased by 10 % upon submission and approval of the project by the Portuguese Environment Agency.
- Spain. A higher tax credit rate currently applies to expenses in technological innovation activities for new or relevant improvements in production processes in the value chain of the automotive industry in Spain.

3. Public intervention for directed R&D investments?

In the past decade, the rationale for government intervention in R&I has shifted from a predominantly market or system-failure argument to a system or transformative-change approach. Public interventions seek to channel innovation efforts and support towards addressing societal challenges. There is a strong rationale for policy that seeks to increase the amount of innovation in the economy. First, knowledge spillovers for clean innovations are over 40 % greater than their high-carbon counterparts in the energy production and transport sectors (Dechezleprêtre et al., 2014). Second, R&I are subject to path dependences: investments in early-stage clean technologies are generally perceived as riskier than the more traditional alternatives (Gaddy et al., 2017), leading to tighter financing constraints. Finally, clean products can be more expensive for consumers. Unlike digital technologies, for which people are ready to pay more for state-of-the-art products, consumers are not necessarily willing to pay more for clean products as the beneficial effects are less direct for them. A key implication is that socially and environmentally related technologies may not be able to overtake dirty technologies without government intervention that can shift the economy onto a clean and inclusive equilibrium path (Stern and Valero, 2021).

In this context, providing a degree of directionality to national and EU R&D investments will ultimately help to deliver on EU priorities[9], notably the green and digital transitions, to strengthen resilience and to maintain Europe's competitive edge.

Furthermore, the analytical basis for the 2030 Climate Target Plan and Fit for 55 shows that the decarbonisation pathway is feasible, but that the full roll-out of these technologies represents a significant investment challenge (an increase of almost EUR 400 billion per year in investment needs compared to investments in the previous decade).

EU public and private investment in R&D in climate mitigation activities has grown, but at a slow pace over the last five years (EIB, 2021). Overall, the United States has experienced a higher increase and remains the world leader in climate-related R&D. Due to a very high increase, China overtook the EU in 2018 and has a significant lead in 2019. In the EU, energy-related automotive R&D grew steadily for several years and stabilised in 2018 and 2019 (EIB, 2021). This might be due to a decrease in car sales and the imperative to invest in new models and improve manufacturing supply chains.

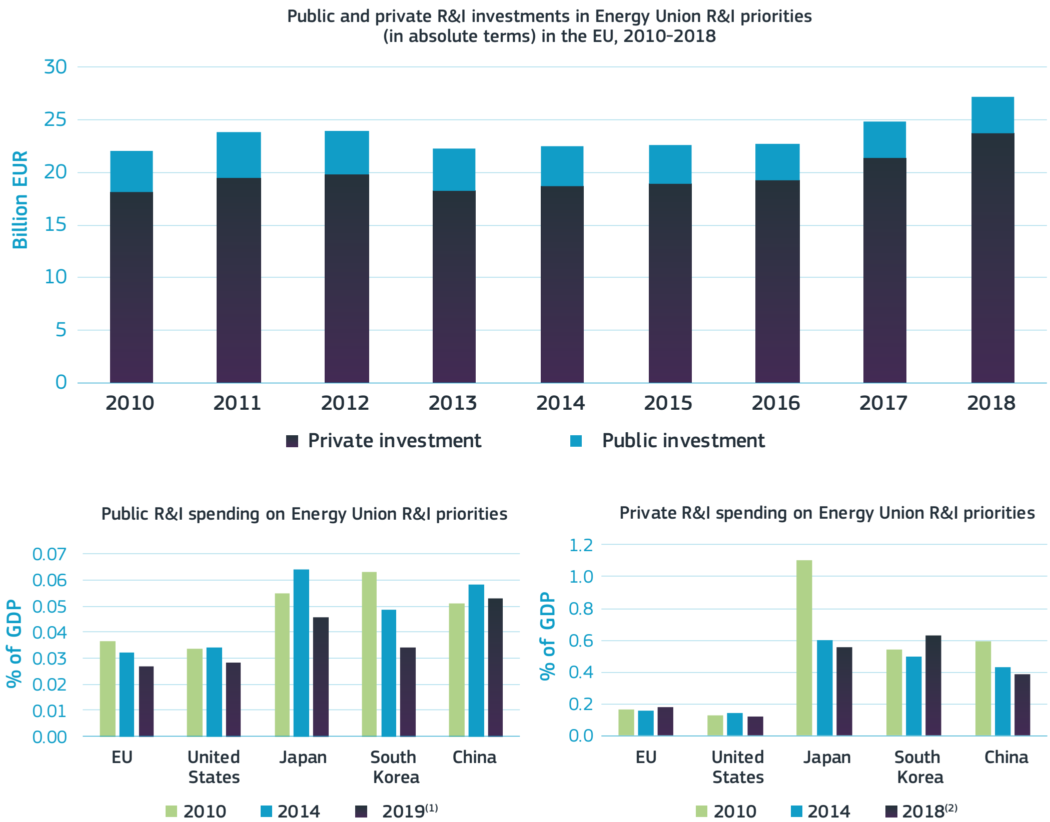
Public and private investments in R&I prioritised by the Energy Union have increased in absolute terms 2014-2018 (European Commission, 2015). After the economic crisis of 2008, public investments went into decline for half a decade, showing signs of recovery only after 2014 (Figure 5.2-18). Since then, EU Member States have invested on average EUR 3.5 billion per year, but spending is still lower than that observed a decade ago. Besides, this increase in public and private investments in the total Energy Union R&I priorities has not kept pace with increases in GDP or R&I spending in other sectors.

9 See Council Conclusions on the New European Research Area, 1 December 2020 https://data.consilium.europa.eu/doc/document/ST-13567-2020-INIT/en/pdf

Measured as a share of GDP, the EU investment rate (0.027%) is currently the lowest of all major global economies, just below the USA, although levels seem to be decreasing or stable for all economies. In addition, the **EU private sector experienced a 7% reduction in overall energy R&I spending in 2020, possibly due to the COVID-19 pandemic.** Only spending in renewable energy R&I specifically was more resilient and continued to grow (European Commission, 2021b).

In the EU, public R&D investments in energy have switched from nuclear to a more diversified mix, including a high share dedicated to renewables and energy efficiency. Figure 5.2-19 shows that over the past forty years, EU public investment in energy R&D has become progressively more diverse. Nuclear power, which accounted for 78% of the total in Europe in 1977, has declined over the years to 29% in 2020. **R&D budgets for fossil fuels, which were at**

Figure 5.2-18: Public and private R&I investment in Energy Union R&I priorities (absolute terms and as% of GDP) in the EU and major economies



Science, Research and Innovation Performance of the EU 2022

Source: European Commission. Joint Research Centre (2021e), based on International Energy Agency (2021) and their own work

Note: [1]Public R&I data for China and Italy (in EU total) refer to 2018. [2]Private R&I data for 2018 are provisional.

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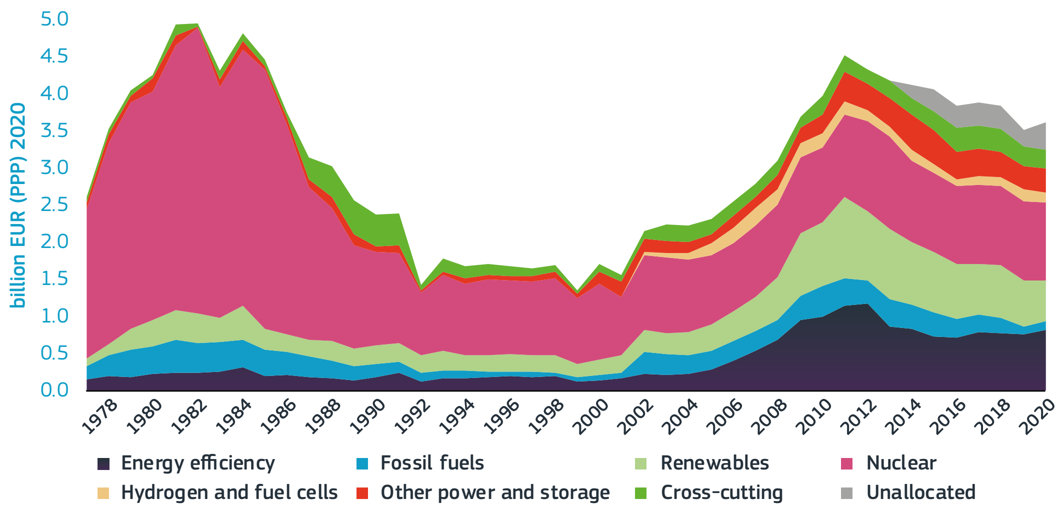
their highest in the 1980s, have declined since 2013 and budgets for both energy efficiency and renewables expanded significantly faster during the 2000s. Besides, in 2019, around 80% of worldwide public R&D spending on energy was dedicated to low-carbon technologies – energy efficiency, CCUS, renewables, nuclear, hydrogen, energy storage and cross-cutting issues such as smart grids. However, budgets for hydrogen and tfuel cells maintained their share at 3-4% for 2000-2020. In addition, increasing amounts of public R&D spending went to low-carbon technologies (IEA, 2021).

Energy – low-carbon energy in particular – represents a high share of the total public R&D investment in many EU countries, but less than in other major economies, such as in the USA or Japan (Figure 5.2-20). After the USA (35%) and Japan (15%), France has the highest share of such investments in the EU, at 9%. **In 2020, through Horizon 2020, the EU spent a fifth of its total R&D budget on power and storage technologies, making it the largest spender worldwide for this category.** More generally, sustainable development is one of the general objectives of the EU R&I programme. More than 80% of the Horizon 2020 investment addressed at least one SDG (European Commission, 2020).

Figure 5.2-19: Public R&D investments in energy in the EU(1), 1977-2020



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on International Energy Agency

Note: (1)Only 20 of the 27 Member States were taken into account: AT, BE, CZ, DK, EE, FI, FR, DE, EL, HU, IE, IT, LI, LU, PL, PT, SK, ES, SE. It does not include the European Union R&D FP budget.

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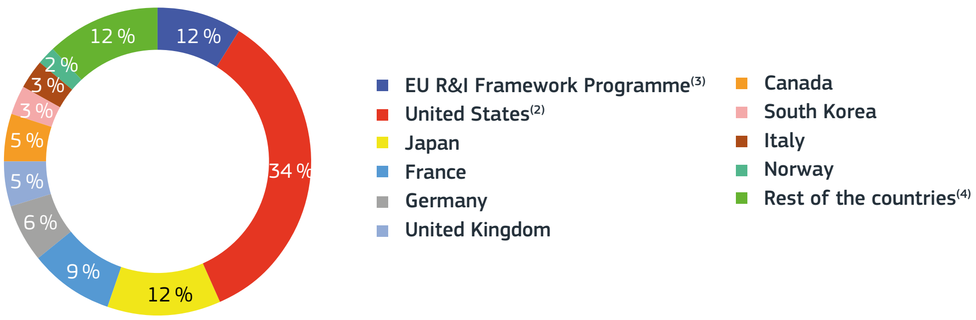
Figure 5.2-20: Public energy R&D budgets for selected countries and Horizon 2020 budget of the European Union, 2020[1] (% of total energy budgets)



Source: International Energy Agency, 2021

Notes: [1]The amounts shown are based on 2020 energy R&D budgets for: Belgium, Canada, Czechia, Denmark, Estonia, Germany, Hungary, Mexico, Norway, Poland, Portugal, Slovakia, Sweden, Switzerland, the United States and the European Union. The amounts shown are based on 2019 energy RD&D budgets for: Australia, Austria, Finland, France, Ireland, the Netherlands, New Zealand, Spain and the United Kingdom. For the other countries, data refer to 2018. [2]Data for the United States were estimated by IEA Secretariat. [3]European Union refers to the European Union budget under Horizon 2020, and not to the sum of national budgets of European Union member countries. [4]the Rest of the countries correspond to all other IEA countries (https://www.iea.org/countries).

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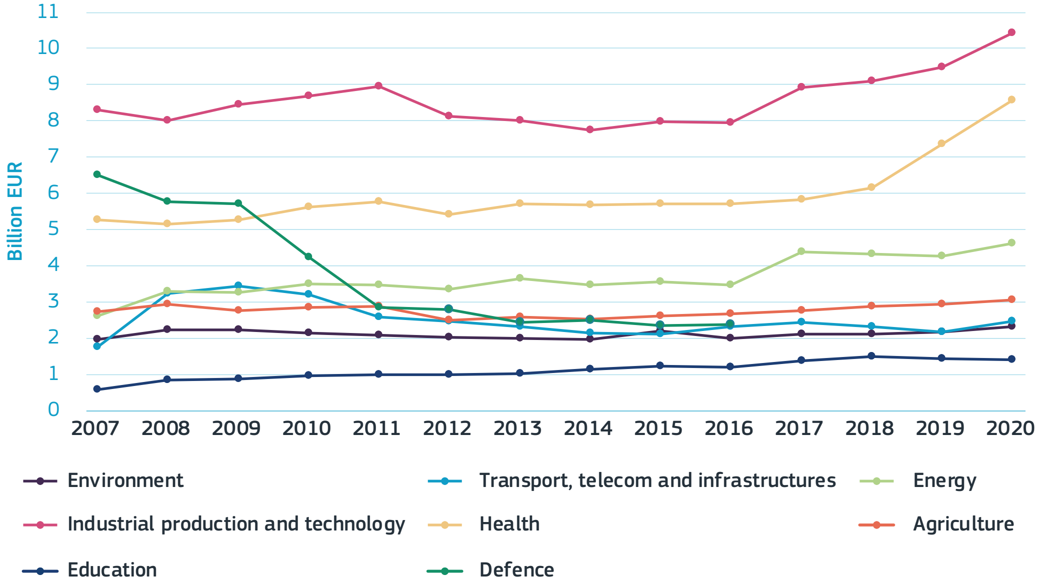
Member States are slowly steering their public national budget allocations for R&D towards societal and environmental challenges. Figure 5.2-21 shows an increase in health, industrial production, technology and energy-related government budget allocations for R&D (GBARD) at the European level. Growth in the budget allocations for total civil and environment R&D investment are more modest. Transport and communications increased mainly from 2007 to 2009, but then slowly decreased to stagnate from 2011 onwards. In contrast, the R&D budget for defence has decreased significantly in recent years.

Figure 5.2-21: Evolution of government budget allocation for R&D by socio-economic objectives in the EU, 2007-2020

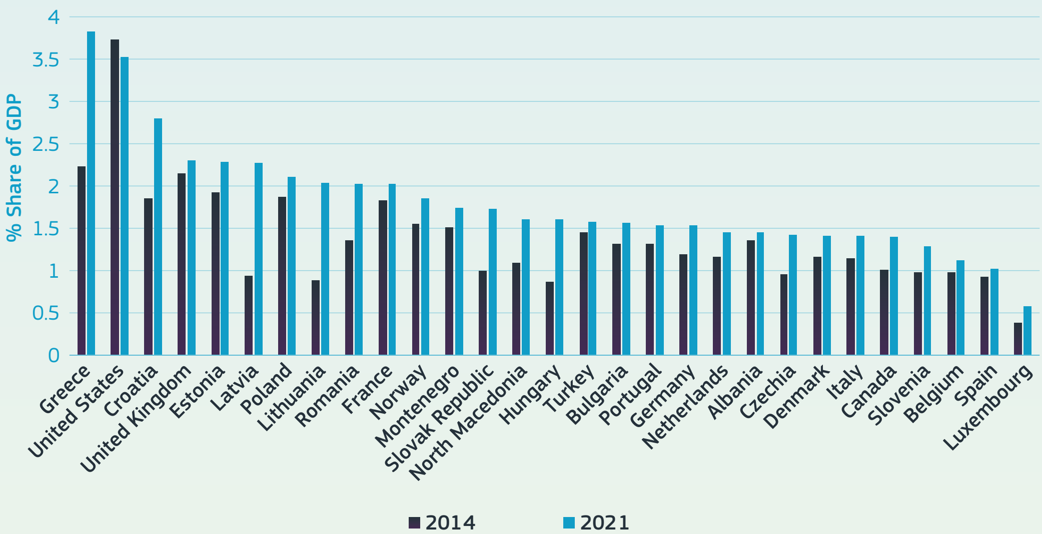


Science, Research and Innovation Performance of the EU 2022
Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Eurostat (online data code: gba_nabsfin07)
Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-2-21.xlsx

Box 5.2-3: R&D investments in defence

The invasion of Ukraine by Russia in February 2022 naturally brings the defence industry, and related R&D, to centre stage. In 2020, the five biggest spenders on defence were the United States, China, India, Russia and the United Kingdom, representing together 62 % of world military spending. Among these countries, China showed a significant increase of 76 % in its military expenditure over 2011-2020 (Lopes da Silva et al., 2021). The NATO guidelines suggest that member countries should spend 2 % of their GDP on defence. This 2 % guideline is met today by the USA, UK and eight EU Member States (NATO, 2021): Greece (the highest share amongst the NATO members, with 3.8 % of GDP), Croatia, Estonia, Latvia, Poland, Lithuania, Romania and France (Figure 5.2-22). Since 2014, the share of GDP invested in defence has increased for all NATO member countries, except the USA. The Russian war against Ukraine may also reinforce this trend. For example, announcements in Germany include a special defence fund that can boost German defence spending from around 1.5 % of GDP to at least 2 % (*The Economist*, 2022b).

Figure 5.2-22: Defence expenditure as a share of GDP, 2014 and 2021



Science, Research and Innovation Performance of the EU 2022

Source: NATO

Note: [(1)]Figures for 2021 are estimates.

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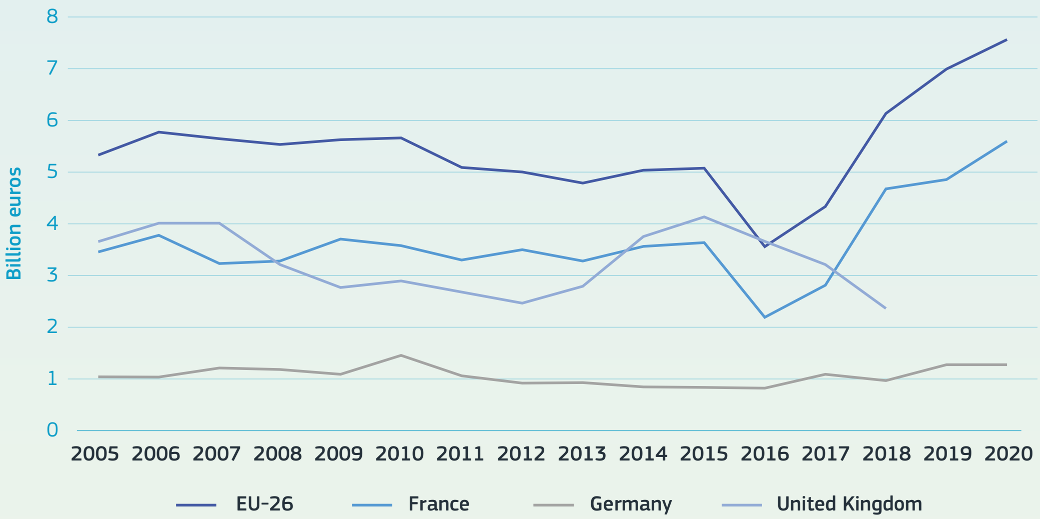
Spending on defence R&D in Europe is low. Compared to the other largest OECD economies, the United States spends a much greater share of GDP on defence R&D (Congressional Research Service, 2020). In the EU, most countries spend little on defence R&D, with the exception of France. The EU budget for defence R&D (without Denmark) amounted to EUR 7.6 billion in 2020[10], which includes 91% from both France (EUR 5.6 billion) and Germany (EUR 1.3 billion). The total amount of defence R&D in the EU was stable over 2005-2015, then increased significantly after 2016, mainly driven by increased French expenditure (Figure 5.2-23). EU expenditure on research and technology[11] corresponds to 1.25% of total defence expenditure in 2020, which is below the 2% benchmark of the European Defence Agency.

Compared to traditional civil sectors, the defence sector has specific characteristics, such as cost escalation over time of defence equipment and higher R&D costs (EC, 2018b). The cost escalation is a long-term trend for a sector that is driven by intense technological competition at the technology frontier, which is vastly expensive (Hove and Lillekvelland, 2016). The ratio of R&D costs to recurring costs of defence programmes is considered several times higher than the corresponding ratio for civil programmes (EP, 2016). These factors can limit the launch of new defence programmes, especially making them out of reach of single EU Member States, and can impact the competitiveness and innovation capacity of the EU industry. Furthermore, the defence market does not follow the conventional rules and business

Figure 5.2-23: Defence R&D Expenditure (in billion EUR), 2005-2020



Science, Research and Innovation Performance of the EU 2022

Source: European Defence Agency

Note: (1) EU-26 includes EU countries other than Denmark. Figures include any R&D programmes up to the point where expenditure for production of equipment starts to be incurred.

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-2-23.xlsx

10 Source: European Defence Agency

11 Expenditure for basic research, applied research and technology demonstration for defence purposes. It is a subset of R&D expenditures, which includes any R&D programmes up to the point where expenditure for production of equipment starts to be incurred (source: European Defence Agency).

models of more traditional markets: demand is almost entirely driven by Member States and their defence budgets, and the sector is strictly regulated. Therefore, the industry is not expected to spontaneously launch self-funded defence R&D projects and rather works on demand for a state (EC, 2018b).

Hence, **R&I in the defence sector hinges on public demand** (Moura, 2011; EC, 2018b). Several recent policy developments related to defence R&I can be observed. Of particular importance is the diminishing dichotomy between the civilian and the defence sector. At the EU level, the European Defence Fund supports defence research with a budget of close to EUR 8 billion over 2021-2027, while Horizon Europe has an exclusive focus on civil applications (Table 5.2-2 for an overview of programmes and instruments related to defence and security R&I). In its 2022 communication on the roadmap on critical technologies for security and defence (EC, 2022b), the Commission highlights that these technologies increasingly originate in the civilian domain and use critical components of a dual-use nature. Against this backdrop, it has announced the preparation of an approach for encouraging dual-use R&I across EU programmes and instruments. In a recent declaration[12] drawing lessons from the ongoing military aggression against Ukraine, EU leaders also stressed the importance of investing more and better in defence capabilities and innovative technologies. It was agreed to substantially increase defence expenditure, foster synergies between civilian, defence and space R&I, and invest in critical and emerging technologies and innovation for security and defence.

Table 5.2-2: EU programmes and instruments supporting R&I on critical technologies relevant to security and defence

Programme/instrument	Link to defence and security
European Defence Fund	EUR 8 bn to defence R&I
Horizon Europe	EUR 1.6 bn 'Civil security for Society' cluster to address challenges to border control, to counter cybercrime and to improve disaster-resilience and security of critical infrastructure; Critical technologies also supported under other clusters (e.g. 'Digital, Industry and Space' cluster); Complementary activities under Excellent Science, the European Innovation Council, the European Institute of Innovation and Technology and European partnerships.
Digital Europe Programme (DEP)	Deployment activities related to cybersecurity, AI and supercomputing
Cybersecurity Industrial, Technology and Research Competence Centre and the Network of Coordination Centres	These will adopt a strategic agenda on cyber investments feeding into Horizon Europe and DEP. Synergies between civilian and defence technologies and dual-use applications may be explored through links to EDF in line with applicable rules.
European structural and investment funds	The funds can be used in support of the European Defence Technological and Industrial Base
Other	Other relevant EU programmes, funds and instruments include the Space Programme, CEF, InvestEU Programme, the Recovery and Resilience Facility (RRF), the LIFE Programme, public-private partnerships, blending facilities

Science, Research and Innovation Performance of the EU 2022

Source: Authors' elaboration based on the communication on the roadmap on critical technologies for security and defence (European Commission, 2022b)

12 https://www.consilium.europa.eu/media/54773/20220311-versailles-declaration-en.pdf

At the European level, R&I funding programmes – in particular Horizon 2020 – have fully integrated the principle of directionality. It aims to focus on the areas with the greatest potential to deliver on the SDGs, and it maintains the 35 % target for climate action in Horizon 2020. As a new feature, it implements EU-wide R&I Missions (European Commission, 2017; 2018) with ambitious goals to tackle major societal challenges for Europe (climate change, healthy oceans, climate-neutral and smart cities, and soil health and food). Partly inspired by the Apollo 11 mission to put a man on the moon, the mission-oriented approach allows challenges to be transformed into concrete, measurable and achievable targets while mobilising and engaging citizens, policymakers and a broad range of actors well beyond the usual R&I stakeholders. The Missions are expected to be an instrument for delivering European public goods and transforming Europe into a greener, healthier and more resilient continent.

The European R&I funding programmes, including Horizon 2020, are responsible for 7.2 % of public R&I funding in 2019 in Europe and a significantly higher percentage when looking only at competitive funding (Figure 5.2-24). Horizon 2020 contributed to 0.1 % of the EU R&D intensity, estimated at 2.23 % in 2019[13]. Each euro invested in the programme mobilised an additional 0.25 euro of public and private investment in R&I projects for a total of EUR 16.9 billion[14]. An estimated additional EUR 9.5 billion was also leveraged by the EU framework programme research teams (EUR 4.2 billion) and as private follow-up investments attracted by EIC accelerator portfolio companies (EUR 5.3 billion).

Over 2014-2030, Horizon 2020 is expected to bring GDP gains of EUR 400-600 billion: each EUR of Horizon 2020 investment brings a GDP increase of EUR 6.0-8.5[15]. Furthermore, **European Union budgets have substantially increased over the last programming periods.** Together with the European structural and investment funds, the European Commission is an important source of R&D funding in many Member States. It represents a high share of the total R&D expenditure in some Member States, such as Latvia, Lithuania, Cyprus.

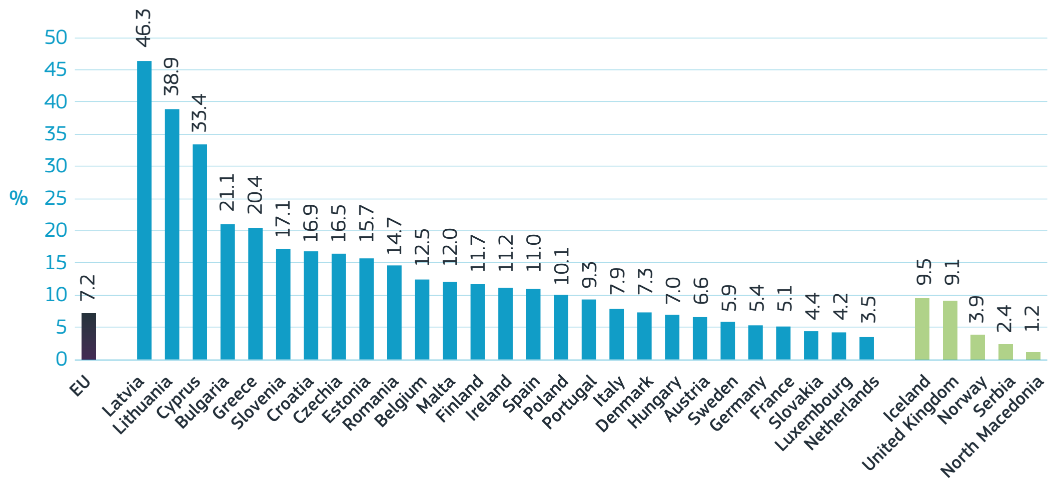
Amongst the different instruments designed under Horizon Europe, the EU Missions embody the paradigm shift that this Commission has committed itself to deliver. In September 2020, Europe's leading experts submitted a set of mission proposals that aim to find solutions for saving more lives from cancer, making Europe climate resilient, restoring our ocean and waters, achieving 100 climate-neutral cities, and ensuring 75 % of EU Member State soils are healthy by 2030. These missions are directly relevant to the delivery of the European Green Deal, a Europe Fit for the Digital Age, and a sustainable recovery (Table 5.2-3). They are at the very core of an economy that works for people and our European way of life. The implementation of these solutions goes far beyond the remit of R&I and can have direct impact on the delivery of a range of policies and portfolios across the Commission.

13 Source: CORDIS, EUROSTAT

14 Horizon Dashboard

15 Interim evaluation of Horizon 2020

Figure 5.2-24: R&D expenditure financed by the European Commission[3] as % of total R&D expenditure financed by the public sector[1], 2019[2]



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Eurostat (online data code: rd_e_gerdfund)

Note: [1]Public sector is defined as the sum of GOV, RoW European Commission and international organisations (using the GERD by source of funds). [2]UK:Year 2018. [3]The European Commission budget calculated in this figure represents mainly the budget for the Framework programme for R&I, and may not report the total of the budget dedicated to R&D from the European Structural funds under the correspoding category.

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-2-24.xlsx

The Horizon Europe Partnerships and the Horizon Policy Support Facility are also expected to drive EU-wide transformations towards a greener, socially relevant and digitally enabled society and economy, and will directly support the priorities of the Commission. Partnerships trigger additional private and public R&I investments, resources and activities around EU priorities. Horizon 2020 already supports 26 partnerships. Several partnerships are directly relevant for achieving the European Green Deal. The partnerships culminate in large coalitions and provide experimental platforms to test and develop innovative solutions for societal challenges and industrial transformation. As of December 2021, 49 partnerships are foreseen under the first strategic plan (2021-2024) of Horizon Europe. The **Horizon Policy Support Facility** (in operation since 2015) **provides policy advice** to Member States and Associated Countries (to Horizon 2020) **in the design, implementation and evaluation of R&I reforms** to improve the quality and impact of their R&I systems, investments and policies.

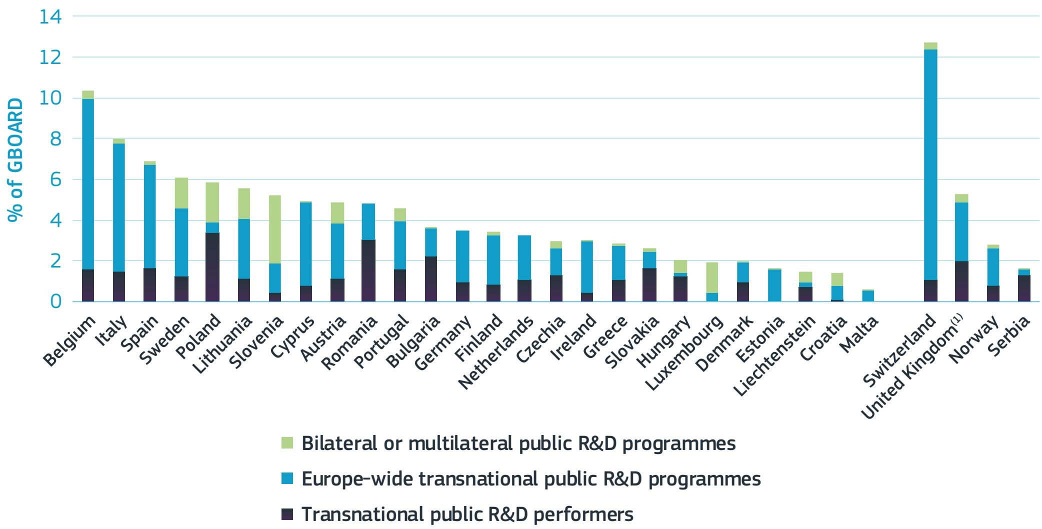
Table 5.2-3: Mapping of the Missions and European policy objectives

	Adaptation to climate change	Ocean, seas and waters	Climate-neutral and smart cities	Soil health and food	Cancer
Energy transition, mobility and housing		√	√		
Circular economy	√	√	√	√	
Jobs and skills in the local economy	√	√	√	√	√
Air quality	√	√	√	√	
Sustainable land use			√	√	
Climate adaptation and mitigation	√	√	√	√	
Digital transition	√		√		√
Urban poverty and inclusion of migrants and refugees		√	√	√	√
Territorial Agenda, post-2020 Urban Agenda and Interreg	√	√	√	√	√
Artificial intelligence		√		√	√
European data strategy	√	√	√	√	√
European industrial strategy	√		√	√	
High-performing computing	√	√			√
Digital transformation of businesses			√	√	
Connectivity	√	√	√	√	√
Digital skills	√	√	√	√	
Climate action (including Climate Pact and adaptation)	√	√	√	√	√
Biodiversity	√	√		√	
Farm to Fork	√	√		√	√
Sustainable industry	√	√	√	√	√
Clean energy	√	√	√		
Sustainable mobility	√	√	√		
Eliminating pollution	√	√	√	√	√
New European Bauhaus	√		√		

Science, Research and Innovation Performance of the EU 2022
Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on a publication by César Dro (DG R&I), Kathrin Kapfinger (DG R&I) and Ruzica Rakic (DG R&I)

The European Research Area is a multi-level governance initiative launched in 2000 to create a single, borderless market for research, innovation and technology across the EU and also embed the principle of directionality. It helps countries to cooperate more effectively, by strongly aligning their research policies and programmes. Furthermore, the ERA aims to reduce fragmentation of regulatory and administrative frameworks[16]. The ERA, together with the 3% Barcelona target and the accompanying action plan, was part of the Lisbon Strategy, which aimed to turn the EU into the most competitive and dynamic knowledge-based economy of the world. **Under the ERA transition forum launched in 2021, the European Commission proposed that national public funding to a transnationally coordinated R&D target would replace the 5% target for joint R&D investments**. This target would include EU funding under the Structural Funds. In 2019, the EU average was 4.25% of the total government budget for R&D (GBARD) allocated to transnationally coordinated R&D activities (Figure 5.2-25). Member States would all perform inside the bracket of a **minimum of 0.61% and a maximum of 8.85%** of total GBARD in 2019. A possible EU orientation indicator for the future Pact for R&I could be realistically set at **10% of total GBARD by 2030**, as both ambitious and attainable. It would in fact require the **doubling of efforts for cross-border European R&D investments**.

Figure 5.2-25: National public funding to transnationally coordinated R&D by source as a % of GBARD, 2020



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation, Chief Economist - R&I Strategy & Foresight Unit based on Eurostat

Note: (1)Data for UK is 2019

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16 Council Resolution of 15 June 2000 on establishing a European area of research and innovation, Lisbon European Council conclusions (24/3/2000)

The recovery and resilience facility scheme proposed by the Commission will also support directed R&D. According to the Single Market Report 2022, **around 40%** of the total allocation in Member States' Recovery and Resilience Plans **is related to measures supporting climate objectives, and more than 26% on the digital transition**. The horizontal R&I investments include a variety of cross-cutting measures such as strengthening of innovation ecosystems, upgrading research infrastructures, grants for researchers, support for business innovation, including start-ups and SMEs, and facilitation of public-private R&I cooperation. **The thematic R&I investments are targeted at specific areas**, such as **energy** (15% of total R&I expenditure, including, e.g., development of hydrogen solutions), **environment** (5%, e.g. supporting public and business environmental R&I or research in innovative green technologies), **transport/smart mobility** (4%, e.g. for development of electro-mobility), and the circular economy (3%, e.g. for development of re-use and recycling technologies). **R&I investments in digital technologies account for approximately 24% of total R&I expenditure** and include, for instance, development of advanced technologies (microprocessors, cloud, quantum computing, etc.), cybersecurity, 5G, and digital technologies of a more horizontal impact. Another important area of R&I investments is **health** (5% of total R&I expenditure). These investments include, for example, the development of alternative production processes for nuclear medicine for cancer treatment and the establishment of a centre for precision medicine.

Furthermore, **most Recovery and Resilience Plans includes R&D expenditure-based measures to boost R&I investment**. All approved Recovery and Resilience Plans[17] include measures related to R&I. This represents a total of 224 measures (55 reforms and 169 investments) for a budget of around EUR44.4 billion[18]. The amount of R&I investment in the Recovery and Resilience Plans represents typically between 4% and 13% of the Recovery and Resilience Facility grant allocation of a country, with a few outliers below or above this range and an average of about 10%. Investments range from ensuring access to finance for young innovative firms[19], to innovation diffusion and take up amongst SMEs[20]. In fifteen Recovery and Resilience Plans[21], innovation by firms, in particular SMEs, is also supported via reforms such as enhanced R&D tax-incentive schemes, new legal frameworks tailored to the needs of start-ups, innovative SMEs and social entrepreneurs (e.g. a new 'Austrian Limited' company form) and revision of innovation support instruments to make them more accessible to SMEs (e.g. the 'Widening the innovation base' reform in Belgium). Several Member States have also included investments to support Horizon Europe Partnerships and the funding of projects receiving a Seal of Excellence (i.e. projects which were judged to deserve funding under Horizon Europe but could not be financed due to budget limitations).

17 The recovery and resilience plans of the following 22 Member States have been approved so far: Austria, Belgium, Croatia, Cyprus, Czechia, Denmark, Estonia, Finland, France, Ireland, Italy, Germany, Greece, Latvia, Lithuania, Luxemburg, Malta, Portugal, Romania, Slovakia, Slovenia, and Spain.

18 This amount corresponds to the total estimated costs of all measures addressing research, development and innovation priorities, including those directly related to the green or digital transitions.

19 BG, CZ, EL, ES, HR, IT, CY, LT, RO, SK

20 CZ, DK, DE, IE, EL, FR, HR, IT, CY, AT, PL, PT, RO, SK, SE

21 AT, BE, BG, CZ, DK, DE, EL, ES, HR, CY, LV, LT, PL, PT, RO

R&I projects and initiatives at the regional level that meet European priorities are also supported through European Cohesion Policy. In 2021-2027, the first of the EU Cohesion Policy objectives was ‘a more competitive and smarter Europe through innovation and support to small and medium-sized businesses’. This objective is the main priority of the European Regional Development Fund. ESF Social Innovation+ is another initiative and aims to facilitate the transfer and upscaling of innovative solutions to societal challenges. Administered through indirect management (i.e. implemented by an ESF agency on behalf of the European Commission), ESF Social Innovation+ has a budget of EUR 197 million for the 2021-2027 programming period[22]. In past programming periods, European Structural and Investment Funds have directly supported millions of projects, many of which are R&D projects[23]. **Several other EU policy programmes, initiatives and funds also support R&D projects with directionality, such as LIFE**. Since 2018, the LIFE programme has been instrumental in supporting green innovations and cleantech solutions across Europe. As well as funding up to 55 % of each project, the LIFE financial instrument helps with the commercialisation of innovative solutions, easing their entry into the market[24].

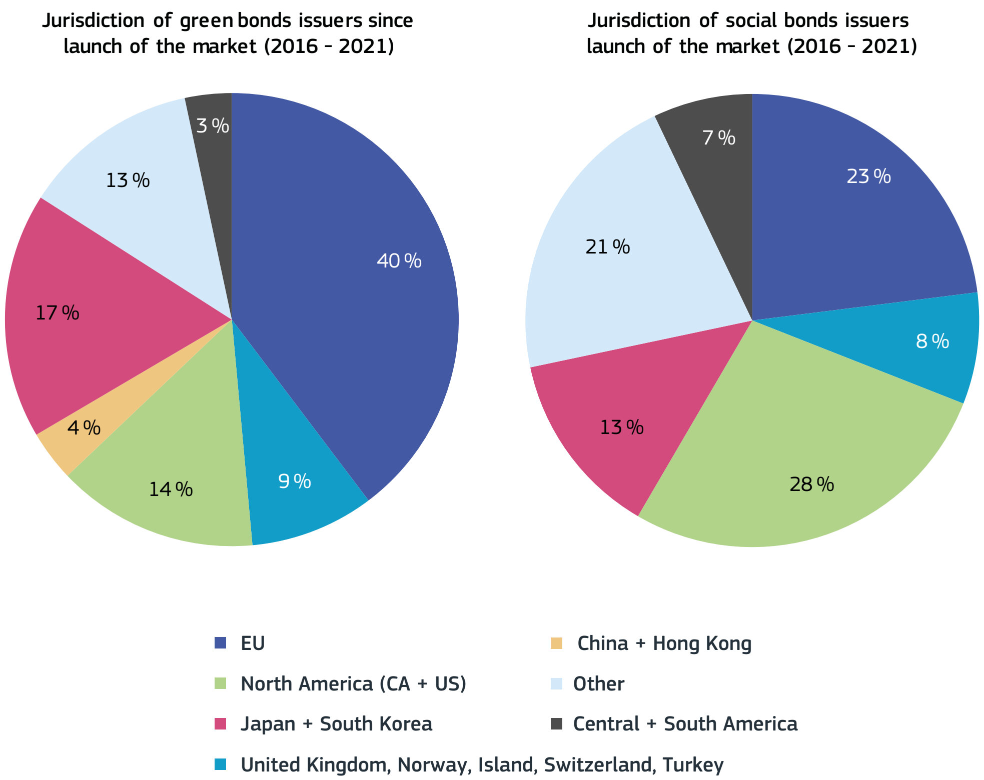
The EU sustainable finance framework has been revised to foster private sustainable and responsible investments, including R&D investments. The 2020 EU taxonomy establishes a list of environmentally sustainable economic activities and should create security for investors, protect private investors from greenwashing, help companies to become more climate-friendly, mitigate market fragmentation and help to shift investments.

In 2021, the European Commission also proposed a regulation for a European green bond standard (EU-GBS) to facilitate the issuance of green bonds by enhancing the transparency, comparability and credibility of the green bond market for both borrowers and investors. Lately, **green and social bonds have been playing an increasing role in financing green and social innovation** (Figure 5.2-26). Their issuance in comparison to total bond issuance has been growing steadily since their inception, both in terms of contracts and volumes. For example, **green bonds worldwide, expressed as a percentage of total bond issuance, doubled in terms of volume and almost quadrupled in terms of the number of deals between 2018 and 2019** (European Commission, 2021d). The market for green bonds has experienced exponential growth since its inception in 2007 and witnessed a high growth rate between 2014 and 2020 (from EUR 31.1 billion to EUR 245 billion).

Social impact bonds, which are typically implemented by social and solidarity-economy entities, have started to emerge over the last decade, both for domestic initiatives and in the framework of international development cooperation. **Recent estimates identify 221 social impact bonds that have been implemented in 37 countries, mostly related to employment and social welfare objectives** (Brookings, 2022). Europe is in the lead worldwide for the issuance of these bonds.

22 ESF Social Innovation+ | European Social Fund Plus (europa.eu)
23 Maps - Regional Policy - European Commission (europa.eu)
24 LIFE close-to-market projects (europa.eu)

Figure 5.2-26: Jurisdiction of green and social bonds issuers since launch of the market (2016-2021)



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on International Capital Markets Associations

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4. Conclusions: boosting directed R&D investments

With just over 2% of its GDP in R&D, the EU has not achieved its 2020 3% target. It is underinvesting in R&D compared to its main competitors, especially in terms of private investments, while Asian countries, in particular China and South Korea, are investing at a rate that is eclipsing both the EU and the United States. If this continues, Europe risks being outpaced irreversibly.

The **EU is well-positioned in some sectors, such as mobility and chemicals, but less in others, notably the highly R&D-intensive sectors, such as health and ICT. Considering the impacts of the COVID-19 pandemic**, which has hit mobility and manufacturing sectors hard but positively impacted health and ICT services sectors, this unbalanced situation may jeopardise its competitiveness in the future.

EU public and private investment in R&D are steering towards societal and environmental challenges, but at a slow pace. Member States use direct support funding, often directed, to increase the EU science and technological base. However, they also use more and more tax relief schemes to foster private R&D investments, with some also featuring some degree of directionality towards sustainable challenges and others focusing on supporting SMEs or young start-ups.

At the European level, **one of the main public investment instruments in Europe is the EU's R&I framework programme**. Horizon Europe, the 2021-2027 framework programme, with its increased budget of almost EUR 95.5 billion, will continue to create new knowledge and solutions to attain the SDGs. It provides even **greater directionality through its mission-oriented approach** (on, for example, climate change, healthy oceans, climate-neutral and smart cities, and soil health and food) and European partnerships. **The European Cohesion policy and structural funds,** and several other EU policy programmes, initiatives and funds, **also support R&D projects with directionality**. Finally, most Member States **include measures to boost R&D investments in their Recovery and Resilience Plans.**

Europe requires **coordinated reform and a modernisation effort** that could be aimed at ensuring the effectiveness and efficiency of increased R&D investments as well as incentivising and leveraging private investments in the future: **investments and reforms must go hand in hand**. The timeline and intensity for such investments as well as structural reforms of the R&I systems could be clearly adapted to the national context and national specificities (e.g. economic structure, structure of the R&I system) in the Member States, in particular as regards the absorption capacity in terms of increased funding and the pace of the modernisation of the R&I sector. This also calls for enhanced **national strategies** that ensure a timely delivery on those key objectives.

References

Agrawal, A.,Rosell C., Simcoe, T. (2020), 'Tax credits and small firms R&D spending', American *Economic Journal: Economic Policy*, 12(2), pp. 1–21.

Almunia, M., Lopez-Rodriguez D. (2018), 'Under the Radar: The Effects of Monitoring Firms on Tax Compliance', *American Economic Journal: Economic Policy*, 10 (1), pp. 1-38.

Appelt, S., Bajgar, M., Criscuolo, C., Galindo-Rueda, F. (2020), *Effectiveness of R&D tax incentives in OECD economies*, VOX, CEPR Policy Portal.

Archibugi, D., Filippetti, A. (2018), 'The retreat of public research and its adverse consequences on innovation', *Technological Forecasting and Social Change*, 127. pp. 97-111.

Chen, Z., Liu Z. Suarez Serrato J.C., Xu D.Y. (2021), 'Notching R&D investment with corporate income tax cuts in China', *American Economic Review*, 111(7), pp. 2065-2100

Coe, D., Helpman E. (1995),- 'International R&D Spillovers', *European Economic Review*, 39, pp. 859–887

Dechezleprêtre, A., Martin, R., Mohnen, M., (2014), *Knowledge Spillovers from Clean technologies: A patent Citation analysis*, CEP Discussion Papers (CEPDP1300), Centre for Economic Performance. LSE.

Dechezlepretre, A., Einiö E., Martin R., Nguyen K-T., Van Reenen, J., (2016), 'Do tax incentives for research increase firm innovation? An RD design for R&D', CEP Discussion Paper 1413.

Dosi, G., Stiglitz J., (2014), *The Role of Intellectual Property Rights in the Development Process, with Some Lessons from Developed Countries: An Introduction*, in Cimoli M., Dosi G., Maskus K., Okediji R., Reichman J., Stiglitz J. (eds). Intellectual Property Rights and Development, Oxford/New York: Oxford University Press.

European Commission (2010), A strategy for smart, sustainable and inclusive growth. COM(2010) 2020 final.

European Commission (2015), Renewables, smart systems, efficient systems, sustainable transport, CCUS and nuclear safety, COM(2015) 80 final

European Commission (2017), LAB – FAB – APP: investing in the European future we want. Directorate-General for Research and Innovation. Report of the independent High Level Group on maximising the impact of EU research & innovation programmes, Publications Office.

European Commission (2017), The Economic Rationale for Public R&I Funding and its Impact,Directorate-General for Research and Innovation, Policy Brief Series

Mazzucato, M., *Mission-oriented research & innovation in the European Union : a problem-solving approach to fuel innovation-led growth*, European Commission, Directorate-General for Research and Innovation, Publications Office.

Borunsky, L., Dumitrescu Goranov, A., Rakic, R., et al. (2020) Aiming for more: R&D investment scenarios for the next decade, European Commission, Directorate-General for Research and Innovation, Publications Office, 2020.

Prange-Gstoehl, H., Rakic, R., Ravet, J., et al., (2021a), R&D investment targets and reforms, European Commission, Directorate-General for Research and Innovation, Publications Office, 2021, https://data.europa.eu/doi/10.2777/156604

European Commission (2021b). Report from the commission to the European parliament and the council. *Progress on competitiveness of clean energy technologies*, COM(2021) 952 final

European Commission (2021c), *Annual Report on Taxation 2021: review of taxation policies in the EU Member States*, Directorate-General for Taxation and Customs Union, Publications Office, 2021.

Grassano, N., Hernández, H., Guevara, H., et al., The 2021 EU industrial R&D investment scoreboard: executive summary, European Commission, Joint Research Centre. Publications Office, 2021

European Investment Bank (2021), *EIB investment report 2020/2021 : building a smart and green Europe in the COVID-19 era*, European Investment Bank, 2021

Evers, L., Miller, H., Spengel, C., (2015), 'Intellectual Property Box Regimes: Effective Tax Rates and Tax Policy Considerations', International Tax and Public Finance, 22, pp. 502-530.

Frontier Economics (2014), *Rates of return to investment in science and innovation*, BIS/14 /990.

Gaddy, B.E., Sivaram, V., Jones, T.B., Wayman, L., (2017), 'Venture Capital and Cleantech: The Wrong Model for Energy Innovation', *Energy Policy*, 102 (2017), pp. 385-395

Hall, B., Van Reenen, J., (2000), 'How Effective Are Fiscal Incentives for R&D? A Review of the Evidence', *Research Policy,* 29(4-5), pp. 449–69.

Hall, B., (2019), *Tax Policy for Innovation*, NBER Working Papers, No. 25773.International Energy Agency (2021), *Net Zero by 2050. A Roadmap for the Global Energy Sector*. IEA Publications.

Kao, C., Chiang, M.-H., Chen B., (1999), *International R&D spillovers: an application of estimation and inference in panel cointegration*, Oxford Bulletin of Economics and Statistics, 61(4), pp. 693–711.

Mazzucato. M., (2013), *The Entrepreneurial State: Debunking Public vs. Private Sector Myths*, London: Anthem Press.

OECD (2020), *The effects of R&D tax incentives and their role in the innovation policy mix: Findings from the OECD microBeRD project, 2016-19*, OECD Science, Technology and Industry Policy Papers, No. 92, OECD Publishing, Paris.

OECD (2016), *R&D Tax Incentives: Evidence on Design, Incidence and Impacts*, OECD Science, Technology and Industry Policy Papers, No. 32, OECD Publishing, Paris.

OECD (2021), OECD *Main Science and Technology Indicators. R&D Highlights in the March 2021 Publication*, OECD Directorate for Science, Technology and Innovation.

OECD (2021). *Measuring Tax Support for R&D and Innovation: Indicators*. OECD Directorate for Science, Technology and Innovation.

Rakic, R. et al. (2021), *Fostering R&D intensity in the European Union: Policy experiences and lessons learned*, Case study contribution to the OECD TIP project on R&D intensity, OECD Publishing: Paris.

Sterlacchini, A., Venturini, F., (2018), 'R&D tax incentives in EU countries: does the impact vary with firm size?', *Small Bus Econ*, 53, pp. 687–708.Stern, N., Valero, A., (2021), 'Innovation, growth and the transition to net-zero emissions', *Research Policy*, 50(9).

UNESCO Science Report: the Race Against Time for Smarter Development (2021), data sourced from UNESCO Institute for Statistics and animated by Values Associates.

CHAPTER 5.3

THE ICT SECTOR AND DIGITALISATION

KEY FIGURES

€63 billion
of value added in the EU ICT sector

4.2 %
share of the ICT sector in total GDP

6 million
workers employed in the EU ICT sector

13 %
share of EU firms using big data analytics

5.4 %
R&D intensity in the EU ICT sector

KEY QUESTIONS WE ARE ADDRESSING

- How is the EU ICT sector performing compared to that of other major economies?
- Where does the EU stand in terms of the digital divide and the integration of digital technologies?
- How does the EU perform in terms of ICT innovation?

KEY MESSAGES

What did we learn?

- The COVID-19 pandemic has accelerated the digitalisation process in the EU but has also exacerbated the digital divide between EU firms, regions and countries.
- The boost to digitalisation after the pandemic has not been sufficient to reduce the gap between the EU and its international competitors.
- Overall, the EU lags behind the USA and China in terms of digital patent applications across several industries, although it remains strong in the automotive sector and in the field of climate change.

What does it mean for policy?

- Increasing asymmetries across EU Member States put the European convergence process in jeopardy.
- R&I policy plays a critical role in supporting the EU digital transition, enabling the development and deployment of digital innovations throughout the EU.
- The digital transition has changed the way the society interacts and operates, calling for increasing efforts to protect and safeguard European citizens' rights and freedoms.

The rapid development of ICT over the last few decades has set in motion an irreversible change in how business is done. The way firms adopt and use ICT determines their ability to cope with the challenges of modern times. Further developing the ICT sector in the EU is critical to increasing competitiveness by allowing European enterprises to take part in global digital supply chains.

ICT plays a central role in promoting innovation and growth across EU countries. The ICT sector is a key determinant of the competitive power of knowledge-based economies as it is a magnet for investors and constitutes a natural environment for innovation (OECD, 2020).

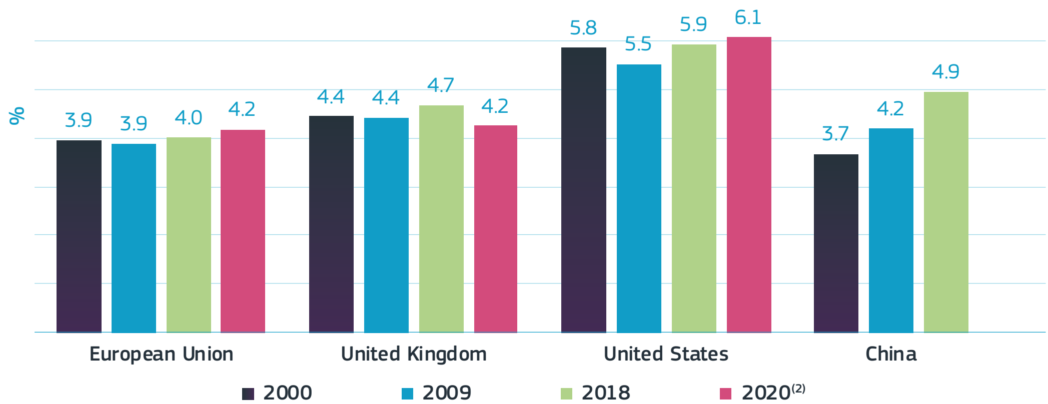
Furthermore, the impacts of the digital transformation are irreversibly transforming the world of work. The non-rival nature of digital innovations has an impact on firms' production technologies, which are often characterised by relatively high fixed costs of development and low (close to zero) marginal costs. Also, digitalisation entails strong network effects that can play an important role in the uptake of digital technologies by end users. Both factors play a role in understanding why the ICT-producing sector is strongly concentrated, with a few dominant tech and digital giants.

1. The ICT sector in the EU

A strong ICT sector[1] enables EU businesses to compete in globalised markets. The European Commission has placed the development of the ICT sector at the heart of its policy agenda. By including 'a Europe fit for the digital age' among its core priorities, the European Commission creates a concrete and comprehensive digital strategy. In this regard, monitoring the evolution of the ICT-producing sector is essential to identify potential sources of innovation and to effectively implement EU and national policy action[2].

The value added of the EU ICT sector has increased by more than 70 % in absolute term, over 2000-2020. In 2019, the value added of the sector stood at EUR 607 billion, a slight increase compared to 2018. The ICT sector stagnated in 2020, due to the COVID-19 crisis, with a value added of EUR 603 billion.

Figure 5.3-1: ICT(1) sector value added as % of GDP by world region, 2000, 2009, 2018, 2020



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit, based on DESI Report 2021 - ICT Sector and Its R&D performance, PREDICT Project; Eurostat (online data code: nama_10_gdp); OECD Database

Note: (1)Data for the ICT sector are aggregated using the operational definition of the ICT sector as defined in the PREDICT project, which does not include the following industries: manufacture of magnetic and optical media (268) and ICT trade industries (465). The operational definition enables the EU to be compared with non-EU countries. (2)US and UK data on GDP for 2020 are taken from OECD Database.

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1 In this chapter, the ICT sector is defined according to the definition provided by the OECD and based on the Statistical Classification of Economic Activities in the European Community (NACE) Rev.2 (2008) nomenclature. Specifically, data are aggregated using the comprehensive definition of the ICT sector from the PREDICT project, when not specified otherwise.

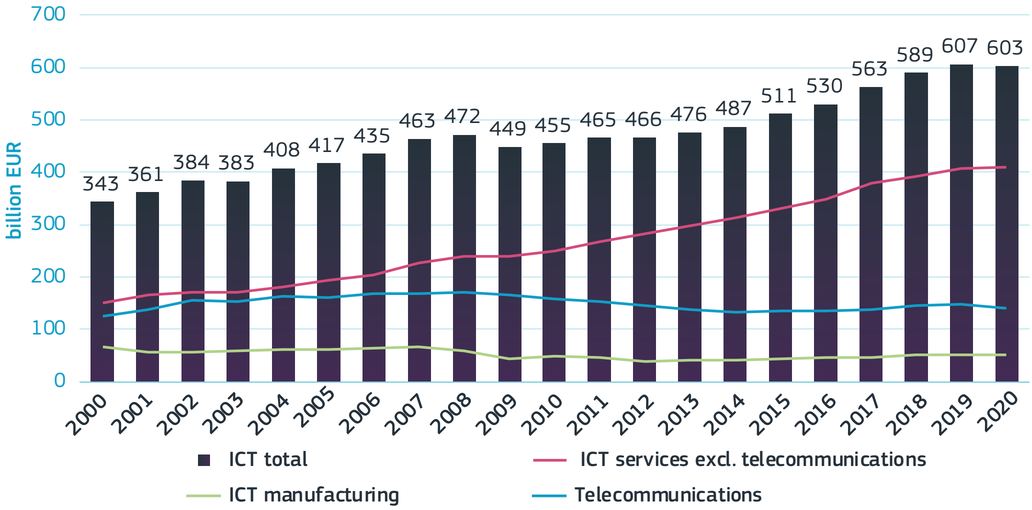
2 Commission Staff Working Document 'Annual Single Market Report 2021' (SWD(2021) 351 final)

Nevertheless, the value added of the ICT sector in the EU as a share of total GDP has been stagnating around 4% over the last decades. When compared to its main international competitors, in 2020 the contribution of the ICT sector to the European economy was lower than in the USA (4.2% against 6.1%) and the same as in the UK (Figure 5.3-1). Nevertheless, when looking at the evolution over time, the share of the ICT sector in national GDP has also been stagnating in the UK and the USA. Although the ICT sector grew by 46% and 74% in the two countries respectively in absolute terms (DESI, 2021a), its weight in national GDP increased only marginally over 2000-2020 in the USA, while it decreased in the UK over the same period. China represents an important exception as the contribution of the ICT sector to Chinese GDP grew significantly over time, increasing from 3.7% in 2000 to 4.9% in 2018.

The performance of the EU ICT sector is not homogeneous across ICT subsectors. ICT services (excluding telecommunications) were the key driver of the overall positive trend of the sector over time. Between 2000 and 2020, it was the only subsector that experienced a significant increase, moving from EUR 151 billion value added in 2000 to EUR 411 billion in 2020. Furthermore, this subsector was the only one reporting a positive performance after the outbreak of the COVID-19 pandemic (Figure 5.3-2). In contrast, both telecommunications and ICT manufacturing experienced a decline 2006-2018 and stagnated thereafter.

Germany, France, Italy, Spain and the Netherlands together accounted for 65% of value added in the EU ICT sector (in 2020). Germany reported the highest valued added in the ICT sector across EU countries, with EUR 142 billion in 2020. France ranked

Figure 5.3-2: ICT sector value added in billion EUR, 2006-2020



Source: DESI Report 2021 - ICT Sector and Its R&D performance, PREDICT Project
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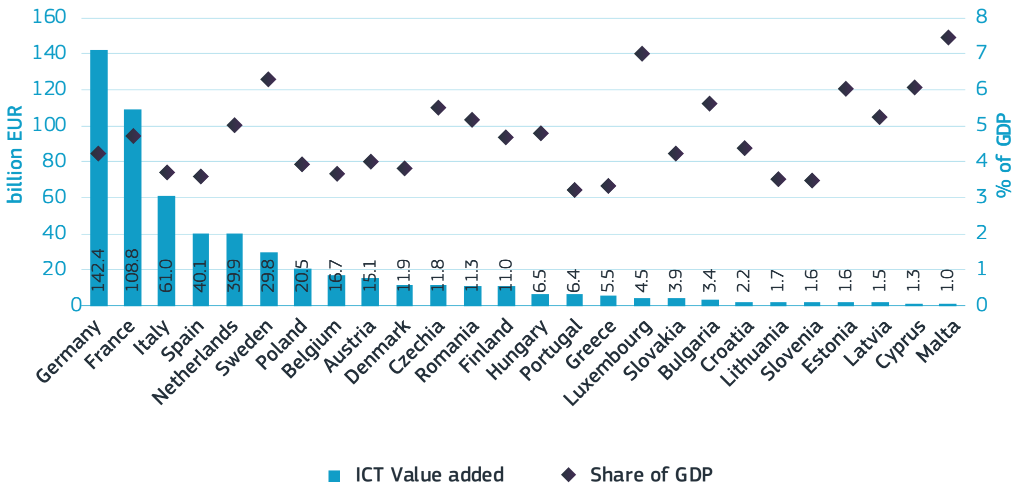
second with EUR 109 billion. Italy, Spain and the Netherlands followed with an ICT value added ranging between EUR 61 billion and EUR 40 billion (Figure 5.3-3).

In terms of GDP contribution, the EU countries with high ICT share were Malta (7.5%), Luxembourg (7.0%) and Sweden (6.3%). Eastern European countries such as Romania, Hungary and Latvia also reported a large contribution of the ICT sector to their GDP, with a share of around 5%.

The EU ICT sector employed over 6 million people in 2020, continuing the upward trend started in the 2000s. The ICT services (excluding telecommunications) subsector accounted for the highest share of ICT employment in 2020, with about 4.7 million employees. It is also the only subsector in which employment has been increasing over a long period (2006-2020). This is in line with the earlier finding of its prominent role for the overall performance of the ICT sector. The telecommunications and ICT manufacturing subsectors experienced a decline in the number of people employed over the same period. The decrease was more significant in the ICT manufacturing segment, which reported a 35.5% drop between 2006 and 2020, from 817 million to 527 million employees.

The government budget allocation to R&D (GBARD) in the ICT sector has remained relatively constant over the last decade. The allocation increased between 2017 and 2019, when the ICT GBARD increased from EUR 5.8 billion to EUR 6.4 billion (Figure 5.3-5).

Figure 5.3-3: ICT[(1)] value added in billion EUR and as % of GDP by EU Member State, 2020



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on DESI 2021 – the EU ICT sector and its R&D performance, PREDICT Project; Eurostat [nama_10_gdp]

Note: [(1)]Data for the ICT sector are aggregated according to ICT sector comprehensive definition, as defined by the PREDICT project; Data for IE not available for 2020.

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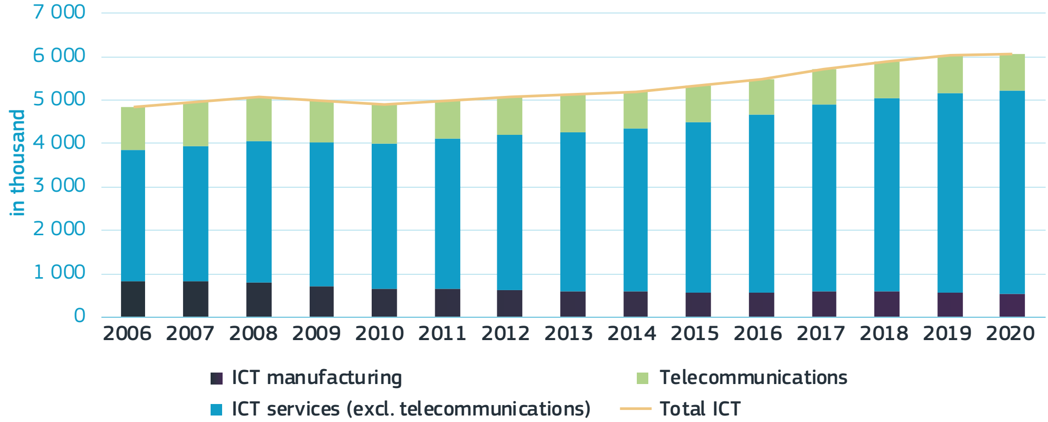
Figure 5.3-4: Employment in the ICT(1) sector broken down by manufacturing and services in the EU, 2006-2020



Science, Research and Innovation Performance of the EU 2022

Source: DESI 2021 – the EU ICT sector and its R&D performance, PREDICT project

Note: (1)Data for the ICT sector are aggregated according to the comprehensive definition of the sector from the PREDICT project. Data for Ireland not available for 2020.

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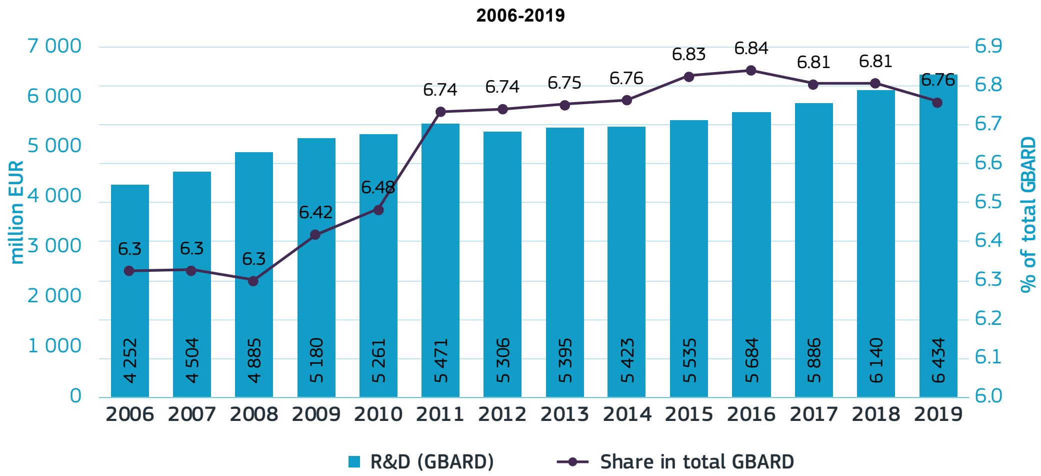
Similarly, the share of GBARD in the ICT sector in total public funding for R&D has remained relatively constant over time, ranging between 6.7% and 6.8% over 2011-2019 (Figure 5.3-5).

In contrast, the share of business R&D expenditure (BERD) in the EU ICT sector over total BERD has decreased over the past decade. Although ICT BERD in the EU has increased over time in absolute terms, its contribution to total BERD has declined over time. In 2006, the share of ICT BERD in total EU R&D expenditure by business enterprises was around 18.6%, whereas in 2020 the share was about 15.3% (Figure 5.3-6).

The R&D intensity[3] of the EU ICT sector was around 5.2% in 2020, well below the EU's main international competitors. South Korea has the most R&D-intensive sector, with a BERD/value added ratio of 20.4% in 2020, followed by the USA with 9.8%. Japan and China also report a higher R&D intensity than the EU, i.e. 7.3% and 6.2%, respectively. In contrast, the UK is lagging behind the EU, with an R&D intensity of 3.6% in 2020.

3 R&D Intensity is measured as BERD over value added.

Figure 5.3-5: Government Budget Allocation to R&D (GBARD) in the ICT[(1)] sector in the EU, 2006-2019



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit, based on DESI Report 2021 - ICT Sector and Its R&D performance, PREDICT Project; Eurostat (online data code: gba_nabsfin07).

Note: [(1)]Data for the ICT sector are aggregated according to ICT sector comprehensive definition, as defined by the PREDICT project.

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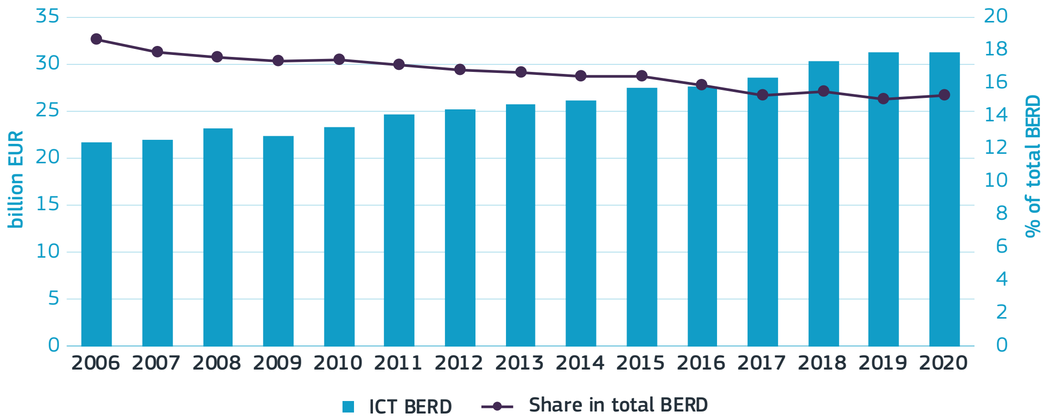
Figure 5.3-6: Business R&D expenditure (BERD) in the ICT[(1)] sector in the EU, 2006-2020



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – ¬Common R&I Strategy and Foresight Service – Chief Economist Unit, based on DESI 2021 – the EU ICT sector and its R&D performance, PREDICT project; Eurostat [online data code: rd_e_berdindr2]

Note: [(1)]Data for the ICT sector are aggregated according to the comprehensive definition of the sector from the PREDICT project.

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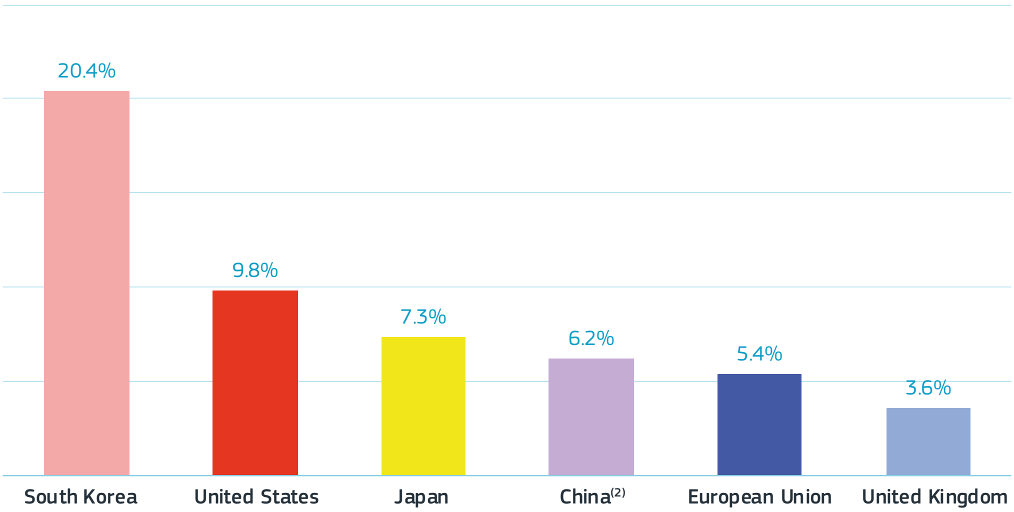
Figure 5.3-7: R&I Intensity in the ICT[1] sector per world region, 2020



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit, based on DESI Report 2021 - ICT Sector and Its R&D performance, PREDICT Project.

Note: (1)Data for the ICT sector are aggregated using the operational definition of the ICT sector as defined in the PREDICT project, which does not include the following industries: manufacture of magnetic and optical media (268) and ICT trade industries (465). The operational definition enables the EU to be compared with non-EU countries. (2)CN: year 2018

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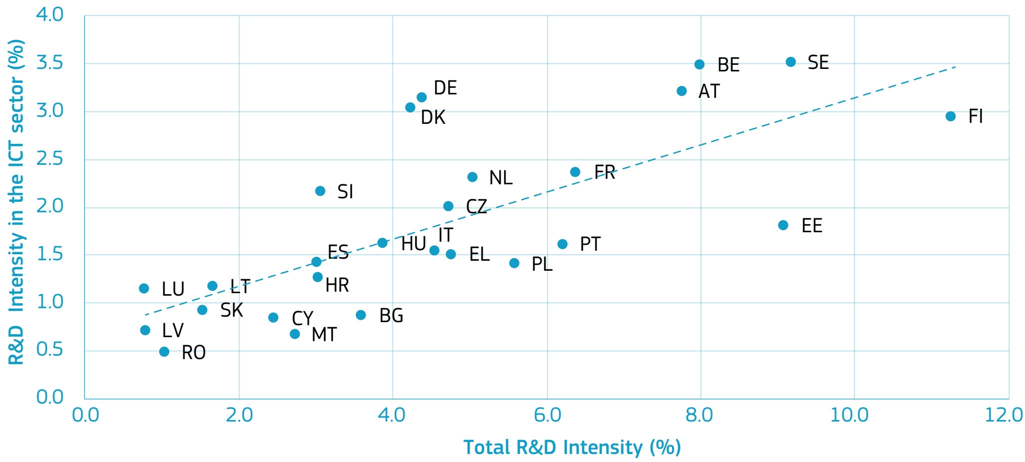
Finland, Sweden and Estonia report the highest R&D intensity in the ICT sector. Finland also confirmed its role as an innovation leader in 2020, with an R&D intensity in the ICT sector equal to 11%. Sweden followed with 9%, continuing its strong performance (DESI, 2021a). Estonia reported the same R&D intensity as Sweden, showing an improvement compared to the 6% registered in 2018 (DESI, 2021a). Other strong performers were Belgium and Austria, also both with an R&D intensity close to 8%. Countries such as the Netherlands, Czechia and Italy performed very closely to the EU average, while the R&D intensity in ICT was only about 1% in Romania, Latvia and Luxembourg (Figure 5.3-8).

Interestingly, the Member States reporting the highest R&D intensity in the ICT sector also performed very well in terms of national R&D intensity[4]. In 2020, Sweden and Belgium reported the highest total R&D intensity in the EU (3.5% for both). Other countries with a high R&D intensity were Austria (3.2%) and Finland (2.9%) (Figure 5.3-8).

4 Total R&D intensity is calculated as the percentage of R&D expenditure over GDP.

Figure 5.3-8: Total R&D Intensity vs R&D intensity in the ICT[(1)] sector by EU Member States, 2020



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit, based on DESI Report 2021 - ICT Sector and Its R&D performance, PREDICT Project; Eurostat (online data code: rd_e_berdindr2).

Note: [(1)]Data for the ICT sector are aggregated according to ICT sector comprehensive definition, as defined by the PREDICT project.

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2. The EU digital divide

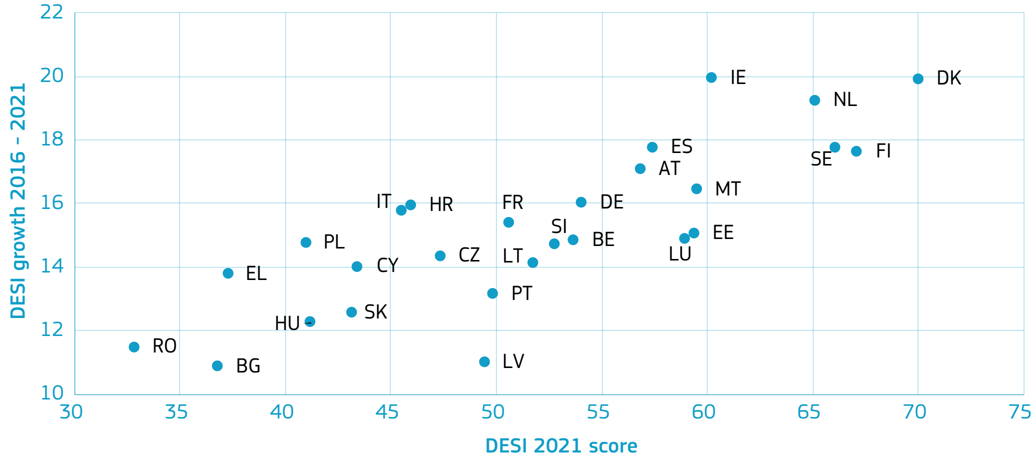
Digitalisation goes beyond the ICT sector. The digital transition affects different aspects of society, as it influences the way people work and live and how businesses operate. For instance, the diffusion of ever more sophisticated digital technologies calls for workers' re- and up-skilling to cope with the challenges of the digital age (see chapter 4.3 – Skills in the digital era). Furthermore, the massive shift to remote teleworking after the outbreak of COVID-19 allowed firms to ensure a certain degree of business continuity, thereby partially counteracting the disruptive effects of the pandemic (see chapter 1 – COVID-19, recovery and resilience).

Digitalisation has accelerated the pace at which R&I activities are performed. The increasing automation levels, use of big data analytics, Internet of Things (IoT) and AI have increased researchers' productivity capacity, which also contributes to the opening of new research fields. The rapid uptake of digital technologies across several industrial sectors has enabled the creation of new and more efficient business processes and products, allowing for a broad set of new applications and breakthrough innovations (European Commission, 2021). Digitalisation has also intensified the spread and application of knowledge by boosting open innovation and opening access to larger talent pools. Furthermore, digitalisation has increased the speed at which technology proliferates, and changed firms' innovation strategies. This is especially true for consumer-driven innovations, linked not only to the faster spread of digital business-to-consumer activities, but also to the increase in consumer participation in firms' innovation processes (European Commission, 2021).

Despite the high proliferation of digital tools, the digital divide is increasing. The digital divide refers to the gap between individuals and economic actors who have access to ICT and are able to take part in the information society, and those who are excluded from these digital services. Digital literacy is not homogeneous across EU Member States, and substantial differences also remain within countries between more industrialised and rural areas, as well as across different age groups (see chapter 4.3 – Skills in the digital era).

Digital performance varies widely across EU countries. The DESI provides an overview of the digital performance of EU countries, allowing a distinction to be made between digital innovators and those Member States still lagging behind in terms of digital performance (DESI, 2021b). Between 2015 and 2020, Ireland and

Figure 5.3-9: EU Member States' progress in their digital performance, DESI index 2016-2021



Source: DESI 2021 – the EU ICT sector and its R&D performance.
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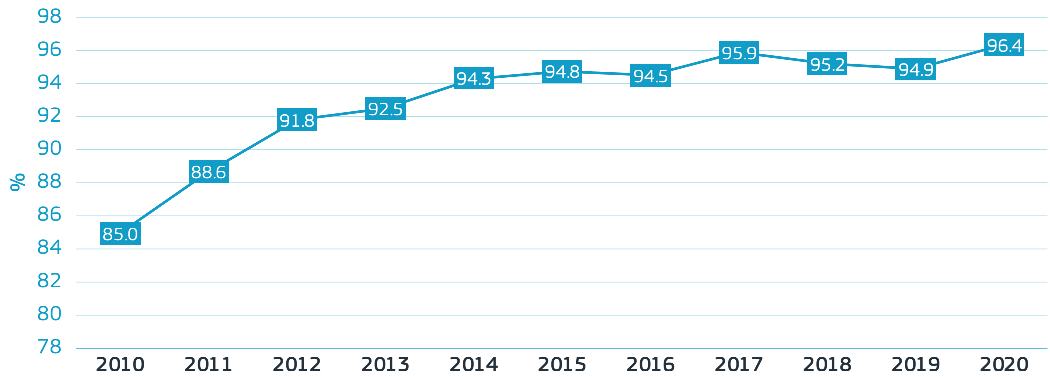
Denmark advanced well in making their economies fit for the digital age. The Netherlands, Spain, Sweden and Finland also reported an improvement in their digital performance over the same time span (Figure 5.3-9). Denmark, Finland, Sweden and the Netherlands were also the main digital innovators in the EU in 2020, according to the DESI ranking (DESI, 2021). Ireland, Malta and Estonia performed quite well in terms of DESI ranking, while Greece, Bulgaria and Romania lagged significantly behind the rest of the EU countries. Bulgaria and Romania showed only slow progress over the last five years.

Almost all firms in the EU have a broadband connection. The number of European enterprises with a broadband connection has increased steadily over time. In 2020, 96.4% of firms in the EU had a broadband connection at their disposal, compared to 85% in 2010 (Figure 5.3-10). With the acceleration of the digital transition, businesses are progressively relying on digital technologies to carry out their activities. Nowadays, access to internet is an integral part of the way of doing business worldwide (OECD, 2020).

Nevertheless, divergences persist across Member States in terms of the number of employees using computers with internet access. Looking at the share of employees able to work with an internet-connected device provides a better overview of the extent to which ICTs have been embedded in EU businesses (OECD, 2020). Sweden, Finland and Denmark report the highest share of employees using computers with internet access, ranging between 83.3% and 77.4% (Figure 5.3-11). Greece, Hungary, Latvia and Portugal report shares well below 50%.

5 The 2016 and 2021 DESI indexes refer respectively to data for 2015 and 2020

Figure 5.3-10: Share of businesses with a broadband connection in the EU, 2010 – 2020 (includes both fixed and mobile)



Science, Research and Innovation Performance of the EU 2022

Source: OECD ICT Access and Usage by Businesses Database, December 2021

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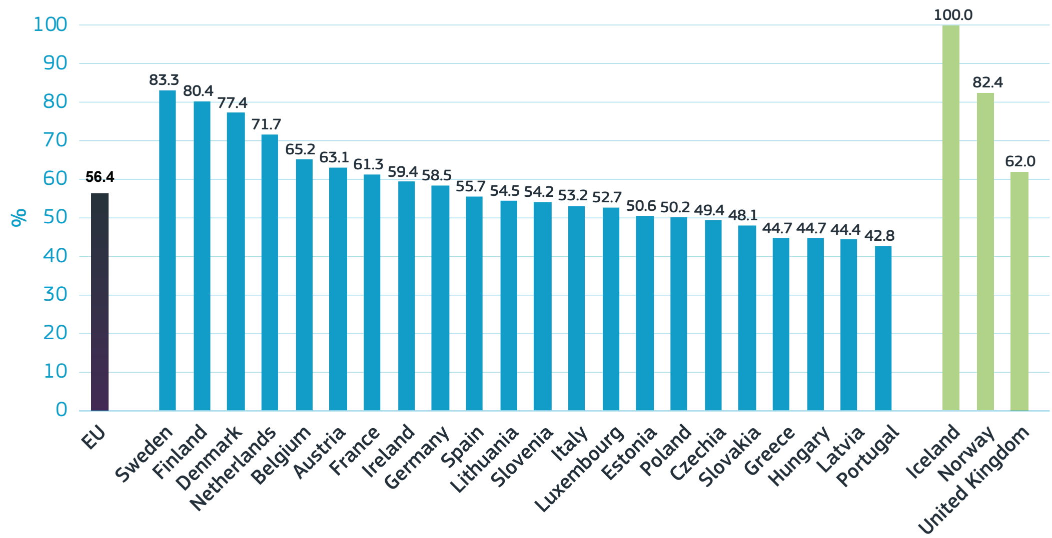
Figure 5.3-11: Share of employed persons using computers with internet access, 2020



Science, Research and Innovation Performance of the EU 2022

Source: ICT Access and Usage by Businesses' database, OECD, accessed December 2021

Note: Data available for 22 EU Member States.

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-3-11.xlsx

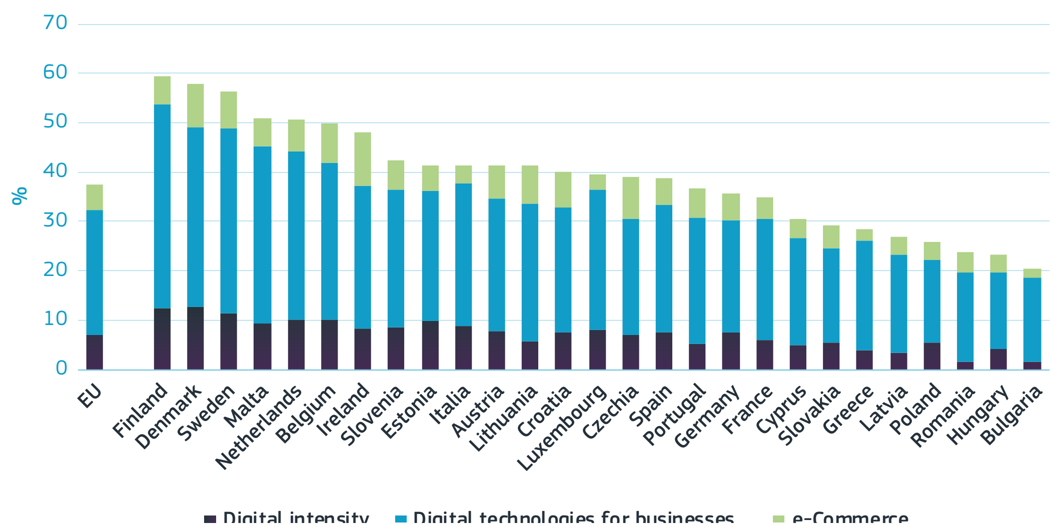
3. The adoption of digital technologies in the EU – implications of the COVID-19 crisis

Speeding-up the digitalisation of the EU economy is at the heart of the EU policy agenda. In the Communication '2030 Digital Compass: the European way for the Digital Decade', the European Commission set out its objectives for the digital transformation by 2030. Key ingredients of the EU strategy for a human-centred, sustainable and more prosperous digital future are digital sovereignty in an open and interconnected world and increasing the empowerment of people and businesses. In this regard, increasing the adoption of digital technologies in the EU economy is essential to meeting EU objectives and successfully tackling the challenges of the digital age.

EU firms are struggling to catch up with US and Chinese companies, which are the global frontrunners in terms of digital technologies. The rapid change of the global innovation landscape poses important challenges to the EU's digital ambitions. The share of firms that adopted at least one digital technology in 2019 among EU manufacturing firms was 66 %, against 78 % in the USA (EIB, 2020).

The degree of adoption of digital technologies varies significantly across EU Member States. Finland, Denmark and Sweden are the top performers in terms of integration of digital technologies, with a score well above 50 (DESI, 2021). Bulgaria, Hungary and Romania report the lowest levels of adoption (Figure 5.3-12).

Figure 5.3-12: **Adoption of digital technologies in the EU, 2021**



Source: Digital Economy and Society Index 2021, European Commission

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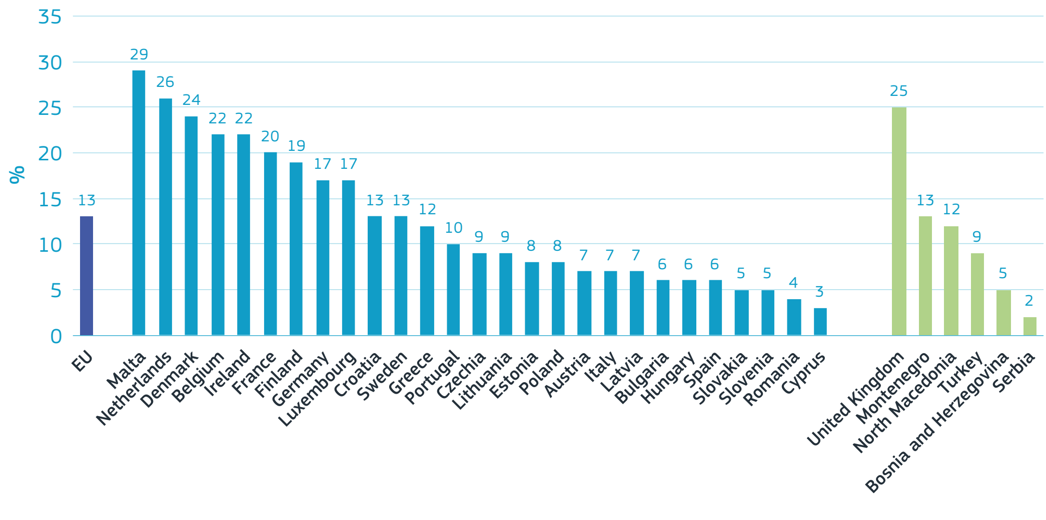
Differences across the EU also exist in terms of big data uptake. More than 20% of firms in Malta, the Netherlands, Denmark, Belgium and Ireland use big data analytics, whereas this share is below 5% in Slovenia and Cyprus (2020 data) (Figure 5.3-13).

The COVID-19 crisis has accelerated the digitalisation of EU businesses, with large enterprises taking the lead. Digital technologies such as cloud computing and big data analytics gained importance during the COVID-19 crisis. According to a recent survey, 46% of EU firms decided to integrate more digital services in their businesses because of COVID-19 (EIB, 2022). Micro and small firms reported a more modest reaction to the COVID-19 crisis as compared to companies of bigger size. Only 36% of micro firms took action to become more digitalised, against 54% of large firms. As of 2020, more than 60% of large-sized firms in the EU use cloud computing services within their businesses, as opposed to 46% and 33% of medium and small firms, respectively. Similarly, the use of big data is less diffuse in medium (19%) and small (11%) companies, while large companies show a higher uptake (31%). The same pattern is observed across other digital technologies, such as 3D printing and IoT (Figure 5.3-14).

Figure 5.3-13: Share of enterprises performing big data analysis[(1)], 2020



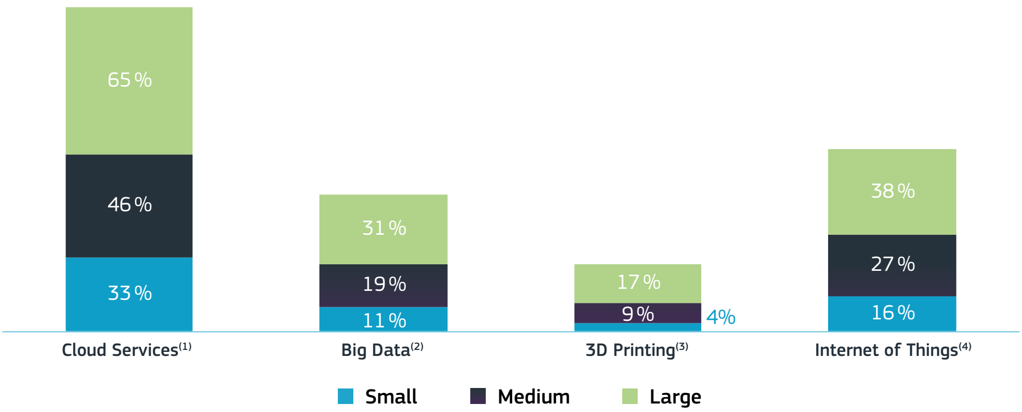
Science, Research and Innovation Performance of the EU 2022

Source: Eurostat [online data code: isoc_eb_bd]

Note: [(1)]Share calculated as number of enterprises analysing big data internally (from any source) in total enterprises (i.e., all enterprises, without financial sector, 10 or more employees and self-employed persons)

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-3-13.xlsx

Figure 5.3-14: Share of enterprises using digital technologies in the EU per firm size, 2020



Science, Research and Innovation Performance of the EU 2022

Source: Eurostat (online data codes: isoc_cicce_use, isoc_eb_bd, isoc_eb_p3d, isoc_eb_iot)

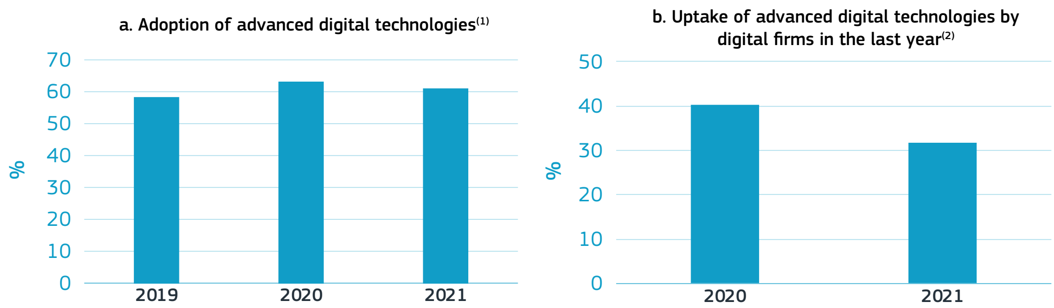
Note: (1)Cloud Service – share calculated as number of enterprises relying on cloud computing services used over the internet. (2)Big Data - share calculated as number of enterprises analyzing big data internally (from any source) in total enterprises. (3)3D Printing - share calculated as number of enterprises using 3D printing. (4)IoT – share calculated as number of enterprises using interconnected devices or systems that can be monitored or remotely controlled via the internet (Internet of Things).

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-3-14.xlsx

There are important inter-sectoral differences in the effects of the COVID-19 pandemic on EU firms' digitalisation. Companies operating in the services industry put more effort in the digitalisation of their businesses. As a response to the pandemic, 49% of firms in this industry indicated that they had invested more in digitalisation, compared to 32% of companies active in the construction industry (EIB, 2022).

In addition, the digital progress triggered by the COVID-19 pandemic differed across technologies. In the wake of the COVID-19 crisis, firms invested more in basic digital technologies, leaving aside the adoption of new and more advanced digital technologies (e.g. 3D printing, advanced robotics, IoT, big data analytics and AI) (EIB, 2022). The rate of adoption of advanced digital technologies increased between 2019 and 2020, from 58% to 63%, but mildly contracted to 61% in 2021 (Figure 5.3-15a). Furthermore, the adoption rate of advanced technologies by digital firms dropped considerably over 2020-2021 (Figure 5.3-15b), suggesting that **firms' investment choices triggered by the pandemic were mostly directed towards meeting their immediate needs, while more complex investment projects were given less priority** (EIB, 2022).

Figure 5.3-15: Share of firms adopting advanced digital technologies in the EU, 2019-2021



Science, Research and Innovation Performance of the EU 2022

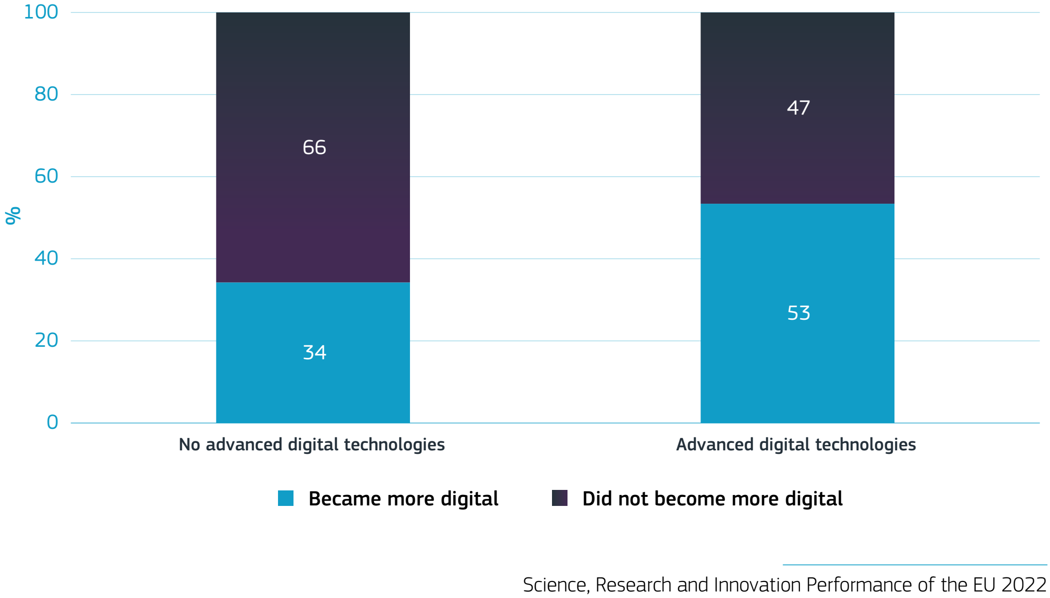
Source: EIBIS (2019, 2020, 2021), firms in EU.

Note: [(1)]A firm is identified as having adopted an "advanced digital technology" if at least one digital technology specific to its sector was implemented in parts of the business and/or if the entire business is organised around at least one digital technology. Firms are weighted using value added. [(2)]The question on whether any new digital technology was introduced in the last year was not asked in EIBIS 2019. Firms are weighted using value added.

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-3-15.xlsx

The COVID-19 pandemic acted as a catalyst for digitalisation, especially in firms already implementing digital technologies as part of their businesses (EIB, 2022). Already well-performing firms further strengthened their position, while digital laggards continued to fall behind (EIB, 2022). As such, the COVID-19 appears to have widened the digital gap between EU firms. Only 34% of EU firms increased their adoption of basic digital technologies in response to the COVID-19 pandemic, while the share of those reporting no digital progress was over 40%. Nevertheless, 53% of firms already using advanced digital technologies further invested in their digitalisation as a result of the pandemic (Figure 5.3-16).

Figure 5.3-16: EU firms[1] investing in the digitalization process as a response to the COVID-19 pandemic



Source: EIBIS (2021), firms in EU.
Note: [1]Firms are weighted with value added.
Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-3-16.xlsx

This digital acceleration experienced after the outbreak of the pandemic has been insufficient to catch up with the USA, where 58 % of firms adopted digital technologies in response to the pandemic (against the 46 % reported in the EU). The gap also remains or has even widened further in terms of the adoption of advanced digital technologies. In the USA, around 66 % of firms have already incorporated advanced digital technologies as a result of the pandemic, compared to 61 % in the EU (EIB, 2022).

Box 5.3-1: Technological uptake and sustainability

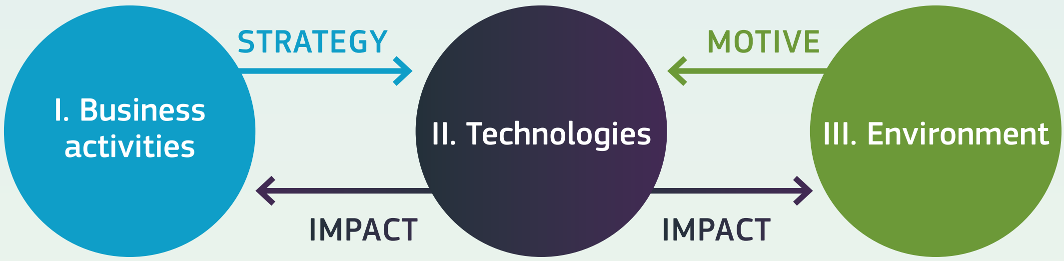
Digitalisation and green transition are strongly interlinked. The adoption of digital tools may help to reduce the economy's carbon footprint. At the same time, it is key to ensure that digital technologies become more energy efficient to allow a smart and sustainable use of resources[6]. In this regard, it is important to understand what factors drive firms' digital uptake and environmental goals.

Firms' technological uptake is mainly driven by their business strategy. Firms choose the technologies based on their set of objectives, including in terms of sustainability (Ipsos and iCite, 2021).

Firms adopt new technologies mainly to improve their products and services. According to a recent survey, ICT uptake is mainly driven by business decisions, as the most common motivations for the use of AI and cloud computing are 'improving product or services' (reported by 82 % of respondents) and 'reducing operating costs' (70 %) (Ipsos and iCite, 2021).

Nevertheless, around 60 % of EU enterprises reported 'reducing the environmental footprint' as a main motivation for their ICT uptake. To pursue their environmental goals, 60 % of EU enterprises have adopted collaborative platforms, 58 % use AI and 55 % use cloud computing and cloud storage (Figure 5.3-18).

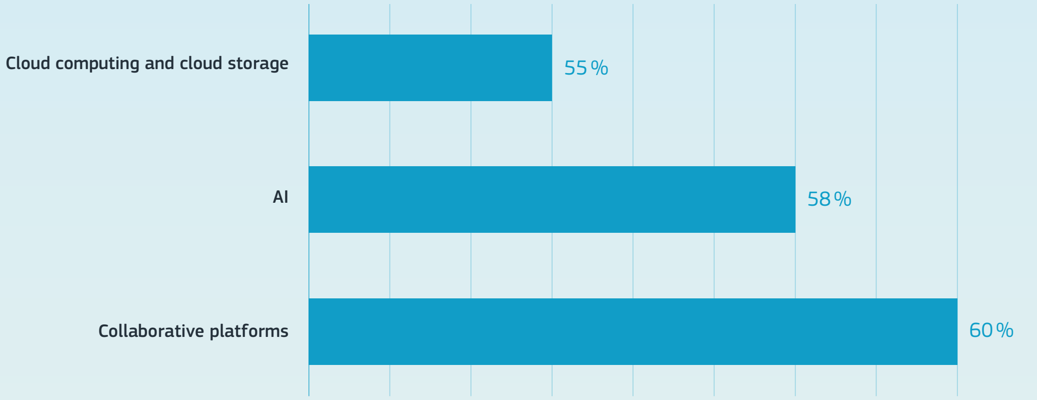
Figure 5.3-17: Technology uptake and firms' environmental footprint



Source: Ipsos and iCite, 2021
Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-3-17.xlsx

6 Commission Communication 'Annual Sustainable Growth Survey 2022' (COM(2021) 740 final)

Figure 5.3-18: **Green motivation behind the ICT uptake of EU firms, by technology type**



Science, Research and Innovation Performance of the EU 2022

Source: Ipsos and iCite, 2021
Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-3-18.xlsx

ICTs particularly helped in facilitating teleworking. When looking at the actual contribution of ICT to environmental actions, 83% of firms reported the facilitation of teleworking as the main environmental action undertaken through the adoption of ICTs. The reduction of business travel follows, with 78%. Given that the survey was carried out in the aftermath of the COVID-19 outbreak, the results are significantly driven by the pandemic context. Nevertheless, they confirm that the adoption of ICT technologies was crucial to allowing business continuity under the imposed restrictions (DESI, 2021b). Of the respondents, 73% also declared that digital technologies helped to reduce the use of materials, equipment or consumables, as well as to produce less waste (72%) or to use less energy (70%) (Ipsos and iCite, 2021).

There exists a positive relationship between firms' digital intensity and their green performance. On average, 81% of EU firms agreed that digital technologies indirectly impact their environmental footprint, while 60% agreed that their environmental goals influence their choice to adopt ICT. Nevertheless, replies varied according to firms' levels of digitalisation. While the relationship between digital technologies and firms' environmental footprint is confirmed by 87% of highly digitalised firms, this figure drops to 68% for firms with lower levels of digitalisation. Similarly, 65% of highly digitalised enterprises reported that their environmental objectives influenced their choice of digital technologies, against 52% of less digitalised companies (Ipsos and iCite, 2021).

The ability of EU businesses to continue to integrate digital technologies will play a key role in boosting their productivity performance. To deliver on the digital transition, it is essential to increase investments in digital technologies as well as in R&I activities in the ICT sector. Such an effort is required not only to catch up with other major economies but also to avoid a further exacerbation of the digital divide within the EU.

The Recovery and Resilience Plans adopted by EU Member States aim to contribute EUR 117 billion to the digital transformation, trying to reduce the digital investment gap with other major economies. EUR 17 billion is allocated to the development of digital innovation, including advanced digital technologies such as AI and high-performance computing. Important efforts are also put into the digitalisation of the public sector (with EUR 43 billion allocated to the digital transformation of public services) and the business sector (EUR 24 billion)[7].

Horizon Europe plays a key role in enabling the deployment, uptake and rollout of digital R&I activities. Compared to Horizon 2020, the new R&I framework programme is characterised by a significant increase in the budget for digital R&I activities. Additionally, the new Missions embedded in Horizon Europe will allow delivery on common European objectives and can act as an accelerator for the digital transition.

7 Commission Communication 'Annual Sustainable Growth Survey 2022' (COM(2021) 740 final)

Box 5.3-2. The role of the RRF and Horizon Europe in the digital transition

Recovery and Resilience Facility

The Recovery and Resilience Facility (RRF) represents the largest component of Next Generation EU (NGEU), the new set of EU instruments designed to tackle the impacts of the COVID-19 pandemic and to support the recovery of the EU economy. **Digitalisation is a main priority of the RFF**. EU Member States benefitting from the RRF are required to allocate and spend at least 20 % of the resources available on digitalisation and related impacts.

The reforms and investments proposed by Member States in their national plans have exceeded the intended target, with total digital expenditure of about 26 %. The planned allocation to digital transformation varies significantly across Member States (Figure 5.3-19). Italy and Spain, the EU Member States receiving the largest amount of RFF funds in absolute terms, are allocating 25 % and 30 %, respectively. Croatia, which received the largest share of RFF funds as a percentage of GDP, reports an allocation of about 20 %. Another Member State receiving a considerable share of RFF resources in GDP terms is Greece, which plans to allocate around 23 % of its RFF resources to digitalisation overall. Similarly, the reforms and investments proposed by the Member States have also allowed them to exceed the target for climate change (37 %). As reported in Figure 5.3-19, the expenditures allocated to the green transition at EU level amount to 40 % of the RRF.

Horizon Europe

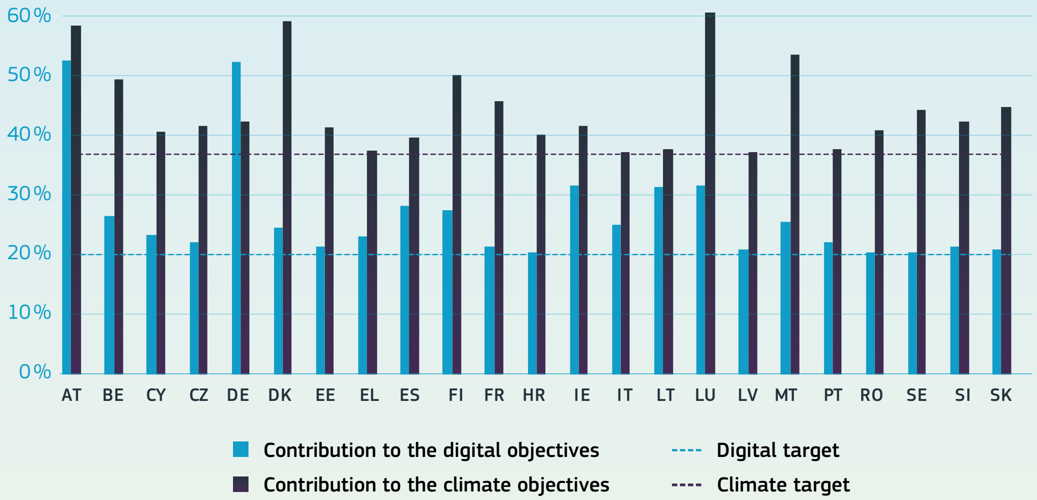
It is expected **that around 35 % of Horizon Europe funding will support projects on digitalisation**[8].

The new R&I framework programme Horizon Europe includes a dedicated sub-programme focusing on 'Digital, Industry and Space' (Cluster 4 – Pillar II). The overarching objective of the **EUR 15.3 billion budget for Cluster 4** is to foster European competitiveness and technological leadership by building an efficient, digital, low-carbon and circular economy[9].

Cluster 4 is expected to support R&I activities in key enabling technologies, e.g. artificial intelligence and robotics, high-performance computing, big data, and 6G technology, to enable a faster and more profound digital and industrial transformation across Europe. Similarly, support for the application of digital technologies is also embedded in the other Horizon Europe clusters, as well as in the EIC. In this regard, the new framework programme aims to foster the adoption of digital technologies in all key strategic areas, including health, transport and energy.

8 https://digital-strategy.ec.europa.eu/en/activities/funding-digital
9 https://op.europa.eu/en/publication-detail/-/publication/1f107d76-acbe-11eb-9767-01aa75ed71a1

Figure 5.3-19: Share of RRP estimated expenditure towards climate and digital objectives



Science, Research and Innovation Performance of the EU 2022

Source: Recovery and Resilience Scoreboard https://ec.europa.eu/economy_finance/recovery-and-resilience-scoreboard/index.html?lang=en

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-3-19.xlsx

4. AI and other advanced digital technologies

Platforms and advanced robotics are the most widely adopted digital technologies in the EU. The types of advanced digital technologies adopted by EU firms after the onset of the pandemic remained the same as in the pre-COVID-19 period. Furthermore, the rate at which advanced digital technologies were adopted did not significantly change as a result of COVID-19. Exceptions were IoT technologies, whose implementation decreased in the aftermath of the pandemic, and drones, which experienced an increase in 2021 (EIB, 2022).

AI[10] technology is one of the most path-breaking technologies currently available, able to produce significant economic and social impacts. Given its general-purpose nature, AI has the ability to impact transversally across different sectors. AI is therefore also expected to play an essential role in the twin transition (EIB, 2021), and in achieving the Sustainable Development Goals (SDGs). Furthermore, the European Commission places the acceleration of the adoption of AI technologies at the heart of its strategy to establish EU global technological leadership[11]. The 2021 Coordinated Plan on Artificial Intelligence lays out the actions to be undertaken by EU Member States to accelerate AI investments and reduce fragmentation within the EU Single Market[12].

Accelerating investment in AI technologies is essential to facilitate the uptake of new digital solutions. The EU still significantly underperforms in this regard compared to other major economies. AI investment in EU shows a positive trend over 2015-2020 (Figure 5.3-21).

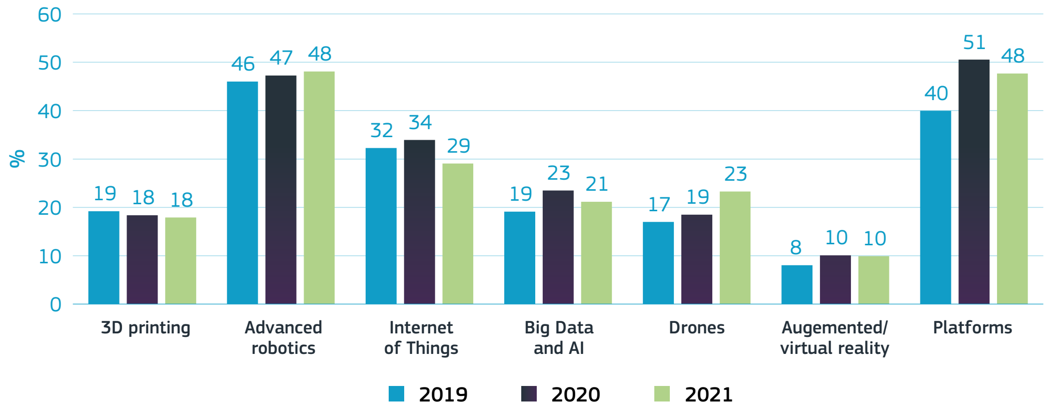
Nevertheless, the increase is not sufficient to close the gap with the USA and China. The USA is clearly leading in terms of private investment in AI, amounting to USD 23.6 billion in 2020. AI private investment in China was less than half of US private investment levels in 2020, presumably due to the fact that Chinese AI investment largely comes from the public sector (Zhang et al., 2021).

10 The European Commission High-Level Expert Group on Artificial Intelligence defines AI as 'systems that display intelligent behaviour by analysing their environment and taking actions – with some degree of autonomy – to achieve specific goals.' 'A definition of AI: main capabilities and scientific disciplines', High-Level Expert Group on Artificial Intelligence

11 Commission communication 'Coordinated Plan on Artificial Intelligence' (COM(2018)795 final)

12 Commission communication 'Fostering a European approach to Artificial Intelligence' (COM(2021) 205 final).

Figure 5.3-20: Share of EU firms adopting digital technologies, per technology type and year



Science, Research and Innovation Performance of the EU 2022

Source: EIBIS (2019, 2020, 2021), firms in EU.
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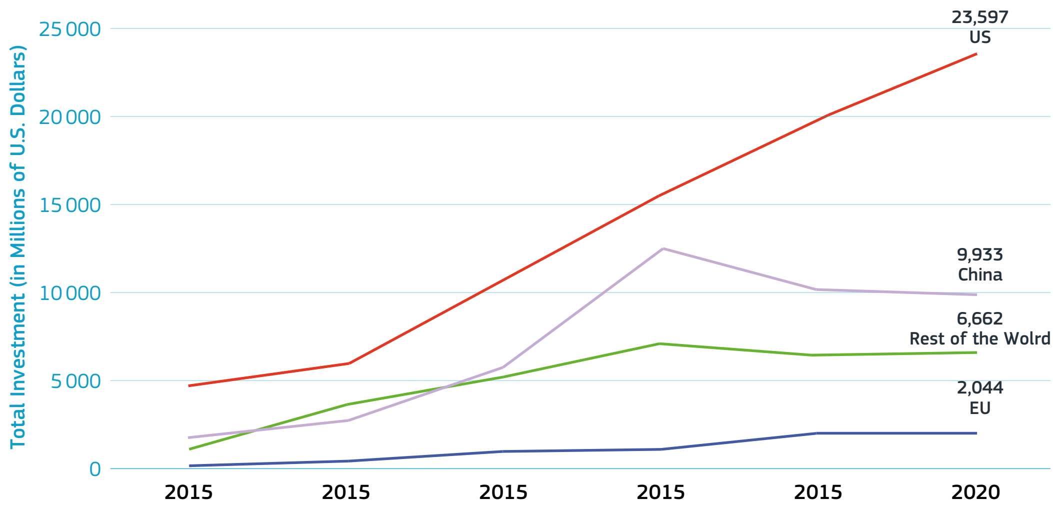
Figure 5.3-21: Private investment in AI by world region, 2015-2020



Science, Research and Innovation Performance of the EU 2022

Source: Zhang et al. (2021), based on CAPIQ, Crunchbase and NetBase Quid (2020)
Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-3-21.xlsx

The opportunities presented by AI technologies can be further enhanced by combining AI applications with other emerging technologies, such as blockchain[13]. The combined application of these advanced technologies allows for a better integration of supply chain systems and new business models leveraging shorter distance and time to market. The possibility for the EU to take up a strong position in the new digital race will strongly hinge on its ability to adapt to new market conditions through a deep integration of these emerging technologies across businesses and sectors (Veugelers et al., 2019).

The EU still lags behind other major economies in terms of number of enterprises with blockchain technologies. When looking at the number of SMEs using blockchain technologies, the EU ranks third, with 242 enterprises, after the USA and China (with 542 and 406 SMEs, respectively). The UK, Canada and Japan follow with 104, 39 and 15 blockchain SMEs, respectively (EIB, 2021). The picture changes when accounting for the size of the workforce in each geographical area. The USA keeps its leading position with 3.3 blockchain SMEs per 1 million workers, while EU takes the fourth position with a density of 1.1, after UK (3.1) and Canada (1.9) (Figure 5.3-22).

The EU is also not among the best performers in the field of high-performance computing (HPC)[14]. The largest number of applicants of quantum computing are headquartered in the United States, followed by Japan, Canada, and only then Europe (Travagnin, 2019). The demand for HPC will significantly increase in the coming years (DESI, 2020a).

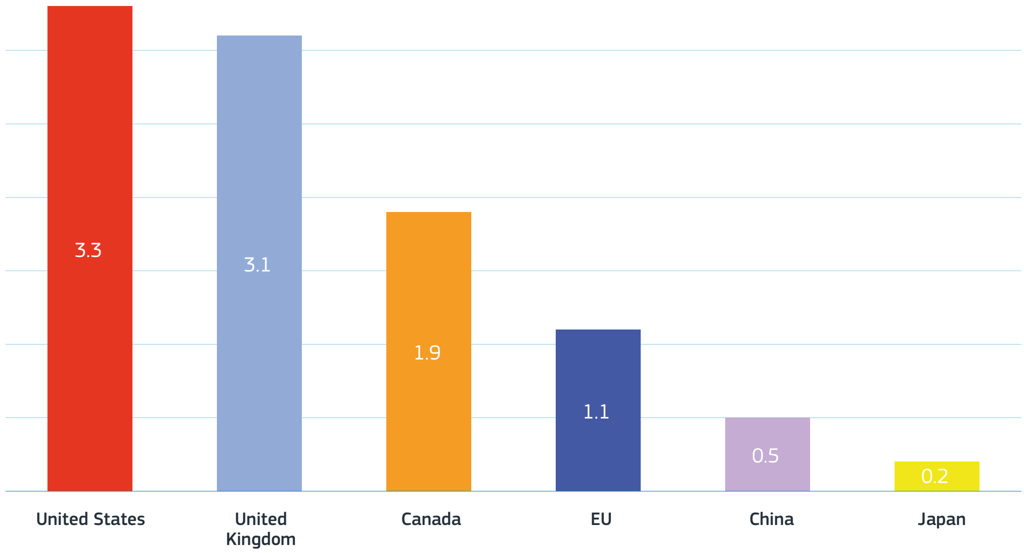
HPC will help with understanding and responding to several socioeconomic challenges, ranging from digital models to tackle climate change to data processing in the health field. Revenues from the global HPC market are expected to grow from around USD 27 billion in 2018 to almost USD 40 billion in 2022 (DESI, 2020b).

Europe lags behind in terms of supercomputing infrastructure. Only one of the world's top 10 supercomputers was in the EU as of September 2019 (DESI, 2020b). In terms of the world top 500 supercomputers, the EU ranked third in the 2019 global ranking, with a share of 15% (Figure 5.3-23). China dominates the international scene, with 228 of the top 500 systems installed (46%), followed by the USA with 117 installations (23%) (DESI, 2020b).

13 Blockchain is defined as 'a technology that allows people and organisations to reach agreement on and permanently record transactions and information in a transparent way without a central authority', 'Blockchain Strategy', Shaping Europe's digital future, European Commission.

14 HPC, also known as supercomputing, is used to solve highly complex computational or data-intensive problems (DESI, 2020b).

Figure 5.3-22: Number of blockchain SMEs in major economies per million workers, April 2020

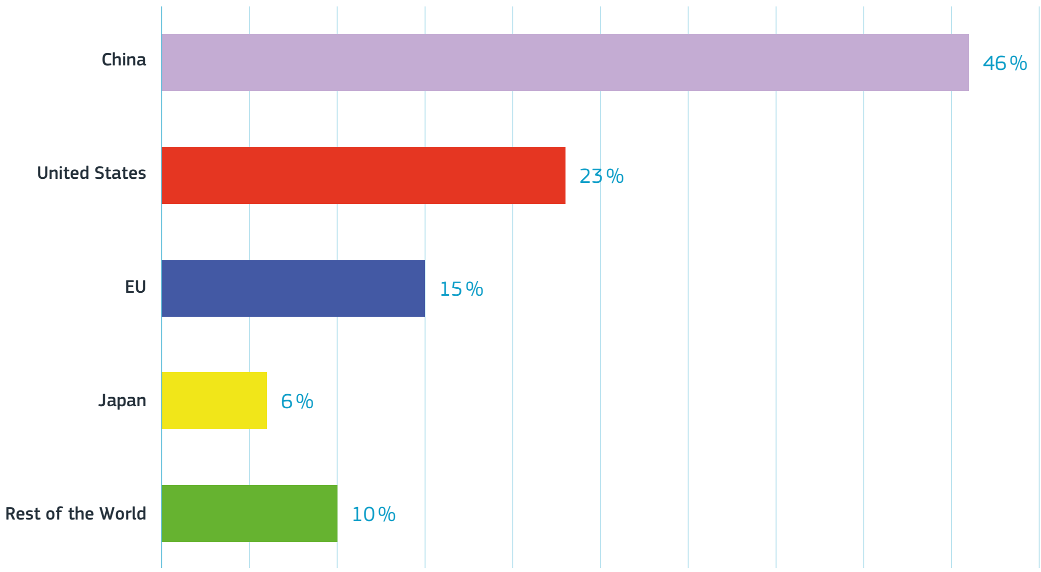


Science, Research and Innovation Performance of the EU 2022

Source: EIB (2021), based on Crunchbase data and World Bank data

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-3-22.xlsx

Figure 5.3-23: World share of the Top 500 supercomputers per world region, 2019



Science, Research and Innovation Performance of the EU 2022

Source: DESI (2020), based on Top500.org list.

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-3-23.xlsx

It is important that the EU increases its efforts in HPC technologies. Quantum computing markets are expected to considerably grow in the next ten years (Rasanen et al., 2021). As such, the EU should not miss the opportunities coming from this strategic field and should put increasing efforts into the commercialisation of HPC-related technologies. **It is important to strengthen academia-business partnerships, improving the EU's ability to translate academic excellence into viable market solutions**. In doing so, the EU must leverage its vibrant start-up ecosystem, supporting high-growth enterprises that are best placed to become innovation leaders in advanced technology fields. In this regard, **unicorn companies have the potential to play a key role**, as they present sufficient size and innovation capabilities to compete successfully on the global market (Rasanen et al., 2021). As such, unicorn companies **can act as a conduit to foster a stronger EU-based quantum ecosystem**, reducing the gap with Asia and the USA (Rasanen et al., 2021).

See more in chapter 11 – Artificial intelligence for social good: the way forward

The chapter investigates the interlinkages between the data and AI revolution and sustainable development. The author provides a comprehensive overview of both opportunities and challenges related to AI within the context of the 17 SDGs, discussing how data-driven AI methods are able to help addressing the SDGs, and the limitations they pose that might hinder the realisation of such potential.

5. Digitalisation vs digital innovation

EU firms adopting more advanced digital technologies typically invest more in R&D and innovation (EIB, 2022). In contrast, less-digital companies are less likely to allocate resources to the development of new products, processes or services.

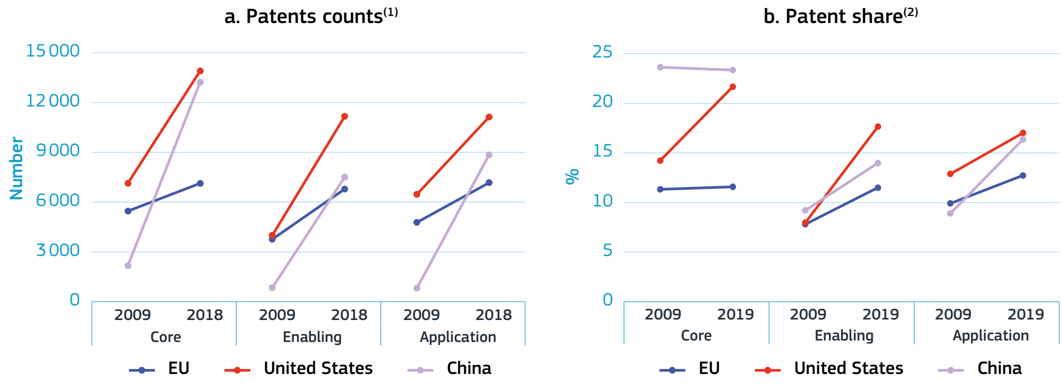
The EU lags behind the USA and China in terms of patent applications in digital technologies. In what follows, digital patent applications are classified according to the methodology proposed by EPO (2017) and based on Industry 4.0 domains. Digital patents are grouped under three domains: core technologies, enabling technologies and application domains[15]. According to this classification, the EU's share in digital patents has remained stable since 2012, while the US share has increased over time, thereby widening the gap between the two economies (EIB, 2022). Although the EU is still ahead of China, Chinese investments in new digital technologies have significantly accelerated over the past ten years (EIB, 2022).

The US and China outperform the EU in all three domains of digital innovations. While the USA consistently dominated the international scene between 2009 and 2018, China improved its performance over the same period, overtaking the EU in 2018 (Figure 5.3-24a). In terms of share of total domestic patent production, China performs particularly well in the domains of enabling technologies and application domains, whereas US patent applications are mainly concentrated in core and enabling technologies (Figure 5.3-24b). The gap between the EU and the USA and China is particularly large in the field of core technologies.

Nevertheless, the EU remains a leading innovator in the automotive sector and in fields related to climate change. The EU ranks first in terms of digital patents in vehicle applications, a category including technologies related to autonomous driving and vehicle fleet navigation devices (EIB, 2022). Nevertheless, both the USA and China are improving their performance in these fields, calling for further efforts at EU level to maintain this leading position. Furthermore, the EU significantly outperforms the USA and China in the development of technologies to tackle the challenges of the green transition, although there has been some stagnation in recent years (EIB, 2022). Furthermore, the EU reports more than half the number of Chinese patents in digital automotive technologies, and also significantly outperforms the USA in this field (EIB, 2022). Given the strategic role played by the automotive sector in the race towards carbon neutrality, it is essential for the EU to continue to strengthen its global position in this area, maintaining its technological leadership (for more information on EU technological sovereignty, see Chapter 2.1 – Zoom out: technology and global leadership.

15 Core technologies represent the basic building blocks upon which the technologies of the fourth industrial revolution are built. Enabling technologies are further built upon and complement the core technologies. The category 'application domains' captures those technologies that are ready to be put on the market, and represents the final applications of digital technologies (EIB, 2022).

Figure 5.3-24: Patent counts and share of patents in the United States, China and the EU, by digital domain



Science, Research and Innovation Performance of the EU 2022

Source: PATSTAT (PCT) data prepared in collaboration with ECOOM

Note: (1)The figure shows the count of digital patents for the three different digital domains. (2)The figure shows the shares of digital patents for the three different digital domains over the respective total domestic patent portfolio.

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-3-24.xlsx

The EU performs less well in the field of healthcare technologies. Before 2019, the global increase in patent applications related to healthcare technologies was mostly driven by US performance (EIB, 2022). With the onset of the COVID-19 crisis, healthcare patent applications increased significantly worldwide. Although this increase in healthcare innovations did not immediately focus on digital technologies, the latter proved to be critical to relieving health-care systems worldwide from the pressure of the pandemic (EIB, 2022). For example, digital technologies enabled the sharing of healthcare research and data, essential to the development of the COVID-19 vaccines. Furthermore, there is significant potential for the development of more sophisticated healthcare applications making use of advanced digital technologies, such as AI and robotics (EIB, 2022).

6. Conclusions: addressing the challenges of the digital age

The COVID-19 crisis has accelerated structural changes in firms. With the outbreak of the pandemic, digital technologies have become imperative to ensuring economic resilience. EU firms have become more digitalised, showing good capabilities for adapting to the changed economic circumstances. Investments in digital technologies undertaken after the spread of COVID-19 mostly focused on basic digital applications. As a response to the pandemic, EU firms mostly increased their uptake of less sophisticated digital technologies necessary to meet their basic needs to ensure business continuity. The adoption of advanced digital technologies did not increase at the same pace.

Nevertheless, the already existing digital divide has continued to increase. COVID-19 has exacerbated the differences between and within EU countries. Top digital innovators in the EU have continued to improve their performance, further distancing the digital laggards. Similarly, already digitalised firms further increased their uptake of digital technologies, making it more difficult for less digitalised companies to catch up (EIB, 2022). **The widening asymmetries between and within EU regions and countries represent an important challenge**. The uneven adoption of digital technologies across EU companies has put European convergence at jeopardy (EIB, 2022). Although increasing the digital uptake was one of the main strategies adopted by all European firms as a reaction to COVID-19, companies in lower-income countries showed a weaker response (EIB, 2022). In this regard, the support issued via the RFF will help to strengthen EU economic convergence, supporting the structural transformation of the EU economy, especially in lagging Member States.

R&I policy is critical to delivering the digital transition. The successful digitalisation of the EU economy requires a better transformation of R&I results into market viable solutions, as well as a more entrepreneurial-minded R&I policy. To tackle the challenges of the digital age, the EU needs to strengthen the interlinkages between public and private sectors, building partnerships able to support individuals and organisations willing to bring about the necessary technological, economical and societal transformations.

The digital transition also has the potential to support the EU decarbonisation process. The key EU policy priorities linked to the digital and green transition, the European Green Deal and 'a Europe fit for the digital age' are closely intertwined and have the potential to mutually reinvigorate each other. The decarbonisation of the EU economy needs to leverage on the availability of digital technologies to speed up the transition. At the same time, it is essential that the digitalisation process is undertaken in a sustainable way. **Digital technologies have to be green**, and initiatives to speed-up the digital progress need to account for the environmental footprint of digital technologies **to ensure full synergies and complementarity between EU priorities**.

Furthermore, digital technologies have become increasingly integrated into the way the whole of society interacts and exchanges information. **To build a strong, human-centred and inclusive digital Europe, it is necessary to put European citizens at the centre of the digitalisation process**. In its Communication *Establishing a European Declaration on Digital rights and principles for the Digital Decade*, the European Commission reinforces its commitment to build an empowering digital society in which no one is left behind. The Communication proposes a set of principles to guide European action towards achieving its digital targets. The EU digital transformation must be shaped according to European values and law, while ensuring an effective regulatory framework able to safeguard European citizens' rights and freedoms (see Chapter 7.2 – Other framework conditions) (European Commission, 2022).

Horizon Europe encompasses all these elements. Overall, the EU is still lagging behind its main international competitors in terms of share of digital applications, although remaining strong in some strategic industries (see Chapter 2.1 – Zoom out: technology and global leadership). The new R&I framework programme is characterised by a substantial increase in spending resources devoted to digital R&I activities to ensure that the EU remains at the forefront of global R&I in digital technologies. **Horizon Europe has a key role to play in enabling the deployment, uptake and roll-out of R&I activities in digital**, while supporting a human-centred and ethical development of digital technologies **with the potential to enable and facilitate the transition towards a climate-neutral and circular economy.**

References

Zhang, D., Mishra, S., Brynjolfsson, E., Etchemendy, J., Ganguli, D., Grosz, B., Lyons, T., Manyika, J., Niebles, J. C., Sellitto, M., Shoham, Y., Clark, J., and Perrault, R. (2021), *The AI Index 2021 Annual Report*, AI Index Steering Committee, Human-Centered AI Institute, Stanford University, Stanford, CA, March 2021.

Digital Economy and Society Index (DESI) (2020a), *The EU ICT Sector and its R&D Performance* 2020.

Digital Economy and Society Index (DESI) (2020b), *Emerging Technologies* 2020.

Digital Economy and Society Index (DESI) (2021a), *The EU ICT Sector and its R&D Performance.*

Digital Economy and Society Index (DESI) (2021b), *The Integration of Digital technologies 2021.*

EIB (2020), *Who is prepared for the Digital Age? Evidence from the EIB Investment Survey.*

EIB (2021), *Artificial intelligence, blockchain and the future of Europe: How disruptive technologies create opportunities for a green and digital economy.*

EIB (2022), *Investment Report 2021/2022: Recovery as a springboard for change.*

European Commission (2022), Establishing a European Declaration on Digital rights and principles for the Digital Decade, COM(2022) 27 final.

European Commission, Directorate-General for Research and Innovation (2021), *Science, research and innovation performance of the EU, 2020: 11 recommendations for a fair, green and digital Europe*, Publications Office, https://data.europa.eu/doi/10.2777/520136.

Ipsos and iCite (2021), *Survey on the contribution of ICT to the environmental sustainability actions of EU enterprises.*

Travagnin, M. (2019), *Patent analysis of selected quantum technologies*, ISBN 978-92-79-98120-3, doi:10.2760/938284, JRC115251.

OECD (2019), *ICT investments in OECD countries and partner economies: Trends, policies and evaluation,* OECD Digital Economy Papers, No. 280, OECD Publishing, Paris, https://doi.org/10.1787/bcb82cff-en, OECD (2020), OECD Digital Economy Outlook 2020.

OECD (2021), *The Digital Transformation of SMEs, OECD Studies on SMEs and Entrepreneurship*, OECD Publishing, Paris, https://doi.org/10.1787/bdb9256a-en.

Räsänen, M., Mäkynen, H., Möttönen, M. et al. (2021), Path to European quantum unicorns, *EPJ Quantum Technol,* 8, 5, https://doi.org/10.1140/epjqt/s40507-021-00095-x.

Veugelers, R., Rückert, D., & Weiss, C. (2019), *Bridging the Divide: New evidence about firms and digitalization*, Bruegel.

CHAPTER 5.4

INVESTMENT IN HUMAN CAPITAL

KEY FIGURES

11.4 %
growth in the share of ICT tertiary graduates in the EU 2017-2019

41 %
of 25-34-year-olds in the EU have successfully completed tertiary studies

57 %
of tertiary graduates in the EU are women

1.2 %
of GDP in the EU is spent on tertiary education

KEY QUESTIONS WE ARE ADDRESSING

- How does human capital improve innovation and productivity?
- How are European countries performing in term of human capital?
- How does the EU perform compared to its main international competitors?
- How has COVID-19 impacted human-capital formation?

KEY MESSAGES

What did we learn?

- Human capital is an important contributor toward the propensity of firms to innovate and the economic performance of countries.
- Most tertiary graduates are women, yet they are underrepresented in ICT and engineering studies.
- Adult participation in learning, R&D personnel and researchers, the share of tertiary graduates among youth, and ICT graduates are rising across the EU, while NEETs are decreasing.
- In the EU, the total public and private expenditure on education as a percentage of GDP is higher than in Japan, yet still lower than in the United States, South Korea and the United Kingdom.
- The COVID-19 pandemic has negatively impacted the formation of human capital, particularly among students from disadvantaged socioeconomic backgrounds.

What does it mean for policy?

- Human capital policies are crucial to increase European innovation capacity.
- Educational policies targeted at students from disadvantaged socioeconomic backgrounds will be fundamental in the post-pandemic era.
- Involving more private contributions in tertiary education, to ensure a smart mix of public and private financing that does not compromise equality of opportunity, could provide the additional resources needed for the EU to compete with its international competitors.
- Further policies that aim to reduce the gender divide between scientific and humanities fields may be considered.

1. Human capital as a driver of innovation

Human capital is a crucial driver of innovation. Indeed, labour productivity and the probability of an industry to innovate are shaped by the investment of its workforce in different types of training (formal and informal), its cognitive skills (literacy and numeracy), its non-cognitive skills (soft skills), and its ICT and STEM skills (Cammeraat et al., 2021). Human capital explains much of the productivity differences and variation in growth performance across European countries (Gennaioli et al., 2013; Madsen, 2010; Baten et al., 2008).

Highly talented individuals can push forward the frontiers of knowledge if they have access to the necessary formal education, facilities and financing. A more educated and trained workforce can generate technological innovation on the job, finding solutions to old and new problems (Acemoglu and Autor, 2012). Human capital increases the 'absorptive capacity' of firms and society as a whole. Absorptive capacity is the ability to identify and make effective use of knowledge, ideas and technologies that are generated elsewhere (Cohen and Levinthal, 1989). Companies investing more in the human capital of their employees build up a greater capacity to spot innovation opportunities and learn from others, leading to higher productivity growth.

Formal education improves innovation capacity and economic performance. The tertiary education of employees is an important contributor toward firms' propensity to innovate and countries' economic performances. The level of formal education positively impacts innovation and prosperity (Griffith et al., 2004; Vandenbussche et al., 2006). However, it is not only the length of studies, but what is learnt at school or university matters: i.e. the skills learned and the quality of education (Hanushek and Woessmann, 2015).

Cognitive, non-cognitive and task-based skills (the skills that workers need to perform a job task) improve innovation capacity and economic performance (see Chapter 4.3 – Skills in the digital era). Cognitive skills (such as literacy, numeracy and problem-solving) and non-cognitive skills (such as soft skills) of workers are required for any industry to have success in the global economy (Grundke et al., 2017; Diebolt and Hippe, 2019). Cognitive and non-cognitive skills enhance technology diffusion (Messinis and Ahmed, 2013) while ICT and STEM skills enhance innovation potential (Hall, Lotti and Mairesse, 2013; Peri et al., 2015). Social skills of employees and managers and the communication culture within an organisation play an important role in determining the value of human-capital endowments. Companies with a strong human-capital base but with an ineffective communication culture are likely to waste innovation opportunities due to reduced absorptive capacity. This happens because information flows more slowly or redundantly, increasing the friction cost of obtaining the needed information.

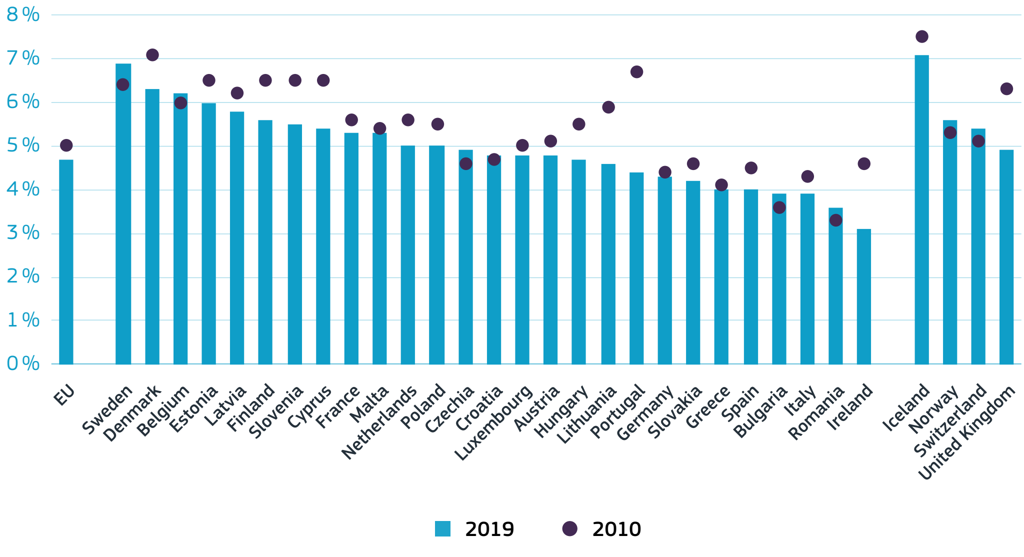
Training, re-skilling and working with others are effective ways of improving companies' human capital and propensity to innovate. Different studies find positive learning spillovers from interaction among workers (Destré, Lévy-Garboua and Sollogoub, 2008) and from training (Dearden, Reed and Van Reenen, 2006; Konings and Vanormelingen, 2015) on productivity. Furthermore, strong links have been found between training and the likelihood to innovate (González, Miles-Touya and Pazó, 2016; Dostie, 2018).

2. Education and researchers across EU Member States

General government expenditure on education as a % of GDP slightly decreased 2010-2019. Sweden, Denmark and Belgium have the highest spending in the EU, while Ireland, Romania and Italy spend the least. On average, governments spend about 5% of GDP on education in the EU. Sweden, Belgium, Norway, Czechia, Bulgaria and Romania have increased their spending on education.

There is strong heterogeneity on how EU countries allocate their resources between the different levels of education (primary, secondary and tertiary). Sweden spends the highest share of its public expenditure on primary education (around 64%, see Figure 5.4-2). EU countries spend on average 34% of public expenditure on primary education, 37% on secondary education, 16% on tertiary education and 12% on other forms. The UK has the lowest public spending on primary education, with 21% of its education spending by the public sector going to primary education. On the other hand, the UK spends a considerably higher share on secondary education (44%), 7 percentage points more than the EU, 8 percentage points more than Germany and 29 percentage points more than Sweden.

Figure 5.4-1: **General government expenditure in education as % of GDP, 2010 and 2019**



Source: Eurostat (online data code: GOV_10A_EXP)
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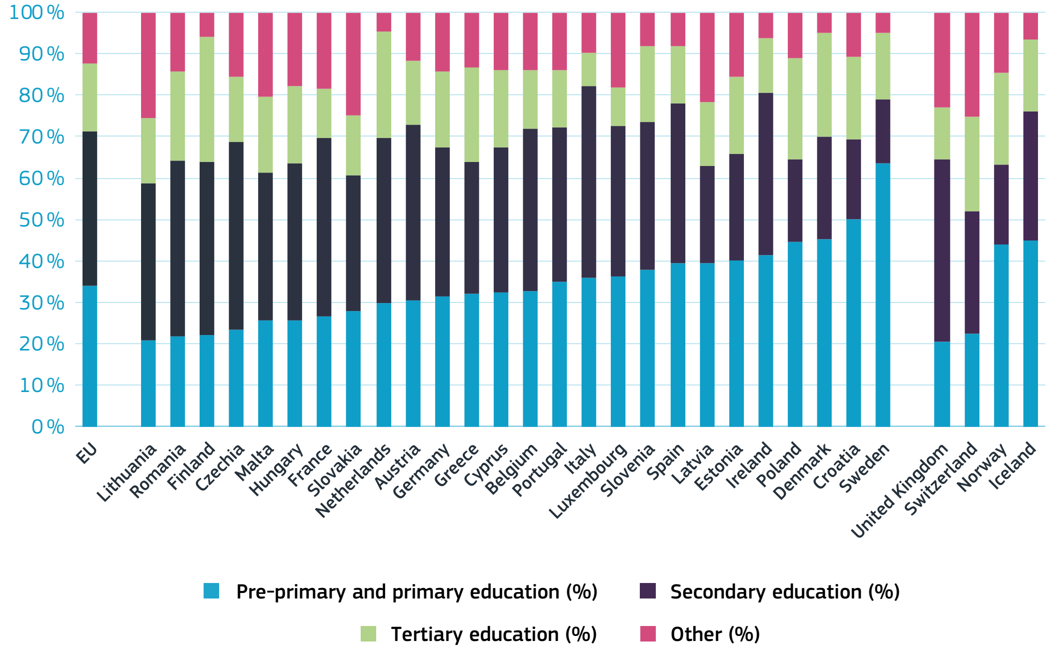
Figure 5.4-2: Share of public expenditure on education by level[1], 2019



Science, Research and Innovation Performance of the EU 2022

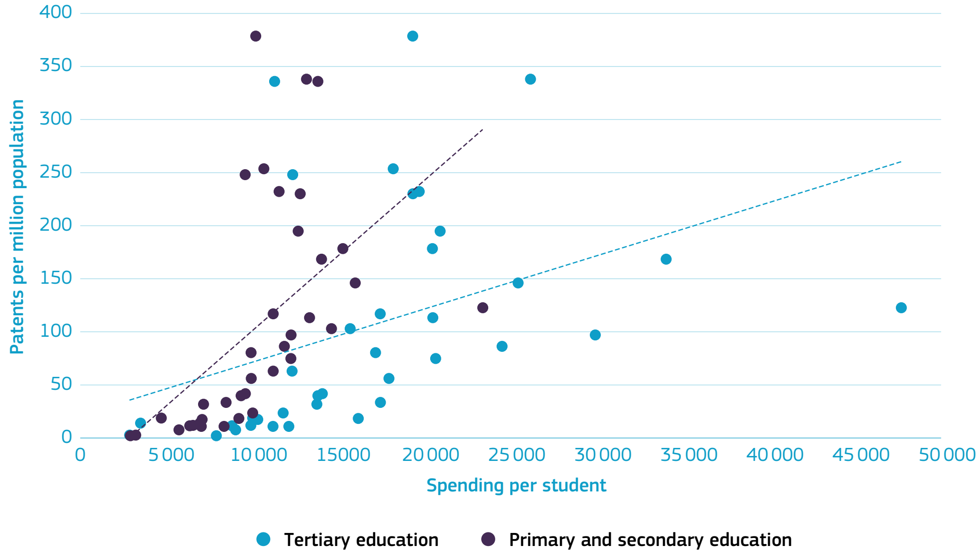
Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Eurostat (online data code: GOV_10A_EXP)

Note: [1]Education by level as percentage of total public expenditure in education, measured in Euro.

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-4-2.xlsx

Expenditure on both lower and higher levels of education contribute to a country's innovation capacity and overall economic performance. The level of expenditure on education per student is positively associated with patent applications (see Figure 5.4-3) and with GDP per capita (see Figure 5.4-4). Primary and secondary education can be seen as an instrument to build up the human capital of the future, while tertiary education as an instrument to help current human capital to push the frontiers of knowledge further. For this reason, research on developing countries mostly focuses more on primary education, while studies on developed countries focus on tertiary education. Spending in education, as well as the quality of the education and the share of individuals completing formal education, are important contributors to a country's stock of human capital. High-quality primary and secondary education guarantees high-quality future human capital that is able to provide the best returns from tertiary education. In Europe, tertiary-education attainment has been found to be one of the main drivers of development and prosperity (Cuaresma, Doppelhofer and Feldkircher, 2014; Madsen, 2010).

Figure 5.4-3: Spending in education vs patenting activity[1]



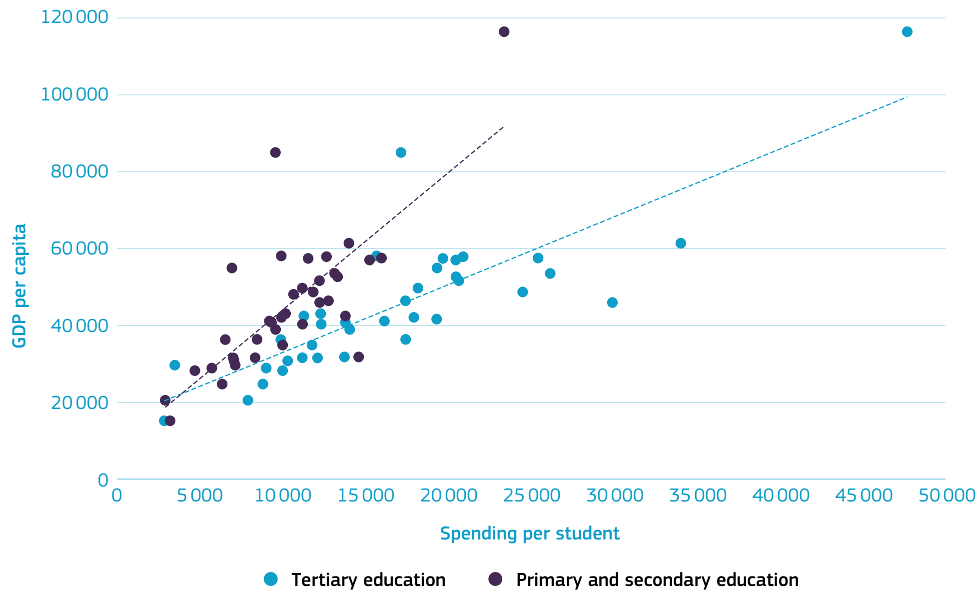
Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Education at Glance 2021, OECD Indicators and OECD (Patents by technology)

Note: [1]Plot of 37 OECD countries. Spending per students in USD PPPs. Patent are defined as patent applications filed under the PCT.

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-4-3.xlsx

Figure 5.4-4: Spending in education vs GDP per capita[1]



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on 'Education at Glance' (2021), Indictors, OECD

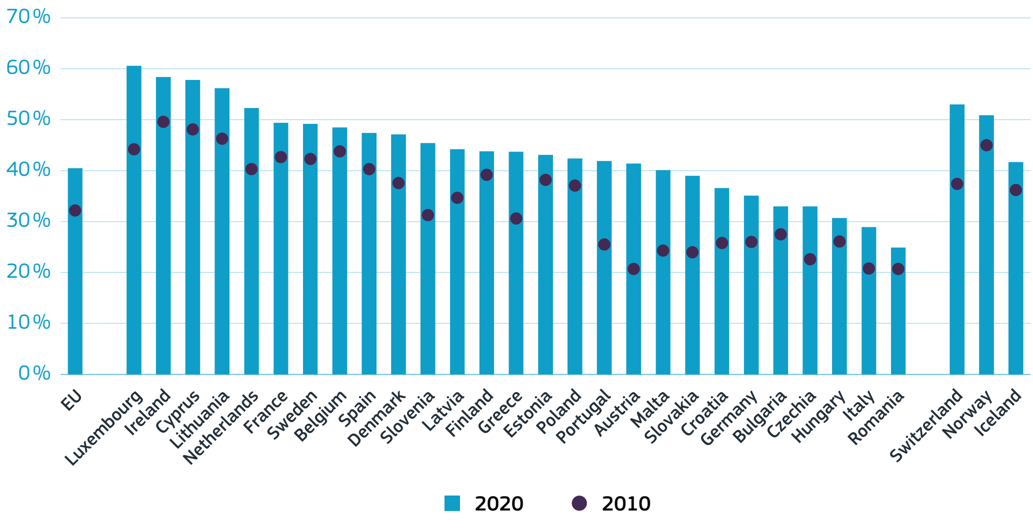
Note: [1]Plot of 37 OECD countries. Both spending per students and GDP per capita are expressed in USD PPPs.

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-4-4.xlsx

Completion of tertiary studies increased in all EU countries from 2010 to 2020. Luxembourg has the highest share of population aged 25-35 that has completed tertiary education, with a remarkable 61 % (see Figure 5.4-5). Ireland follows with 58 % of the population. On average, 41 % of the EU population aged 25-35 has a tertiary education degree, which is a stark increase from 32 % in 2010. Romania has the lowest figure, with 25 %, followed by Italy with 30 %.

The influence of the digital transition is clearly observable in the tertiary graduate trend, with degrees in ICT showing the highest growth 2017-2019 (see Figure 5.4-6). The share of ICT graduates grew by 11.4 % from 2017 to 2019. This is likely to be related to job-market demands. Indeed, ICT is the second most requested competence in the job market, with 25 % of job postings mentioning ICT among the desired competences (see Chapter 3.3 – Skills in the digital era). However, overall, business, administration and law remains the most common degree field, with a share of 24 %. Business, administration and law is also the most frequently requested competence in the job market (see Chapter 4.3 – Skills in the digital era). Engineering, manufacturing and construction is the third most common degree field, with a share of 15 %. The share of tertiary graduates in arts and humanities and education degrees has been declining.

Figure 5.4-5: **Share of population aged 25-34 who have successfully completed tertiary studies, 2010 and 2020**

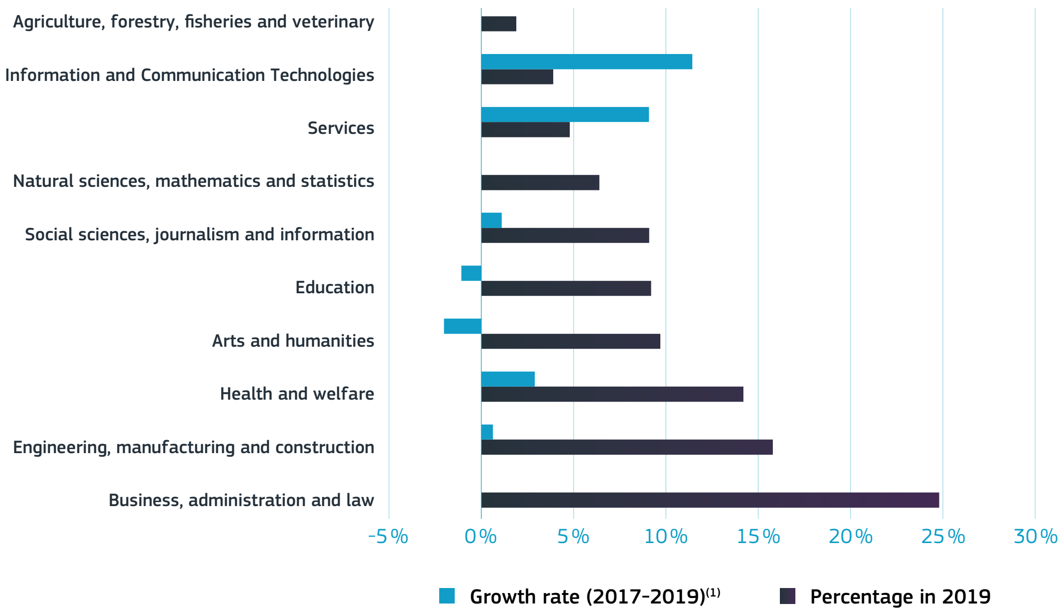


Science, Research and Innovation Performance of the EU 2022

Source: Eurostat (online data code: SDG_04_20)
Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-4-5.xlsx

CHAPTER 5.4

Figure 5.4-6: Share and growth of tertiary graduates by field of study in the EU



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Eurostat (online data code: EDUC_UOE_GRAD03)

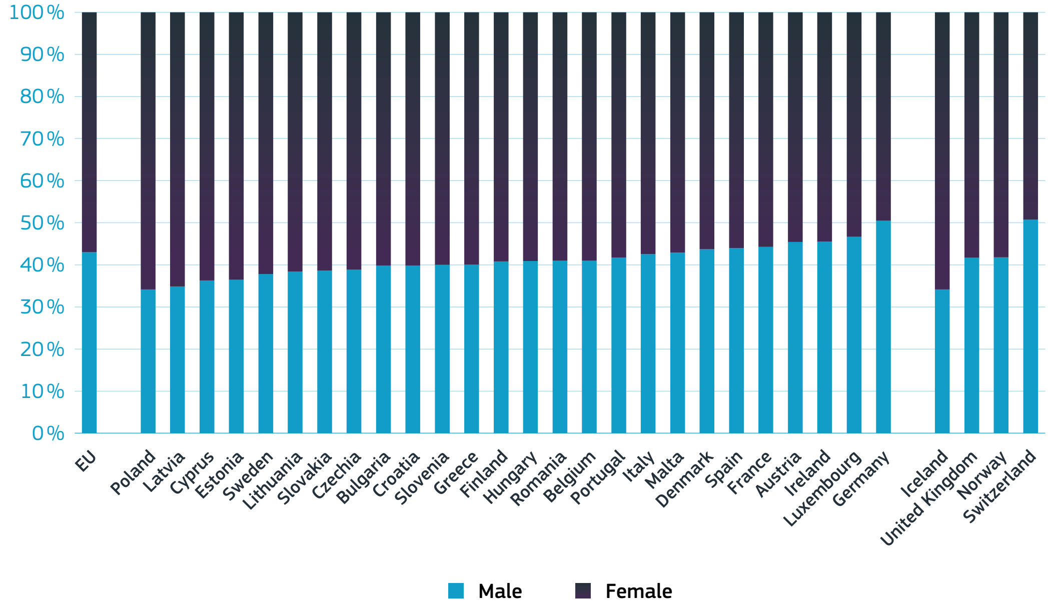
Note: (1)Growth rate from 2017 to 2019 of the percentage of graduates of a field out of the total graduates. As an example ICT graduates increased from 3.5% to 3.9%, implying a growth rate of 11.4% from 2017 to 2019.

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-4-6.xlsx

In the EU, more than half of tertiary graduates are women. On average, 57 % of EU tertiary graduates are women (see Figure 5.4-7). The EU country with the highest share of women graduates is Poland, with only 34 % of male tertiary graduates. Interestingly, Germany has a 50 % share split between men and women graduates.

There are still strong gender differences in the study fields chosen in the EU. Degrees in engineering, manufacturing and construction and in ICT are predominantly chosen by males, while female students are overrepresented in art and humanities, health and welfare, and education degrees (see Figure 5.4-8). Male graduates in ICT are around three times more numerous than females, and the same holds for graduates in engineering, manufacturing and construction. Female graduates in arts and humanities are double the male graduates, while women graduates in education are more than three times the male graduates in the field.

Figure 5.4-7: Share of tertiary graduates by sex, 2019



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Eurostat (online data code: EDUC_UOE_GRAD01)

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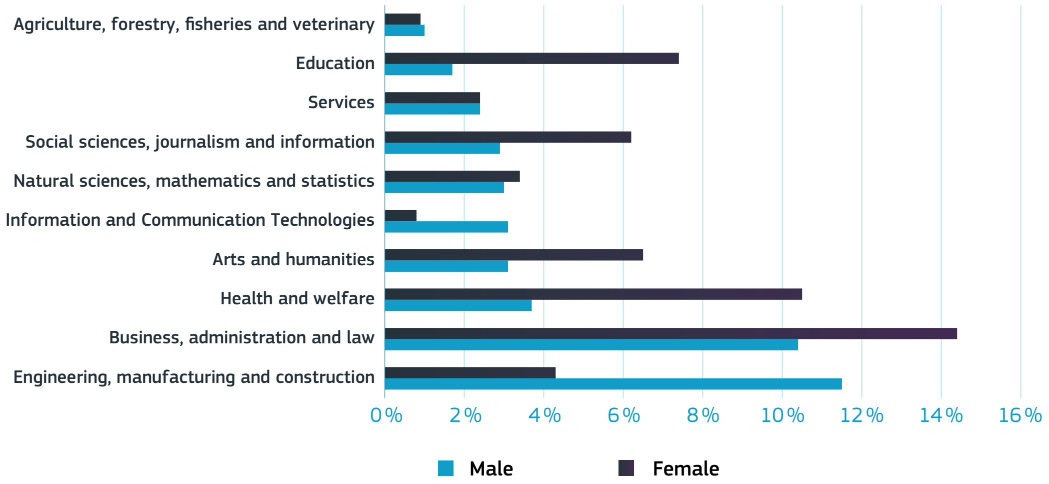
Figure 5.4-8: Share of tertiary graduates by field of study and gender in the EU, 2019



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Eurostat (online data code: EDUC_UOE_GRAD03)

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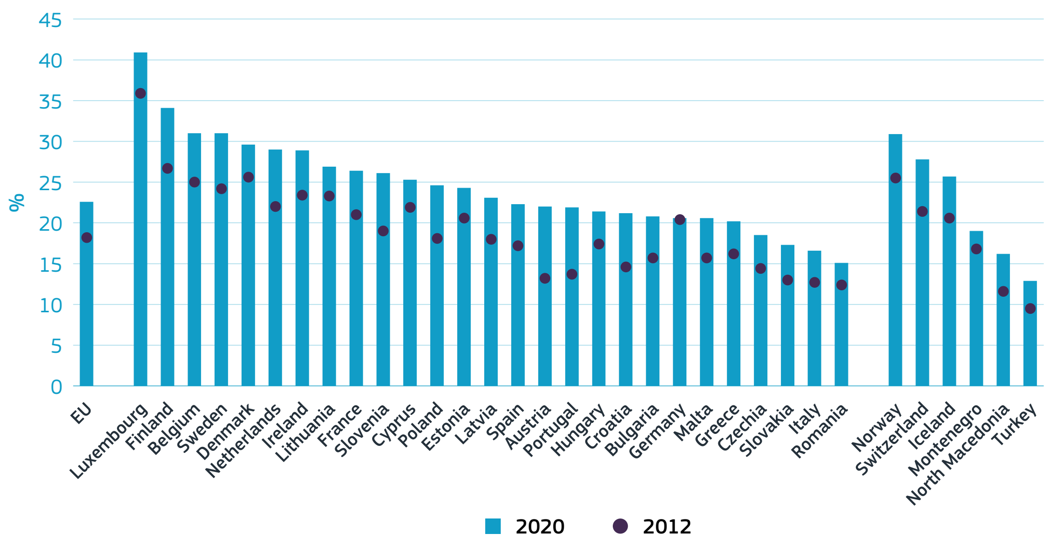
A larger fraction of the labour force are finding employment in the science and technology sectors and has a tertiary education. On average, 23% of EU workforce was employed in science and technology and had a tertiary degree in 2020. This share increased by around 5 percentage points from 2012 to 2020. Luxembourg tops the ranking, with around 41% of its workforce employed in science and technology and with a tertiary education. Finland and Sweden follow just behind, with 34% and 31% respectively. At the bottom, we find Romania and Italy, with around 15% and 17% respectively.

The share of researchers in the workforce is increasing in the EU, although there is a strong variation across EU countries. The share of R&D personnel and researchers increased from 1.1% to 1.4% of the labour force in the EU from 2011 to 2020 (see Figure 5.4-10). In 2020, the countries with the highest share of researchers were Denmark, Belgium, Finland and Norway, while nations with the lowest share were Romania, Cyprus, Malta and Latvia. In the EU, most researchers and R&D personnel work for businesses (see Figure 5.4-11), followed by the higher education sector, the government and the private non-profit sector. The business sector accounts for more than double the numbers of researchers and R&D personnel than in the higher education sector, and more than four times the numbers in the government sector. Furthermore, in the last 10 years, the private sector has increased its number of researchers and R&D personnel the most, growing from about 1.3 million employees (in full-time equivalents) in 2013 to almost 1.8 million in 2020.

Figure 5.4-9: Share of workforce with tertiary education employed in science and technology[(1)], 2012 and 2020



Source: Eurostat (online data code: HRST_ST_NCAT)

Note: [(1)]Percentage of the population aged 15 to 74 years in the work force with tertiary education and working in science and technology occupations.

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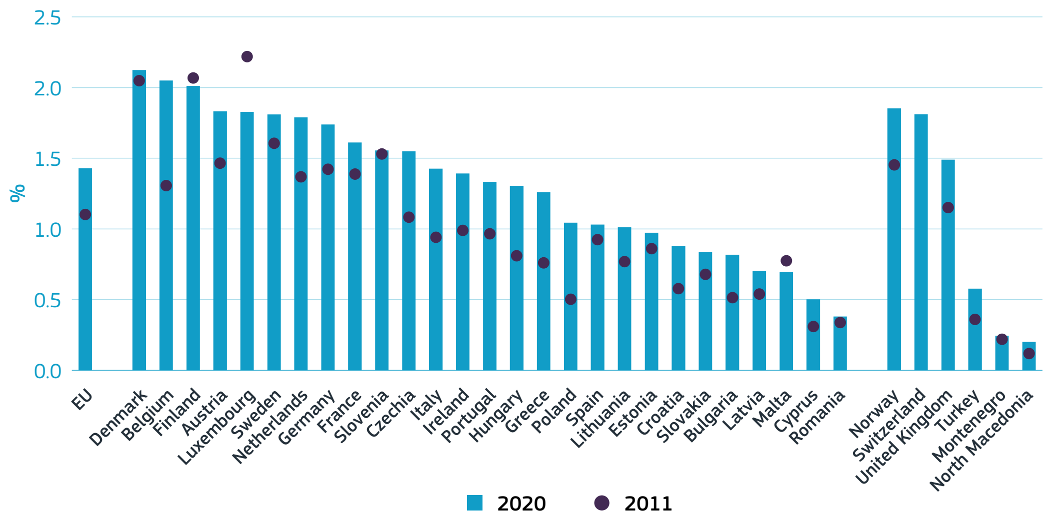
Figure 5.4-10: Share of R&D personnel and researchers in the labour force[1], 2011 and 2020



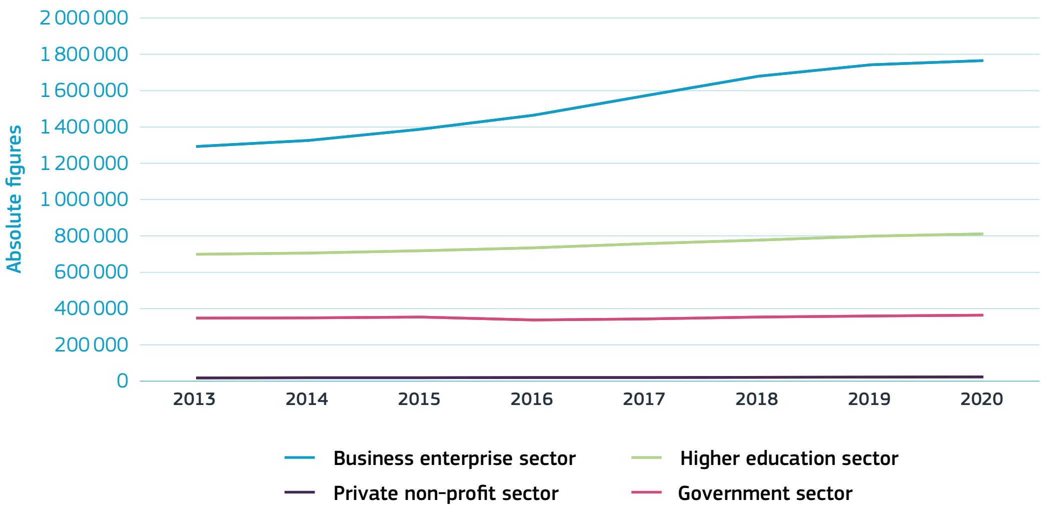
Science, Research and Innovation Performance of the EU 2022

Source: Eurostat (online data code: RD_P_PERSLF)

Note: [1]Share of R&D personnel and researchers (in full time equivalent) is measured respect to the labour force, across all sectors.

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-4-10.xlsx

Figure 5.4-11: R&D personnel and researchers[1] in the EU by sector, 2013-2020



Science, Research and Innovation Performance of the EU 2022

Source: Eurostat (online data code: RD_P_PERSQUAL11)

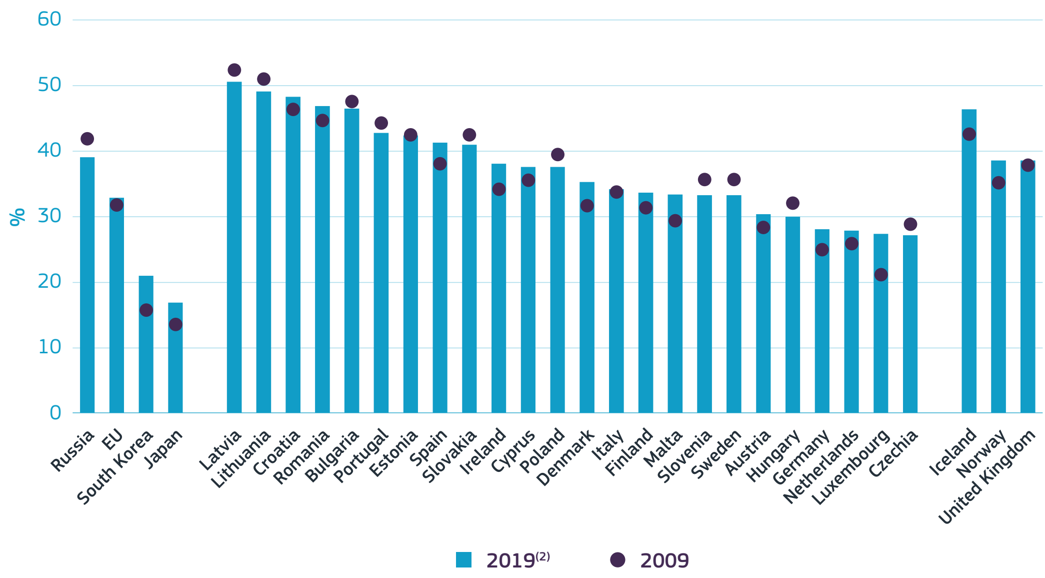
Note: [1]R&D personnel and researchers is expressed in units of full time equivalent.

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-4-11.xlsx

The share of women researchers is slowly increasing in the EU, however wide heterogeneity exists among Member States. In the EU, 33% of researchers are women (see Figure 5.4-12). The Member State with the most women researchers is Latvia, with 51% of women researchers, while the country with the least is Czechia with 21%. The UK has 6 percentage points more female researchers than the EU. That said, such figures are likely to mask the sectorial research specialisation of the different countries. Figure 5.4-13 shows how a large majority of female researchers are in the health and care sector, while very few are in the engineering and technology sector.

The percentage of young individuals who are no longer in the education system and who are not working or enrolled in a training programme (NEETs) has been reducing in most EU countries. In 2010, the percentage of NEETs among young adults was around 15%, while in 2020 it diminished to 14% (see Figure 5.4-14). The country with the highest rate of NEETs is Italy, with a small increase from 2011 (22.5%) to 2020 (23.3%). On the other side of the distribution, the Netherlands (5.7%) and Sweden (7.2%) are the EU countries with the fewest NEETs. High percentages of NEETs not only signify wasted human capital but are also symptomatic of a generation of disillusioned youth, excluded from society, with long-term economic costs for society at large.

Figure 5.4-12: Share of women researchers[1], 2009 and 2019

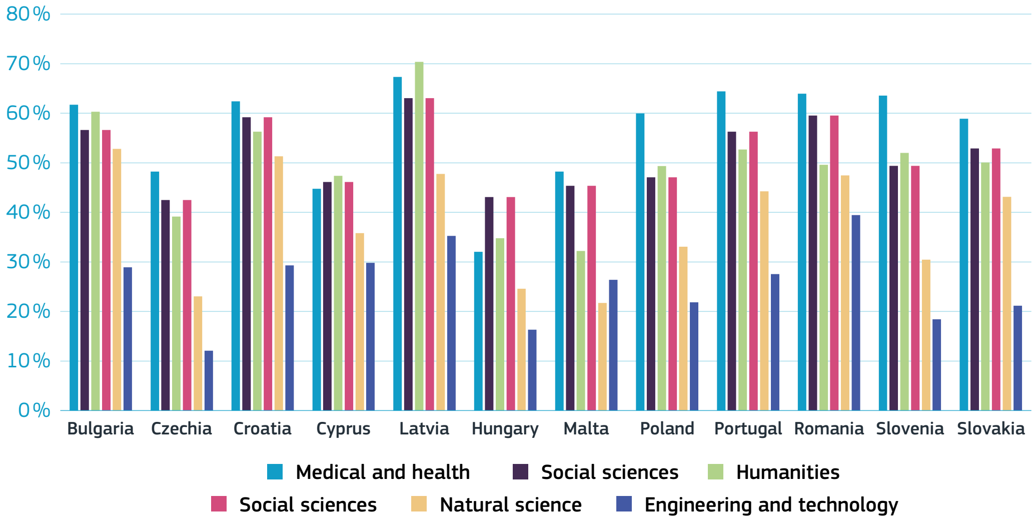


Source: Eurostat (online data code: TSC00005)

Note: [1]The share of women researchers among total researchers in head count in all institutional sectors. [2]UK, IS: year 2018

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-4-12.xlsx

Figure 5.4-13: Share of women researchers by field[1], 2019



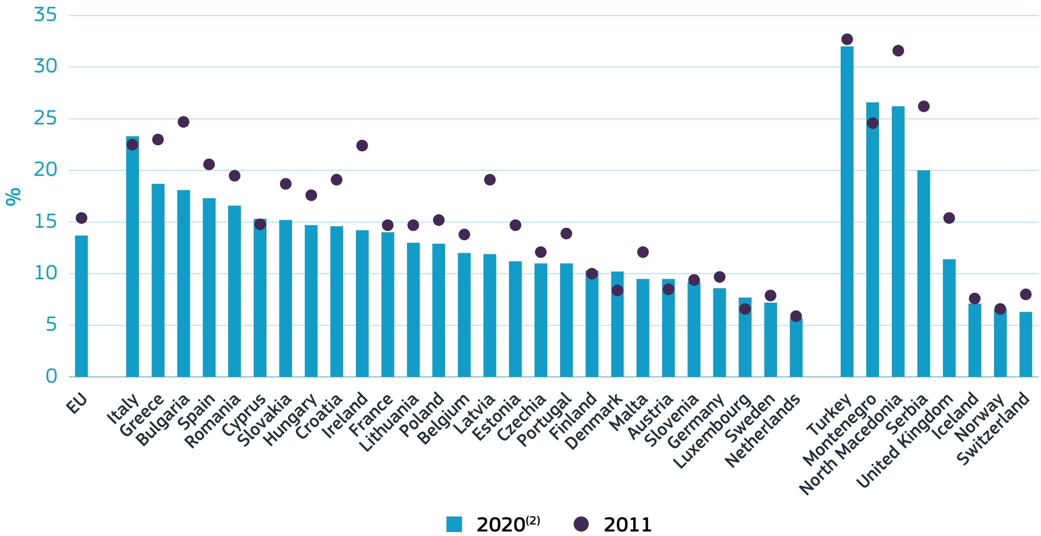
Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Eurostat (online data code: RD_P_PERSSCI)

Note: [1]Share of women researchers out of total researchers by field in Full-time equivalent. Data for the remaining EU countries is not available.

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-4-13.xlsx

Figure 5.4-14: Share of young people[1] neither in employment nor in education (NEET), 2011 and 2020



Science, Research and Innovation Performance of the EU 2022

Source: Eurostat (online data code: EDAT_LFSE_20)

Note: [1]Young people aged 15-29 years in % of the total population in the same age group. [2]UK: year 2019

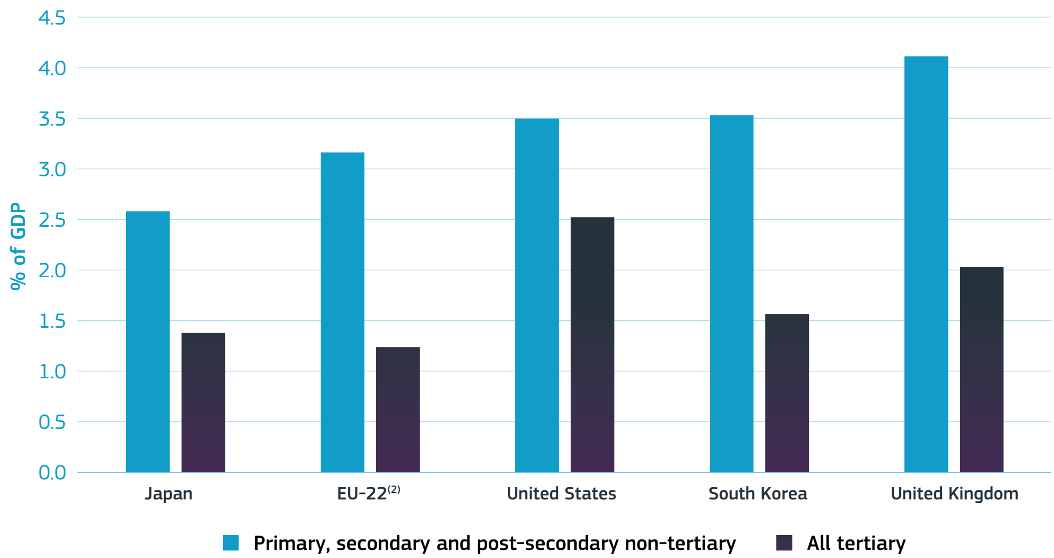
Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-4-14.xlsx

3. EU tertiary education figures compared to world top performers

Total public and private expenditure on education in the EU as a % of GDP is higher than in Japan, yet lower than in the United States, South Korea and the United Kingdom. The USA has the highest expenditure relative to GDP on tertiary education, followed by the UK (see Figure 5.4-15). The UK has the highest share of resources devoted to non-tertiary education, followed by South Korea. On average, EU countries spend 3.3% of GDP on non-tertiary education and 1.2% on tertiary education, less than half the level in the USA.

Private expenditure on education is relatively low in most EU countries, especially for tertiary education. Most expenditure on education in the EU is from the public sector, while other countries (particularly the USA and the UK) have a larger private contribution. The EU-22 has the highest public expenditure (% of GDP) on tertiary education. However, overall, the United States has the highest total expenditure (% of GDP) on tertiary education, followed by the United Kingdom (see Figure 5.4-16). In the USA, UK, Japan and South Korea, private contributions account for the majority of tertiary education spending. US public expenditure on tertiary education accounts for 0.9% of its GDP, while EU expenditure accounts for 1%. At the same time, US private expenditure on tertiary education accounts for 1.6% of its GDP, while in the EU this figure is only 0.2%.

Figure 5.4-15: Total (public and private) expenditure[1] on education, 2018



Science, Research and Innovation Performance of the EU 2022

Source: 'Education at a glance' (2021), Indicators, OECD.

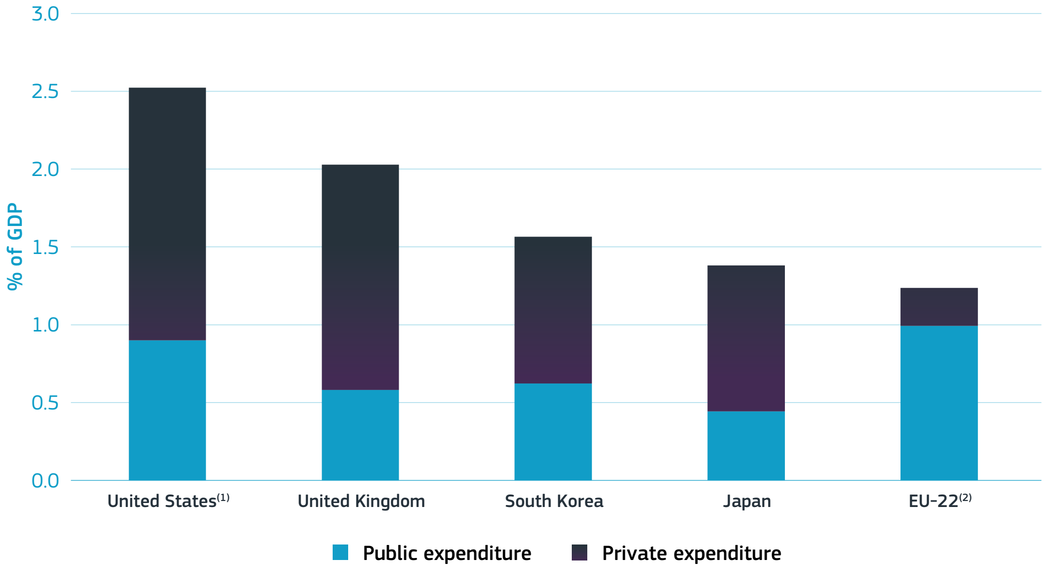
Note: [1]Total expenditure includes public, private and international sources. [2]EU-22 includes: AT, BE, CZ, DK, EE, FI, FR, DE, EL, HU, IE, IT, LV, LT, LU, NL, PL, PT, SK, SI, ES, SE.

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-4-15.xlsx

China is witnessing a rapid expansion in tertiary education participation, both in absolute and relative terms. South Korea has the highest share of young adults enrolled in tertiary education, closely followed by the United States and the European Union (see Figure 5.4-17). China's share of young adults enrolled in tertiary education increased from 32% in 2013 to 54% in 2019. The United Kingdom's share increased from 57% in 2013 to 66% in 2019, and the EU's from 67% to 75%.

The EU is comparable with the USA and the UK in terms of numbers of researchers relative to the population, growing from 2 600 researchers per million inhabitants in 2000 to 4 500 in 2018 (see Figure 5.4-18). Yet South Korea has shown a remarkable increase over the same period, and is outperforming the EU, the USA, the UK and Japan. Despite China's overall growth, its number of researchers relative to population is still relatively low.

Figure 5.4-16: Expenditure in tertiary education, 2018



Science, Research and Innovation Performance of the EU 2022

Source: 'Education at a glance' (2021), Indicators, OECD.

Note: (1)US figures are for net student loans rather than gross, thereby underestimating public transfers. (2)EU-22 includes: AT, BE, CZ, DK, EE, FI, FR, DE, EL, HU, IE, IT, LV, LT, LU, NL, PL, PT, SK, SI, ES, SE.

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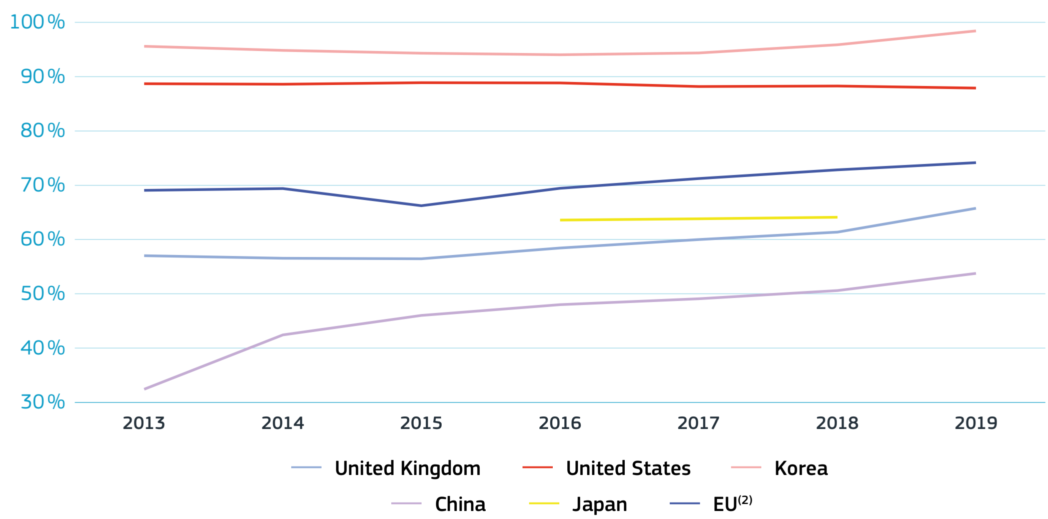
Figure 5.4-17: Gross enrolment ratio for tertiary education[1], 2013-2019



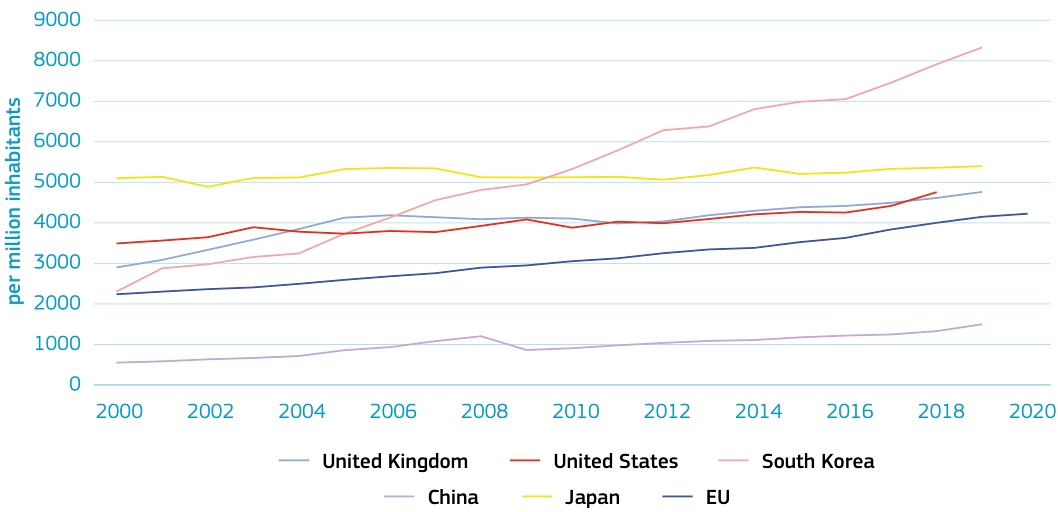
Science, Research and Innovation Performance of the EU 2022

Source: UNESCO data

Note: [1]The number of students enrolled in tertiary education is expressed as percentage of the 5-year age group immediately following upper secondary education. [2]EU average is computed as an unweighted average of gross enrolment ration for tertiary education by DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit.

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-4-17.xlsx

Figure 5.4-18: Researchers per million inhabitants (in FTE), 2000-2020



Science, Research and Innovation Performance of the EU 2022

Source: Eurostat (online data code: rd_p_persocc) and World Bank

Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-4-18.xlsx

4. The human-capital challenge posed by COVID-19

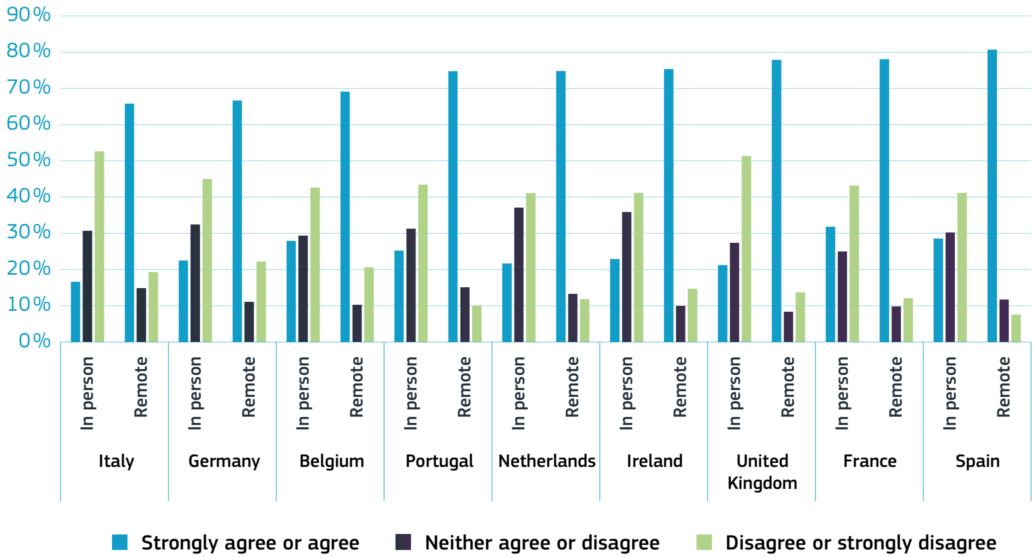
The COVID-19 pandemic has negatively impacted learning outcomes, particularly for students from disadvantaged socio-economic backgrounds (Reimers, 2022). This can cast a long shadow in terms of the human capital endowment of the population, productivity and innovation capacity[1]. Students whose education has been interrupted by the pandemic risk facing long-term losses in income. Economies with an impacted human-capital base in the workforce are likely to face lower economic growth, with substantial welfare consequences (Hanushek and Woessmann, 2020; Azevedo et al., 2021). According to UNESCO, in 'Education: From Disruption to Recovery', over 100 million additional children worldwide will fall below the minimum proficiency level in reading as a result of the COVID-19 crisis[2]. The JRC also highlighted how students from poorer socioeconomic backgrounds will likely be among the greatest losers of the COVID-19 pandemic (Di Pietro et al., 2020).

During the COVID-19 pandemic, students were shown to be more distracted during online classes compared to in-person classes (see Figure 5.4-19). In Germany, 23 % of students declared being very distracted during in-person classes, while 67 % agreed that they are very distracted during online classes. This finding is relatively homogeneous across European countries. Moving from in-person to online classes increases the percentage of students believing that they are distracted by around 49 percentage points in Italy, 41 percentage points in Belgium, 50 percentage points in Portugal, 53 percentage points in the Netherlands, 43 percentage points in France and 52 percentage points in Spain.

Disadvantaged students gain the most from in-school peer interaction and cannot rely on private tutoring at home from well-educated parents or costly private teachers. Students from poorer families may also not always have access to the facilities needed for online learning: a modern computer, a silent room and a fast internet connection (Agostinelli et al., 2022). Furthermore, schoolteachers, particularly in more rural and less-developed areas, do not always have an adequate level of digital proficiency to perform online teaching. For example, primary school closures in Belgium resulted in significant learning losses and a substantial increase in educational inequality (Maldonado and De Witte, 2020). Inequality in learning outcomes, both within and across schools, increased, and socioeconomically disadvantaged students were relatively more affected. Similarly, primary school closures during COVID-19 in the Netherlands and Germany diminished learning outcomes, particularly among students from disadvantaged homes (Engzell et al., 2021; Werner and Woessmann, 2021). Noticeably, this empirical evidence is from countries with very high level of digitalisation, suggesting that the likely effect in less digital-ready nations may be worse. Such disruptions to children's learning today, generated by COVID-19-related school closures, are likely to have a persistent and large impact on the production capacity of the economy and to harm future growth (Fernald and Ochse, 2021). At the same time, for some students, the pandemic provided an opportunity to gain more autonomy in learning, to spend more time with their families and to learn together with their families.

1 Learning loss is global – and significant, McKinsey
2 UNESCO report 2021

Figure 5.4-19: Share of students agreeing with the sentence: "I am often distracted when doing course work or attending classes"



Science, Research and Innovation Performance of the EU 2022

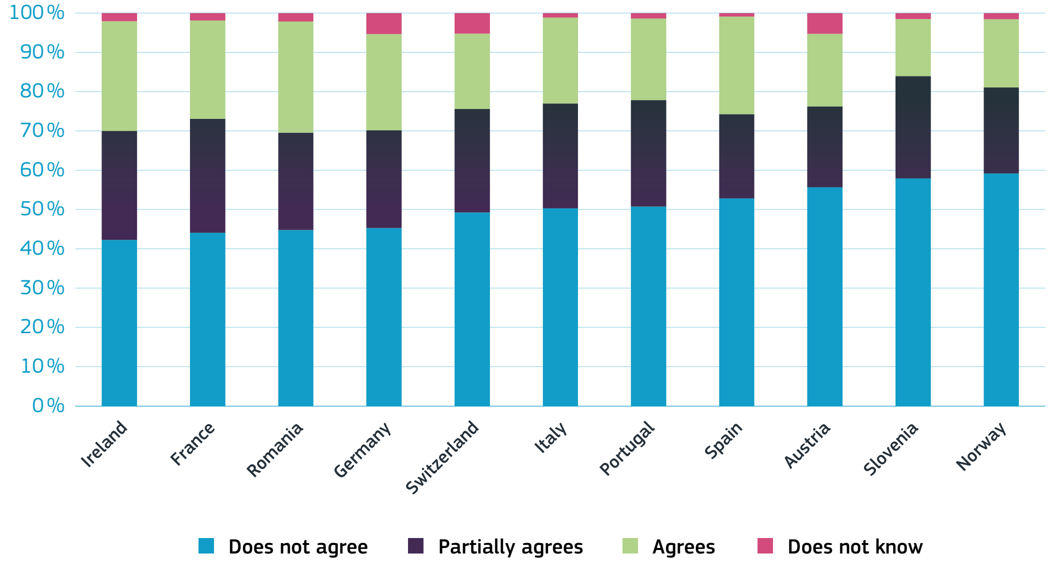
Source: Based on *Student perceptions of remote learning* (Stein, 2020), Harvard Dataverse
Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-4-19.xlsx

Understandably, students from disadvantaged socioeconomic backgrounds could gain the least from such an opportunity, which often translated in a 'sink-or-swim' environment (Reimers, 2022).

During COVID-19, around 50% of students in many European countries felt helpless when they had to do school activities and homework online. In France, 54% of students agreed or partially agreed with the statement 'I feel helpless when I have to do school activities and homework online' (see Figure 5.4-20). In Germany, the same group amounted to 49%, and in Ireland, 56%.

Early age education has well-known long-term impacts on future income and well-being (Dillon et al., 2017; Duflo, 2001; Elango et al., 2016). Even small losses of time

Figure 5.4-20: Share of students agreeing with the sentence: “I feel helpless when I have to do school activities and homework online”



Science, Research and Innovation Performance of the EU 2022

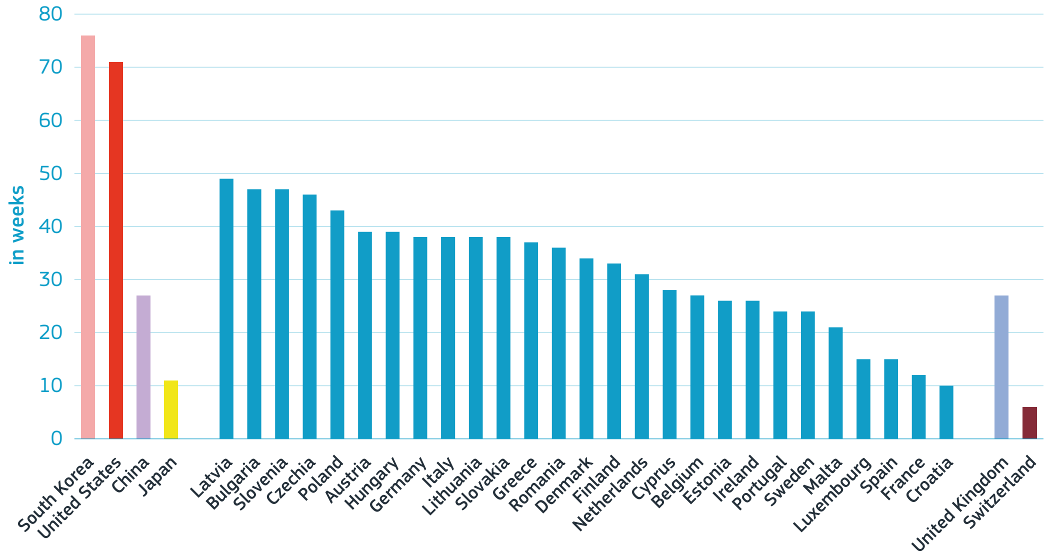
Source: Based on KiDiCoTi consortium calculations
Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-4-20.xlsx

spent at school can have large consequences for the development of skills and abilities (Carlsson et al., 2015; Lavy, 2015). Figure 5.4-21 shows the numbers of weeks lost by students during the pandemic. Significant losses are depicted for all countries, yet with meaningful differences. For example, in Germany and Italy, students faced 38 weeks of full or partial school closure, while in France only 12 weeks. The negative impact of COVID-19 restrictions on the student population calls for urgent implementation of corrective policies.

Students who graduated during the pandemic face higher barriers to entering the job market, which will likely lead to persistent earnings losses, particularly for less advantaged graduates. Indeed, graduating during a recession can permanently affect the long-term income and professional career of individuals (Oreopoulos, 2012). Cutler et al. (2015) found that graduation in a recessionary period permanently lowers income and health later in life.

Online teaching methods are an imperfect substitute for classroom teaching, with a negative impact on learning outcomes, particularly for disadvantaged students (Cacault et al., 2021). Cacault et al. (2021) used a randomised experiment in a public Swiss university and found that attending lectures via live streaming lowers achievement for low-ability students and increases achievement for high-ability ones.

Figure 5.4-21: Duration of FULL and PARTIAL school closures[(1)]



Science, Research and Innovation Performance of the EU 2022

Source: UNESCO global monitoring of school-closures data
Note: [(1)]Data updated until 30 November 2021
Stat. https://ec.europa.eu/assets/rtd/srip/2022/figure-5-4-21.xlsx

Figlio et al. (2013) provided experimental evidence from a US university showing that online education is not a full substitute for traditional live classroom instruction. Alpert et al. (2016) also found similar experimental evidence indicating that purely online teaching reduces learning outcomes relative to the face-to-face format. Bettinger et al. (2017) found that taking a course online, instead of in-person, reduced student success and progress in college, leading to lower grades and reducing the likelihood of remaining enrolled in the programme.

To deal with the negative consequences of school closure, education systems across Europe implemented remedial actions that have helped reducing learning disruptions. Governments allocated additional funding to cover additional costs of hygiene and sanitation of educational spaces and acquisition of IT equipment such as computers and tablets (De Witte and Smet, 2021). Countries implemented broader measures to support the digitalisation of education, improving teacher training and hiring additional teachers and tutors for pupils struggling with online and blended modes of learning. Furthermore, several EU Member States promoted the organisation of summer programmes in 2020 targeted at students from disadvantaged backgrounds, with funding to support their enrolment without cost for their families (Depping et al., 2021; Gambi and Witte, 2021; De Witte and Smet, 2021). The initial results seem to support such compensatory measures, with evidence of their capacity to halt learning losses (Gambi and de Witte, 2021).

5. Conclusions: human capital, the building block of prosperity

Investment in human capital is one of the main drivers of economic growth. The quality and quantity of formal education has long-term effects on the creativity, competence and productivity of individuals. In the knowledge economy, demand for highly skilled workers is rapidly increasing, calling for additional resources to be devoted to the education system, from primary up to tertiary education and including lifelong learning.

An increasing share of the EU population is obtaining a tertiary education. Furthermore, the share of the work force with tertiary education and working in science and technology occupations, as well as the share of researchers in the workforce, is increasing in the EU. However, there is still strong gender disparity among the fields of study, with ICT, engineering and technology dominated by male students, and humanities, health and care prevalently chosen by women.

Considering both public and private spending, the EU invests less in education than the USA, Japan, the UK and South Korea. More effort is required to unlock further public and private resources to be devoted to education, training and reskilling. On the other hand, the EU has the highest share of publicly financed education spending, reducing risks of inequalities and making the spending less sensitive to exogenous shocks.

The number of ICT graduates and employment in the ICT sector are rapidly increasing. At the same time, European companies are expanding their reskilling programmes, shifting to a model of life-long learning fitting the digital era. More and more adults are engaging with learning activities to keep themselves equipped with the right skills for their professional development.

School closures during the pandemic have resulted in learning losses, especially for disadvantaged students. Corrective policies will be needed to support students to recover these learning losses.

References

Acemoglu, D. (2012), 'What does human capital do? A review of Goldin and Katz's The race between education and technology', *Journal of Economic Literature*, 50(2), pp. 426-63.

Agostinelli, F., Doepke, M., Sorrenti, G., & Zilibotti, F. (2022), 'When the great equalizer shuts down: Schools, peers, and parents in pandemic times', *Journal of public economics*, 206, p. 104574.

Alpert, W. T., Couch, K. A., & Harmon, O. R. (2016), 'A randomized assessment of online learning', *American Economic Review*, 106(5), pp. 378-82.

Azevedo, J. P., Hasan, A., Goldemberg, D., Geven, K., & Iqbal, S. A. (2021), *Simulating the potential impacts of COVID-19 school closures on schooling and learning outcomes: A set of global estimates*, The World Bank Research Observer, 36(1), pp. 1-40.

Baten, J., & Van Zanden, J. L. (2008), 'Book production and the onset of modern economic growth', *Journal of Economic Growth*, 13(3), pp. 217-235.

Bettinger, E. P., Fox, L., Loeb, S., & Taylor, E. S. (2017), 'Virtual classrooms: How online college courses affect student success', *American Economic Review*, 107(9), pp. 2855-75.

Cacault, M. P., Hildebrand, C., Laurent-Lucchetti, J., & Pellizzari, M. (2021), 'Distance learning in higher education: evidence from a randomized experiment', Journal of the *European Economic Association*, 19(4), pp. 2322-2372.

Cammeraat, E., L. Samek and M. Squicciarini (2021), 'The role of innovation and human capital for the productivity of industries', *OECD Science, Technology and Industry Policy Papers*, No. 103, OECD Publishing, Paris, https://doi.org/10.1787/197c6ae9-en.

Carlsson, M, G B Dahl, B Öckert and D Rooth (2015), 'The Effect of Schooling on Cognitive Skills', *Review of Economics and Statistics* 97(3), pp. 533–547.

Cohen, W. M., & Levinthal, D. A. (1989), 'Innovation and learning: the two faces of R & D', *The economic journal*, 99(397), 569-596.

Cuaresma, J. C., Doppelhofer, G., & Feldkircher, M. (2014), 'The determinants of economic growth in European regions', *Regional Studies*, 48(1), pp. 44-67.

Cutler, D.M., Huang, W., & Lleras-Muney, A. (2015), 'When does education matter? The protective effect of education for cohorts graduating in bad times', *Social Science & Medicine*, 127, pp. 63-73.

De Witte, K., & Smet, M. (2021), *Financing Education in the Context of COVID-19* (EENEE Ad Hoc Report No. 3, 2021; p. 27), Retrieved from EENEE website: https://eenee.eu/en/resources/library/financing-education-in-the-context-of-covid-19/.

Dearden, L., Reed, H., & Van Reenen, J. (2006), 'The impact of training on productivity and wages: Evidence from British panel data', *Oxford bulletin of economics and statistics*, 68(4), pp. 397-421.

Depping, D., Lücken, M., Musekamp, F., & Thonke, F. (2021), Kompetenzstände Hamburger Schüler*innen vor und während der Corona-Pandemie. In DDS Die Deutsche Schule Beiheft: Vol. 17, Schule während der Corona-Pandemie, Retrieved from https://www.waxmann.com/dds_beiheft_17/.

Destré, G., Lévy-Garboua, L., & Sollogoub, M. (2008), 'Learning from experience or learning from others?: Inferring informal training from a human capital earnings function with matched employer–employee data', *The Journal of Socio-Economics*, 37(3), pp. 919-938.

Di Pietro, G., Biagi, F., Costa, P., Karpiński, Z., & Mazza, J. (2020), *The likely impact of COVID-19 on education: Reflections based on the existing literature and recent international datasets* (Vol. 30275), Publications Office of the European Union.

Diebolt, C., & Hippe, R. (2019), 'The long-run impact of human capital on innovation and economic development in the regions of Europe', *Applied Economics*, 51(5), pp. 542-563.

Dillon, M. R., Kannan, H., Dean, J. T., Spelke, E. S., & Duflo, E. (2017), 'Cognitive science in the field: A preschool intervention durably enhances intuitive but not formal mathematics', *Science*, 357(6346), pp. 47-55.

Dostie, B. (2018), 'The impact of training on innovation', *ILR review*, 71(1), pp. 64-87.

Duflo, E. (2001), 'Schooling and labor market consequences of school construction in Indonesia: Evidence from an unusual policy experiment', *American economic review*, 91(4), pp. 795-813.

Elango, S., García, J. L., Heckman, J. J., & Hojman, A. (2016), 4. *Early Childhood Education* (pp. 235-298), University of Chicago Press.

Engzell, P., Frey, A., & Verhagen, M. D. (2021), *Learning loss due to school closures during the COVID-19 pandemic,* Proceedings of the National Academy of Sciences, 118(17).

Fernald, J., Li, H., & Ochse, M. (2021), 'Future Output Loss from COVID-Induced School Closures', *Future*, 2021, p. 04.

Figlio, D., Rush, M., & Yin, L. (2013), 'Is it live or is it internet? Experimental estimates of the effects of online instruction on student learning', *Journal of Labor Economics*, 31(4), pp. 763-784.

Gambi, L., & Witte, K. D. (2021), *The resiliency of school outcomes after the COVID-19 pandemic. Standardised test scores and inequality one year after long term school closures*. KU Leuwen Working Papers, 50.

Gennaioli, N., La Porta, R., Lopez-de-Silanes, F., & Shleifer, A. (2013), 'Human capital and regional development', *The Quarterly journal of economics*, 128(1), pp. 105-164.

González, X., Miles-Touya, D., & Pazó, C. (2016),'R&D, worker training and innovation: Firm-level evidence', *Industry and Innovation*, 23(8), pp. 694-712.

Griffith, R., Redding, S., & Reenen, J. V. (2004), 'Mapping the two faces of R&D: Productivity growth in a panel of OECD industries', *Review of economics and statistics*, 86(4), pp. 883-895.

Grundke, R., et al. (2017), *Skills and global value chains: A characterisation*, OECD Science, Technology and Industry Working Papers, No. 2017/05, OECD Publishing, Paris, https://doi.org/10.1787/cdb5de9b-en.

Hall, B. H., Lotti, F., & Mairesse, J. (2013), 'Evidence on the impact of R&D and ICT investments on innovation and productivity in Italian firms', *Economics of Innovation and New Technology*, 22(3), pp. 300-328.

Hanushek, E. A., & Woessmann, L. (2015), *The knowledge capital of nations: Education and the economics of growth*, MIT press.

Hanushek, E. and L. Woessmann (2020), *The economic impacts of learning losses*, OECD Education Working Papers, No. 225, OECD Publishing, Paris, https://doi.org/10.1787/21908d74-en.

Konings, J., & Vanormelingen, S. (2015), 'The impact of training on productivity and wages: firm-level evidence', *Review of Economics and Statistics*, 97(2), pp. 485-497.

Lavy, V (2015), 'Do Differences in Schools' Instruction Time Explain International Achievement Gaps? Evidence from Developed and Developing Countries', *Economic Journal,* p. 125.

Madsen, J. B. (2010), 'The anatomy of growth in the OECD since 1870', *Journal of Monetary Economics*, 57(6), pp. 753-767.

Maldonado, J. E., & De Witte, K. (2020), 'The effect of school closures on standardised student test outcomes', *British Educational Research Journal*.

Messinis, G., & Ahmed, A. D. (2013), 'Cognitive skills, innovation and technology diffusion', *Economic modelling*, 30, pp. 565-578.

Oreopoulos, P., Von Wachter, T., & Heisz, A. (2012), 'The short-and long-term career effects of graduating in a recession', *American Economic Journal: Applied Economics*, 4(1), pp. 1-29.

Peri, G., Shih, K., & Sparber, C. (2015), 'STEM workers, H-1B visas, and productivity in US cities', *Journal of Labor Economics*, 33(S1), pp. S225-S255.

Reimers, F. M. (2022), 'Primary and secondary education during Covid-19: Disruptions to educational opportunity during a pandemic', (p. 475), Springer Nature.

Stein (2020), 'Student perceptions of remote learning', https://doi.org/10.7910/DVN/2TGOPH, Harvard Dataverse.

UNESCO (2021), 'One year into COVID: prioritizing education recovery to avoid a generational catastrophe' (Link).

Vandenbussche, J., Aghion, P., & Meghir, C. (2006), 'Growth, distance to frontier and composition of human capital', *Journal of economic growth*, 11(2), pp. 97-127.

Werner, K., & Woessmann, L. (2021), *The legacy of covid-19 in education*.

CHAPTER 6

FROM KNOWLEDGE TO SOLUTIONS AND VALUE

CHAPTER 6.1

SCIENTIFIC PERFORMANCE

KEY FIGURES

20 %
of the world's publications are from the EU

39 %
of the EU's publications are open access

21 %
of the top 10 % most-cited publications are from the EU

21 %
of publications on health are from the EU

KEY QUESTIONS WE ARE ADDRESSING

- How is the EU performing in scientific output and quality?
- How is EU science contributing to the grand societal challenges?
- In which areas is EU science more specialised?

KEY MESSAGES

What did we learn?

- The European Union remains a scientific powerhouse as it produces about 20% of the world's best science despite having just 6 % of the world's population.
- China is the global leader, not only in terms of volume of scientific publications, but also in the top 10% most-cited publications. However, the US is still leading in the top 1% most-cited publications and impact.
- Southern and eastern European countries are catching up in terms of scientific output and scientific quality.
- The EU is ahead of its global competitors in sharing scientific output. Over 39% of EU publications are freely available under at least one open-access publishing pathway.
- EU science is targeted to address societal challenges, particularly in health, and to foster the green and digital transitions.

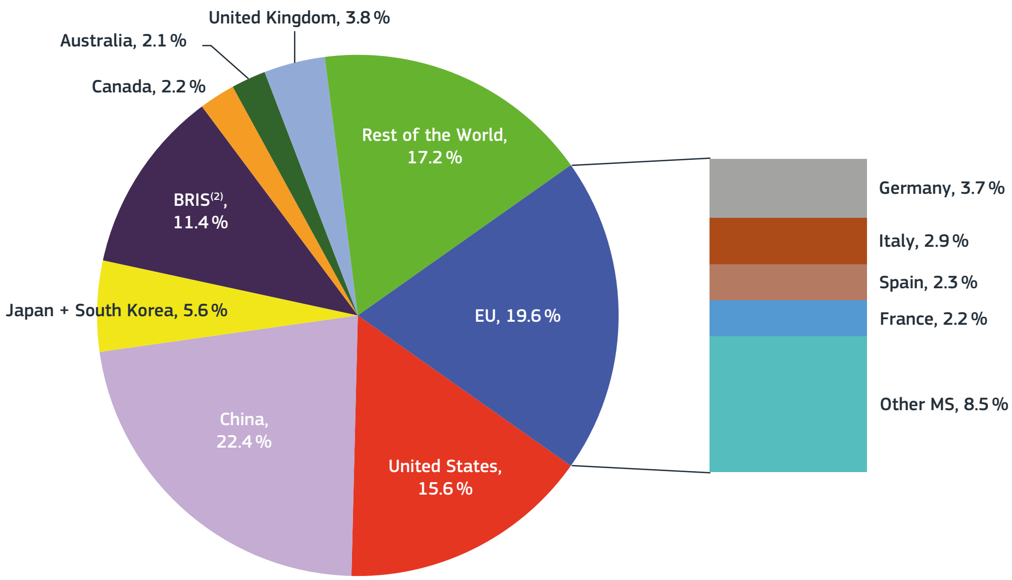
What does it mean for policy?

- For the EU to ensure scientific excellence and remain a key scientific player on the global stage, the effectiveness and performance of EU public research systems must be increased through stronger R&I investments and policy reforms.
- At the same time, it is crucial to continue reinforcing less-developed national and regional research systems in order to narrow the current knowledge gap between EU countries.
- Acknowledging open access to scientific knowledge as a key priority, efforts must be stepped up to lift existing barriers, to create the conditions and to adopt the necessary policies for making the European scientific system more open in knowledge sharing and collaboration.

1. Scientific output

The EU accounts for 19.6% of the total number of publications registered in Scopus, with almost 620000 publications in 2020. Despite the increase in absolute numbers, the EU lost 0.3 percentage points in relative terms compared to 2019. As Figure 6.1-1 shows, China takes the lead with a share of 22.4% of publications. The EU ranks second and the United States is in third position, with a share of 15.6%. Other important contributors to scientific production were Japan and South Korea, with a combined share of 5.6%, and Brazil, the Russian Federation, India and South Africa (BRIS) with a combined share of 11.4%. Other advanced economies were also relevant in the worldwide landscape, in particular the United Kingdom (3.8%), Australia (2.1%) and Canada (2.2%). In the EU, the biggest economies had the largest shares, with Germany, Italy, Spain and France all above 2%. Germany's world share is comparable to that of the United Kingdom (just below 4%) following the significant decline they have both experienced since 2000, when the United Kingdom accounted for 7.5% of the total publications and Germany for 6.5%.

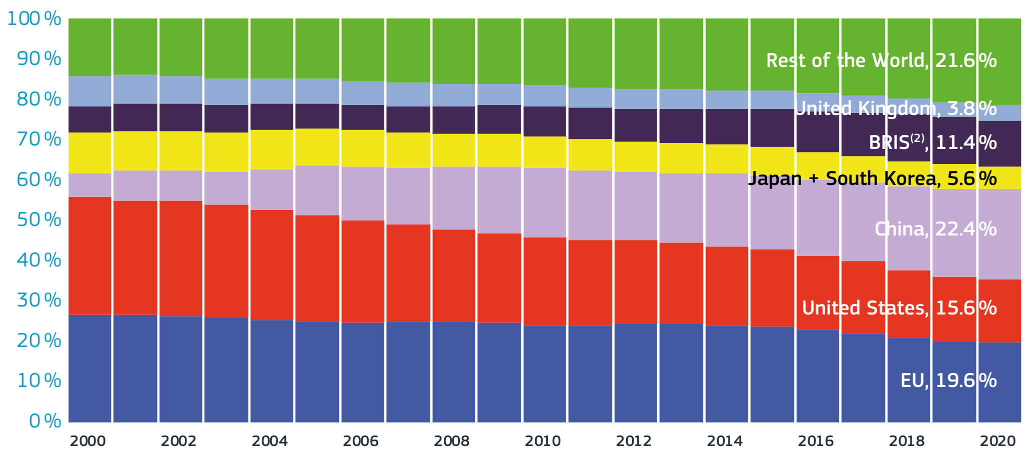
Figure 6.1-1: World share of scientific publications[1], 2020



Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Science-Metrix, using the Scopus database
Note: [1]Fractional counting used. [2]BRIS: Brazil, Russia, India and South Africa.
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-1-1.xlsx

The EU, the United States and China jointly produce more than 60% of the scientific output worldwide. This has been the case for the last 20 years, with China gradually gaining the leading position (Figure 6.1-2). In 2000, China's publication output amounted to 5.9% of world production, placing it in fifth position (Figure 6.1-2). China overtook the United States in 2016 and the EU in 2019 (Elsevier's Scopus database). This incredible increase affected the relative position of the United States, which has lost 13 percentage points since 2000, and to a lesser extent the EU, with a decline of only 7 percentage points. One reason could be the EU's specialisation in less-technological fields such as health and social sciences, where China is still lagging. Interestingly, China's increase from 2019 to 2020 was significantly lower than the year before (only 0.4 percentage points, compared to 1.3 percentage points from 2018 to 2019). It is not yet clear whether this slow-down is linked to the COVID-19 pandemic or to other policy related factors, such as the recent measures taken by the Chinese government to urge its researchers to publish in home-grown journals (Nature editorial, 2020). In contrast, both the United States and the EU saw their shares dropping at a slower pace, 0.3 percentage points in 2020, possibly due to the increase in the volume of scientific publications in areas where both have an advantage.

Figure 6.1-2: World shares of scientific publications[(1)], 2000-2020



Science, Research and Innovation Performance of the EU 2022

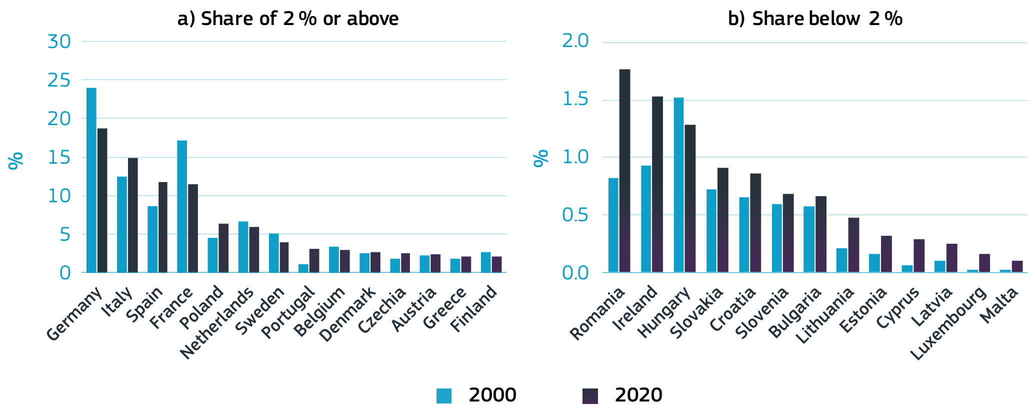
Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Science-Metrix, using the Scopus database

Note: [(1)]Fractional counting used. [(2)]BRIS: Brazil, Russia, India and South Africa.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-1-2.xlsx

Four large EU Member States together (Germany, Italy, Spain and France) produced almost 60% of the total EU publications in 2020. Within the EU, the shares of scientific publications vary significantly, and to a large extent depend on the size of the country (Figure 6.1-3). However, the shares have changed significantly in the last 20 years. Southern and eastern European countries have increased their share over 2000-2020, in contrast to some of the most populated countries such as Germany and France. The countries with the largest absolute increase in their shares are Spain, Italy, Poland and Portugal. On the other hand, the highest growth rates in terms of publication shares were recorded in small countries with a low overall publication volume, e.g. Malta (432%), Cyprus (388%) and Luxembourg (589%), although fast growth was also observed in Portugal (167%) and Romania (117%).

Figure 6.1-3: Share of each EU Member State within the EU for scientific publications[1], 2000 and 2020



Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Science-Metrix, using the Scopus database

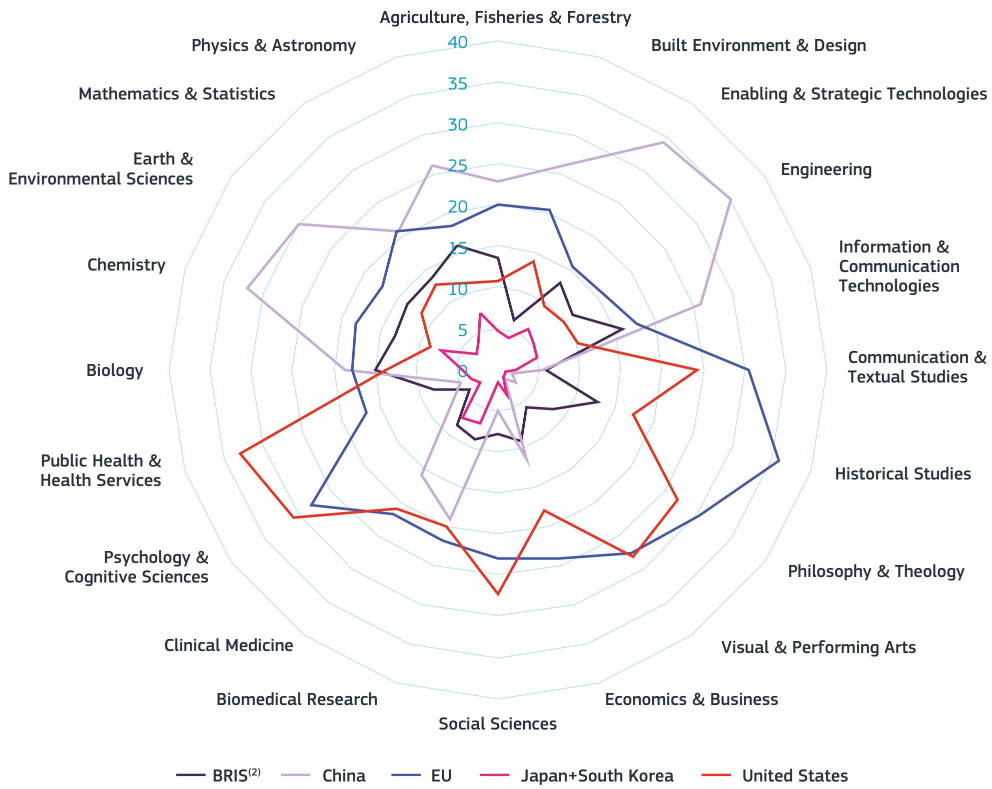
Note: [1]Fractional counting used.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-1-3.xlsx

Comparisons of research productivity across countries lead to different results, depending on the metric used for standardisation. If we compare publications per USD billion GDP, the BRIS countries perform best, followed by China, while the US scores last. If we compare publications per million population, the US is at the top, followed by the EU; and if we compare publications per researcher, the results are very similar, with a slight advantage to the EU. Therefore, the choice of the unit for comparisons must be taken into consideration and results must always be interpreted cautiously.

In 2020, the EU led globally in the domains[1] of economics and social sciences and of arts and humanities. These domains comprise fields such as historical studies, and

Figure 6.1-4: World shares (%) of scientific publications per country and scientific field(1), 2020



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Science-Metrix, using the Scopus database

Note: (1)Fractional counting used. (2)BRIS: Brazil, Russia, India and South Africa.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-1-4.xlsx

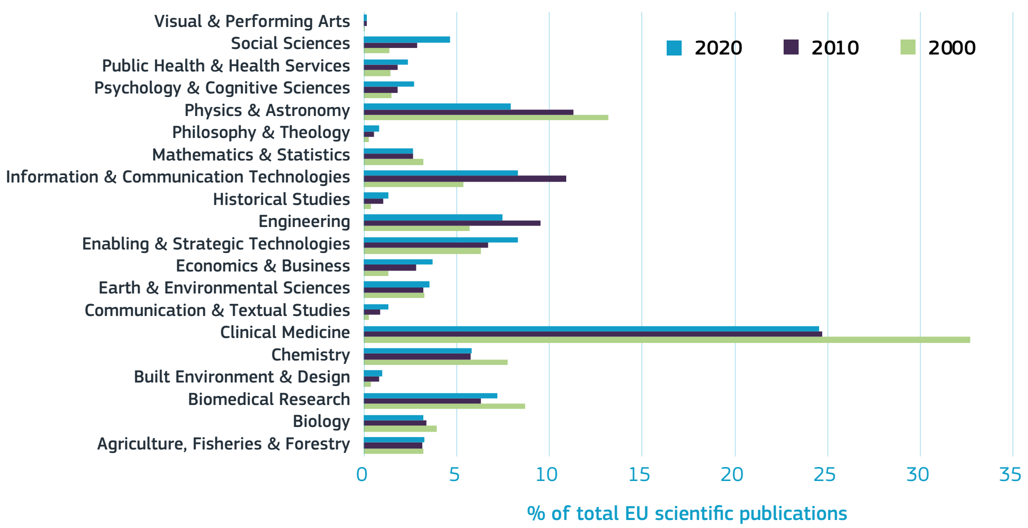
1 Each domain includes several scientific fields.

economics and business, which represent a small share of the articles published annually worldwide. To a lesser extent, the EU also leads in the fields of clinical medicine and of biomedical research. Figure 6.1-4 shows that the United States leads in the domain of health sciences, particularly in the field of public health and health services. In contrast, China leads in applied and natural sciences, especially in the fields of engineering, enabling and strategic technologies and of chemistry.

Approximately one in four EU publications are in the scientific field of clinical medicine, in which the EU leads globally. Its share within EU publications is still the highest, despite a dramatic drop of 8 percentage points since 2000 (Figure 6.1-5). Other scientific fields that have lost prominence over the years are physics and astronomy, chemistry, and biomedical research. In contrast, there has been an increase in the share of publications in the fields of information and communication technologies, enabling and strategic technologies, social sciences, and economics and business. More recently, there has been an increase in the share of publications related to earth and environmental sciences. The changes in the shares of the publications over time may reflect to a certain extent the EU's trajectory towards the green and digital transitions.

Open access means making scientific publications freely available so that anyone can read and reuse them. This free exchange of knowledge encourages creativity and promotes research excellence. There are various types of open-access publishing but the two most common are 'gold' and 'green'. **Gold open access** means immediate access

Figure 6.1-5: EU share of publications[1] per scientific field, 2000, 2010 and 2020



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Science-Metrix, using the Scopus database

Note: [1]Fractional counting used

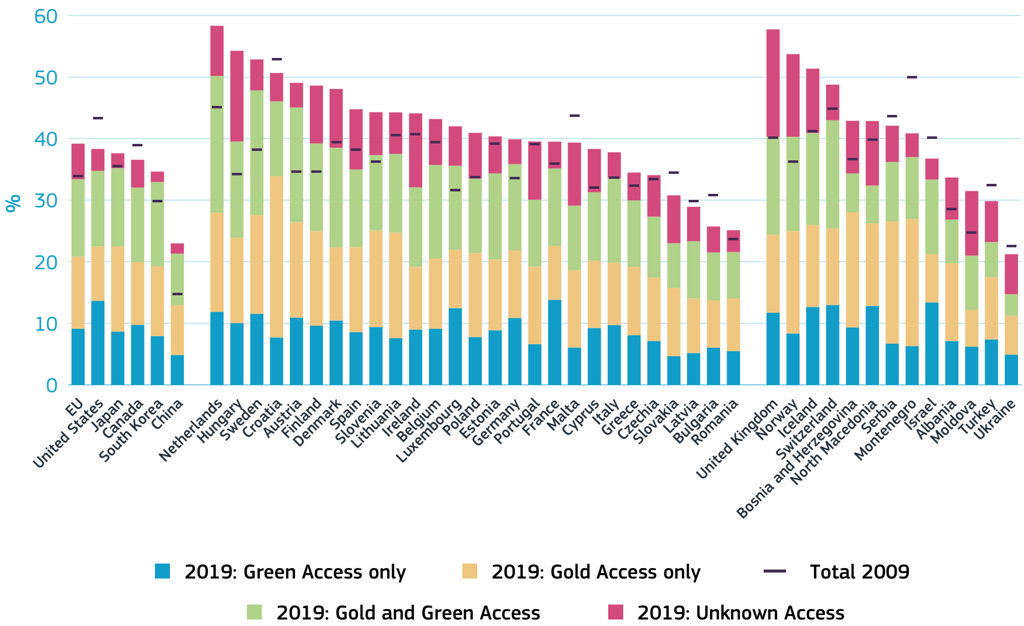
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-1-5.xlsx

to an article in an online journal. Green open access involves publishing in a traditional subscription journal as usual then self-archiving in a publicly and freely accessible repository after an embargo period set by the publisher.

The EU is ahead of its global competitors in applying open access. Over 39% of total EU publications are freely available under at least one open-access publishing pathway (gold, green or other). The United States, Japan, Canada and South Korea are closely behind, with shares ranging from 38 % to 35 %, whereas China's share is much lower and accounts for 23 % of the total scientific production of the country.

The shares vary significantly among EU Member States. The highest share was recorded in the Netherlands (58 %) and the lowest in Romania (25 %). Nevertheless, open-access scientific publications have increased for 22 of the 27 Member States over the last decade, particularly for Finland, Austria and Hungary.

Figure 6.1-6: Open-access scientific publications[1] with digital object identifier (DOI) as % of total scientific publications with DOI, 2009 and 2019



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Science-Metrix, using the Scopus database and 1findrdatabases

Note: [1]Full counting used

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-1-6.xlsx

Open science makes R&I systems more efficient and creative, and reinforces scientific excellence and society´s trust in science[2]. The first international framework on open science was adopted by 193 countries at UNESCO's General Conference in November 2021[3]. The European Commission has already taken steps towards open science. In the New European Research Area adopted in September 2020, the Commission commits to:

- launch, via the Horizon Europe Programme, a platform for peer-reviewed open access publishing;
- analyse authors' rights to enable sharing of publicly funded peer-reviewed articles without restriction;
- ensure a European Open Science Cloud that is offering findable, accessible, interoperable and reusable research data and services (Web of FAIR);
- incentivise open science practices by improving the research assessment system.

The Horizon 2020 programme is in a leading position among funding programmes in terms of the level of open access achieved. The estimated level of compliance with the open-access policy for scientific publications under Horizon 2020 stands at 83 %, which is among the top open-access success rates of funders globally (European Commission, 2021a). The average open-access rate among Horizon 2020 publications has increased steadily over the duration of the programme, from just over 65 % of peer-reviewed publications in 2014 to 86 % in 2019. However, the shares differ between Horizon 2020 programmes' scientific fields and specific disciplines. For example, the percentage of open-access publications was highest within medical and health sciences, as well as in natural sciences.

2 A new ERA for Research and Innovation' (COM(2020) 628 final)

3 https://en.unesco.org/news/unesco-sets-ambitious-international-standards-open-science

Box 6.1-1: Effect of COVID-19 on scientific publications

The pandemic did not affect the overall volume of scientific publications, but it had an impact on the shares between countries and scientific fields. In 2020, the number of publications continued to increase worldwide, but at a lower rate (5.6 % on an annual basis, compared to 7.1 % in 2019). This is still higher than the average increase of 5.4 % over 2000-2010 (see Table 6.1-1). The United States and the EU had the biggest increase, mainly due to their publications in health-related scientific fields, where both are strong.

Table 6.1-1: Growth rate in the volume of the scientific publications (%, fractional counting)

	EU	China	United States	BRIS (Brazil, Russia, India and South Africa)	Japan + South Korea	World
2019	2.4	13.8	0.9	9.4	1.1	7.1
2020	3.6	7.5	3.8	2.8	0.5	5.6
2000-2020 Average growth	3.8	12.9	2.1	8.4	2.3	5.4

Science, Research and Innovation Performance of the EU 2022

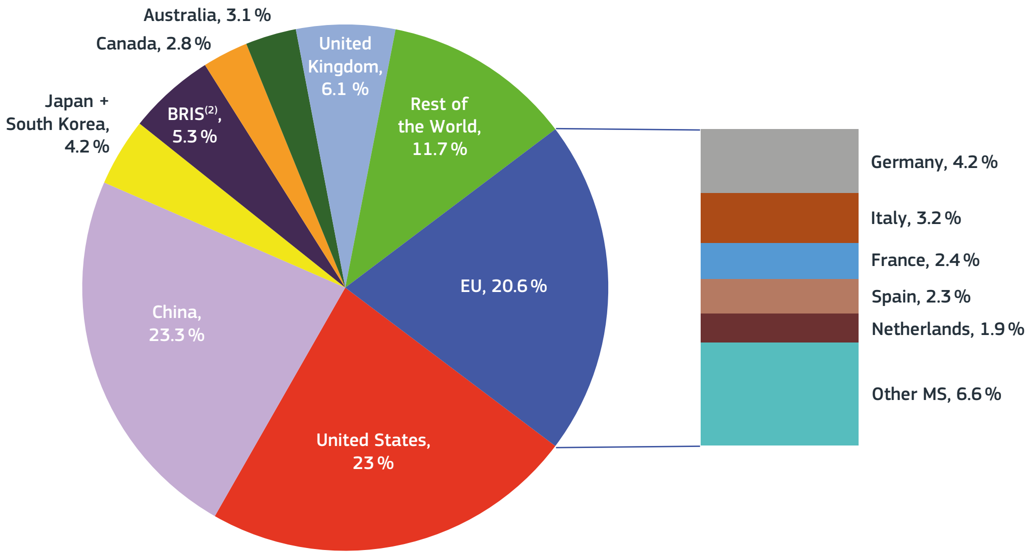
Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit based on Science-Metrix using the Scopus database.

Scientists published well over 100 000 articles on the coronavirus pandemic in 2020 (Else, 2020). The timeline between the submission of a paper and its publication shortened, particularly for papers about COVID-19. Studies on the pandemic were prioritised, with the goal of getting them into the public domain as quickly as possible, which raised some concerns about the quality of the underlying research (Sloane and Zimmerman, 2021). However, during the early phase of the pandemic, scientists from the US and the EU reported a sharp decline in time spent on research. This decline in research activity also impacted scientific output, with a clear gender bias. The growth in submissions from female authors trailed behind growth from male authors across all subject areas, at least during the first half of 2020. These negative impacts on time spent on research were short-lived. A year later, scientists reported only minor differences compared to the pre-pandemic total work time (Gao et al., 2021).

2. Scientific excellence

China now has the highest share of the top 10 % most-cited scientific publications worldwide, overtaking the United States. China has continued to improve the quality of its scientific output, as demonstrated by the impressive increase in the share of the top 10 % most-cited scientific publications, from 2.8 % in 2000 to 23.3 % in 2018. The US, which was still the global leader in 2016, lost its leading position after declining by almost two percentage points. The EU fell to a third place after losing about two percentage points. However, the United States still leads in the top 10 % most-cited publications per million population (159.7 against 104.5 for EU and 37.7 for China) and per researcher. From the EU countries, Germany contributed 4.2 % to the global top 10 % most-cited publications, followed by Italy (3.2 %) and France (2.4 %).

Figure 6.1-7: World share of top 10 % most-cited scientific publications[1], 2018 (citation window: 2018-2020)



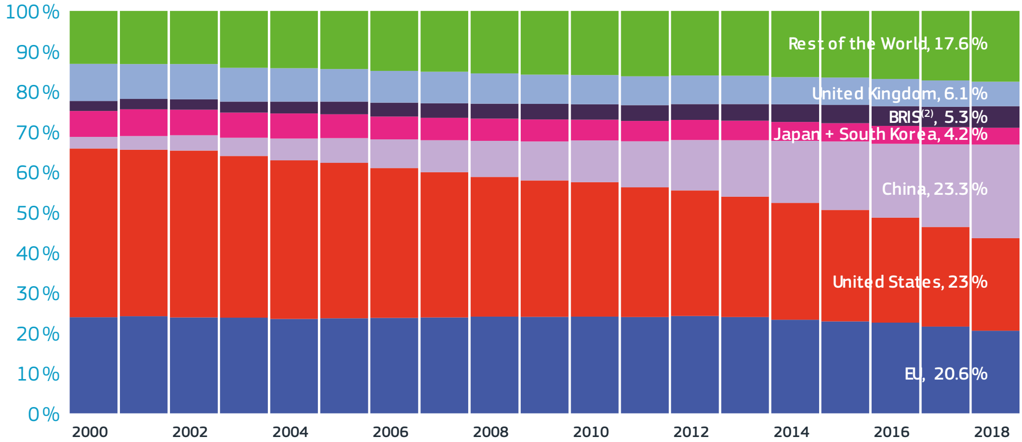
Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Science-Metrix, using the Scopus database

Note: [1]Scientific publications within the 10 % most-cited scientific publications worldwide as % of total scientific publications of the country; fractional counting used. [2]BRIS: Brazil, Russia, India and South Africa.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-1-7.xlsx

Similarly to the scientific volume, China's remarkable improvement in the quality of scientific output over time has primarily affected the ranking of the United States and, to a lesser extent, the EU. Jointly, the three leading global players (China, the EU and the US) have steadily produced about 70 % of the top 10 % most-cited publications over the years (Figure 6.1-8). Another noteworthy finding is the moderate positive trend of the BRIS countries. Other countries, such as Australia, Canada and especially the United Kingdom also contributed significantly to the 10 % most-cited publications.

Figure 6.1-8: World share of top 10 % highly cited scientific publications[(1)], 2000 (citation window: 2000-2002) to 2018 (citation window: 2018-2020)



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Science-Metrix, using the Scopus database

Note: [(1)]Scientific publications within the 10 % most-cited scientific publications worldwide as % of total scientific publications of the country; fractional counting used. [(2)]BRIS: Brazil, Russia, India and South Africa.

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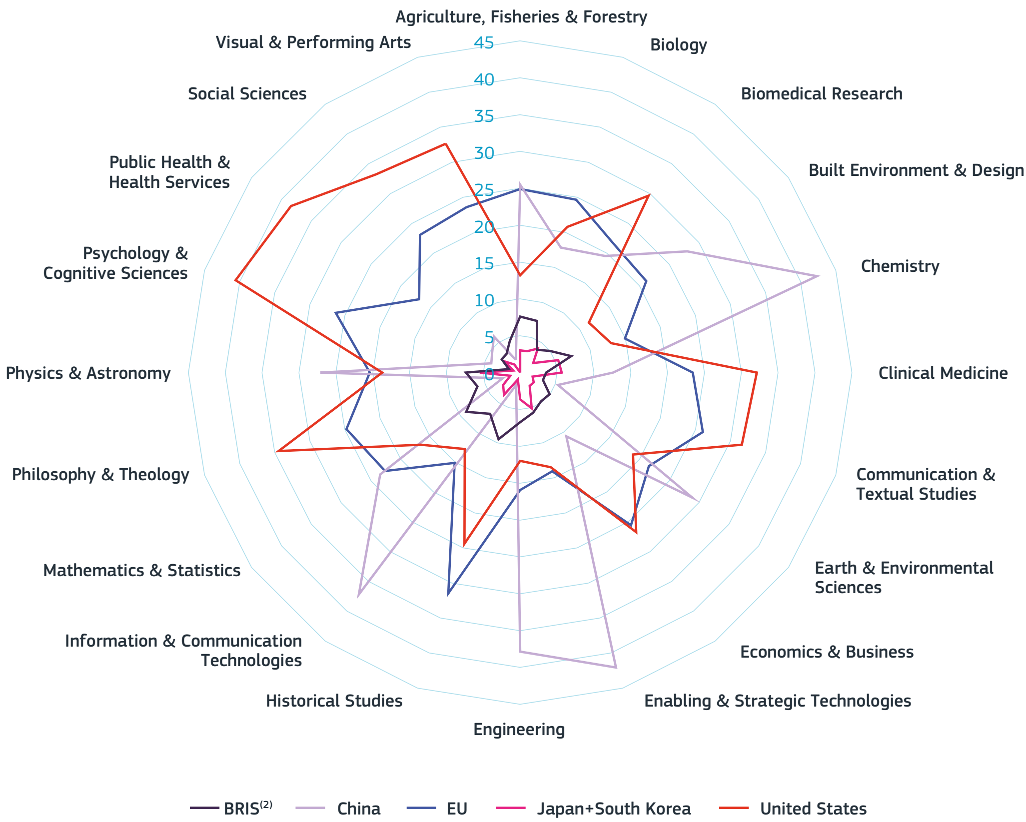
The EU has the highest share of publications among the top 10% most-cited only in the fields of biology and historical studies. The United States leads in the domain of health science and its underlying scientific fields, whereas China leads in applied and natural sciences, and in particular in chemistry, in enabling and strategic technologies, in engineering and in information and communication technologies (Figure 6.1-9).

Figure 6.1-9: World shares of the top 10% most-cited publications by country/region and scientific field[1], 2018



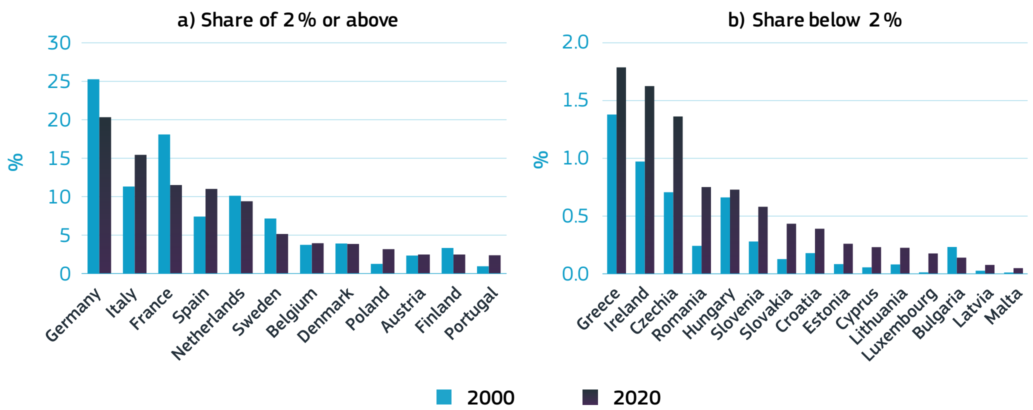
Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Science-Metrix, using the Scopus database

Note: [1]Scientific publications within the 10% most cited scientific publications worldwide. Fractional counting method. [2]BRIS: Brazil, Russia, India and South Africa.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-1-9.xlsx

Southern and eastern European countries are catching up in terms of scientific quality. Except for Bulgaria, all EU Member States with share of less than 2% saw an increase in their contribution to the European share of the top 10% most-cited publications. Among those with shares above 2% (left-hand panel of Figure 6.1-10), Italy, Spain, and Poland improved their share in quality of scientific publications the most. On the other hand, Germany has lost 4.9 percentage points since 2000, and France 6.6 percentage points, falling to the third position after Italy. The Netherlands, despite a small decline compared to 2000, produced almost 10% of the European top 10% most-cited scientific publications, followed by Sweden, whose share declined from 7% in 2000 to 5% in 2018.

Figure 6.1-10: Share of each EU Member State within the EU for the top 10% most cited scientific publications[1], 2000 vs 2018



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Science-Metrix, using the Scopus database

Note: [1]Fractional counting used.

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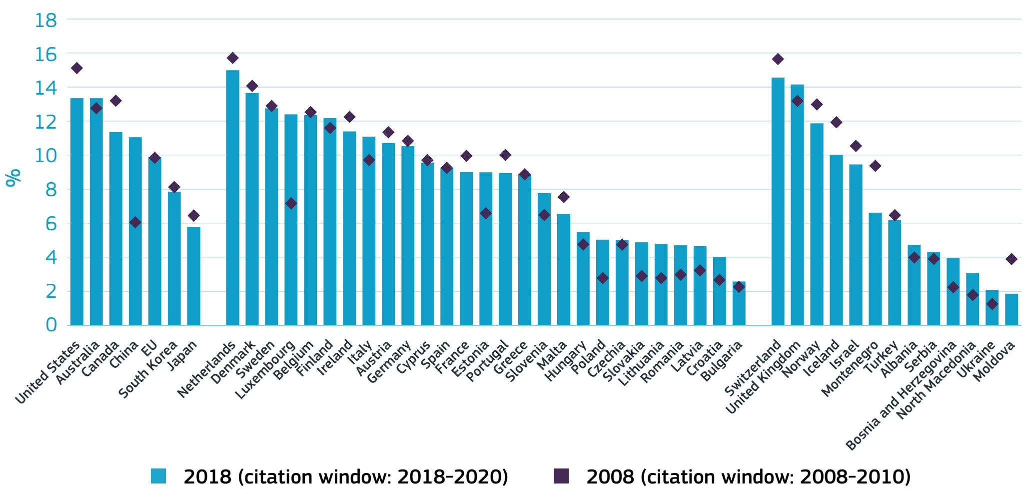
The United States has the highest percentage of publications in the top 10%, followed by Australia and Canada (Figure 6.1-12). The remarkable improvement in the quality of Chinese publications is reflected in the share of publications appearing in the top 10% most-cited publications worldwide. In 2008, only 6% of Chinese publications were in the top 10%. Ten years later, this percentage had almost doubled (11.1% in 2018), placing China in fourth position. The EU fell to fifth place with nearly 10%, which in absolute numbers reflects a stable performance over the last decade.

Within the EU, the percentage of publications in the top 10% most-cited publications varies between 15 and 2%. This indicator measures the quality of the publications for a given country and year. It is calculated as the ratio of the number of publications included in the top 10% most-cited worldwide, over the total number of publications of the country that year. The Netherlands leads globally with 15% of its publications among the top 10% most-cited, ahead of other global leaders, such as Switzerland and the United Kingdom (Figure 6.1-11). Denmark takes the second position within the EU (13.7%), followed by Sweden (12.7%). Germany, the biggest European contributor to the top 10% most-cited publications, scores above the EU average (10.5%), but below other global competitors such as Canada and Australia. Despite some improvement, the gap between northern and southern/eastern European countries persists.

Figure 6.1-11: Top 10% highly most-cited scientific publications[1], 2008 and 2018



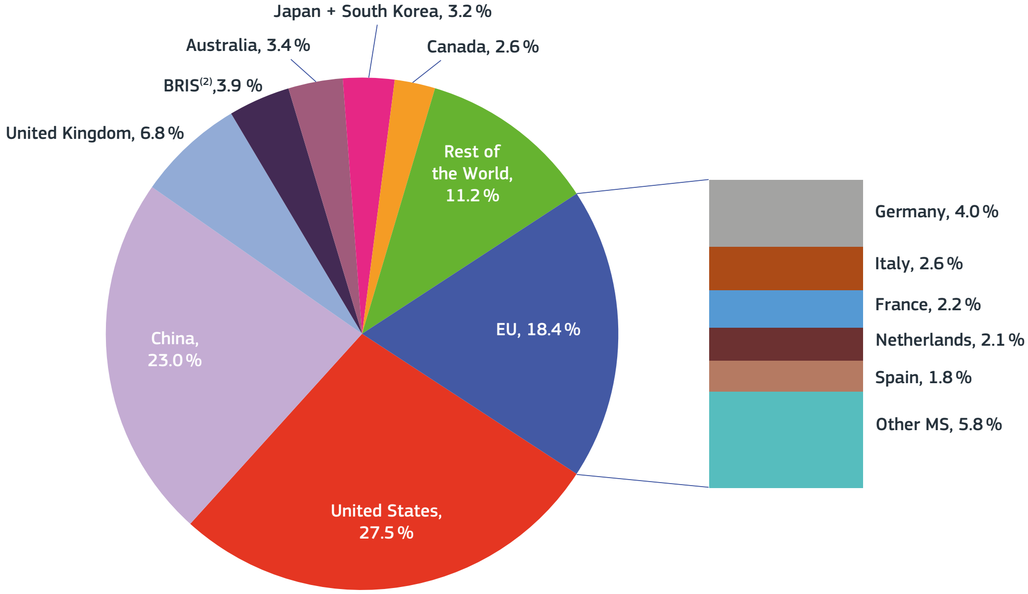
Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Science-Metrix, using the Scopus database

Note: [1]Share of scientific publications within the 10% most-cited scientific publications worldwide by the total number of scientific publications of the country; fractional counting used instead of method.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-1-11.xlsx

China overtook the EU in the world share of top 1 % most-cited publications, and is approaching the US. The EU, with a global share of 18.4 %, is in third position, followed by the United Kingdom with a share of 6.8 %, (Figure 6.1-12). Germany has the highest share among the EU countries with 4.0 %, followed by Italy (2.6 %), which climbed up one position, overtaking France (2.2 %). Australia also stands out with a share of 3.4 %, which is above the share of Japan and South Korea combined. The BRIS, despite their small share, have been improving over time.

Figure 6.1-12: World share of top 1 % most-cited scientific publications[1], 2018 (citation window: 2018-2020)



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Science-Metrix, using the Scopus database

Note: [1]Scientific publications within the 1 % most-cited scientific publications worldwide as % of total scientific publications of the country; fractional counting used. [2]BRIS: Brazil, Russia, India and South Africa

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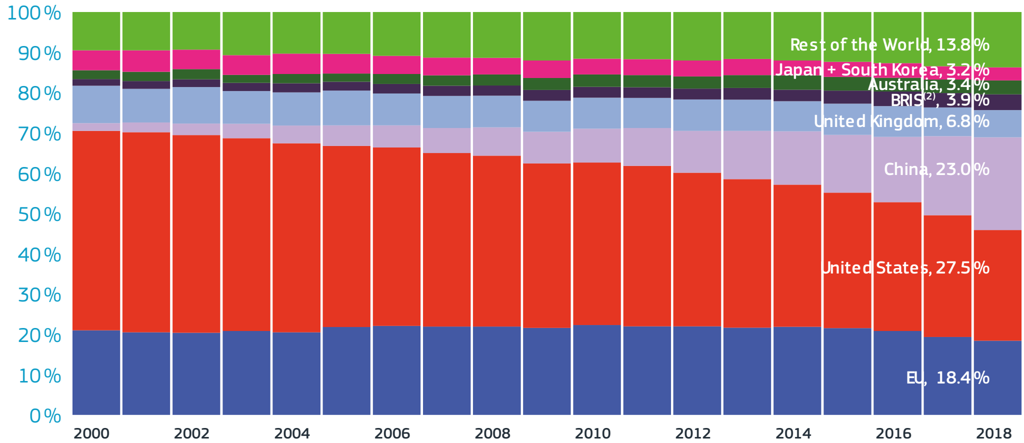
The United States preserved its leading position in the top 1 % most-cited publications. However, since 2000, it has lost about 20 percentage points in the world share of top 1 % most-cited publications (Figure 6.1-13). In contrast, the United States still records the highest number of top publications per million population (19.1), well ahead of the EU, which comes second with 9.4, and China, which comes third with 3.8. Therefore, there can be no doubt that the US still leads the world in terms of research impact.

Figure 6.1-13: World share of top 1 % most-cited scientific publications[(1)], 2000 (citation window: 2000-2002) to 2018 (citation window: 2018-2020)



Science, Research and Innovation Performance of the EU 2022

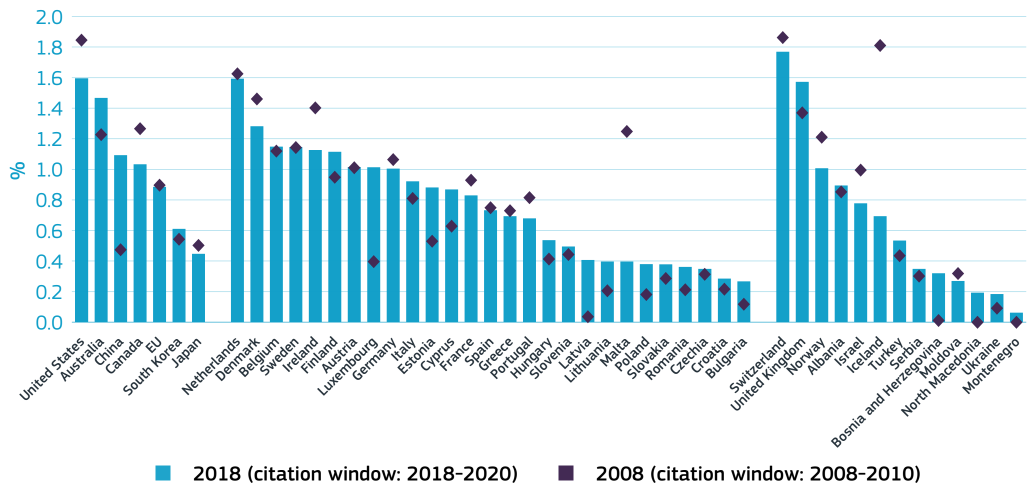
Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Science-Metrix, using the Scopus database

Note: [(1)]Scientific publications within the 1 % most-cited scientific publications worldwide as % of total scientific publications of the country; fractional counting used. [(2)]BRIS: Brazil, Russia, India and South Africa.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-1-13.xlsx

About 0.9% of all EU publications belongs to the top 1% most-cited publications. While the EU performance has remained stable over the last 10 years, the United States has shown a significant decrease over the same period. In contrast, in an impressive upward trend, China overtook Japan, South Korea, the EU and Canada to rank third in 2018, only behind Australia and the United States. The global leader in this indicator remains Switzerland, with 1.7% of its publications being among the top 1% most-cited globally. The Netherlands is third in the global league (the US is second) and first among the EU countries, followed by Denmark. Another noteworthy finding is the sharp rise of Luxembourg, which now scores ahead of the EU average. Nevertheless, given the small number of publications, results should be interpreted with caution.

Figure 6.1-14: Top 1% most-cited scientific publications(1), 2008 and 2018



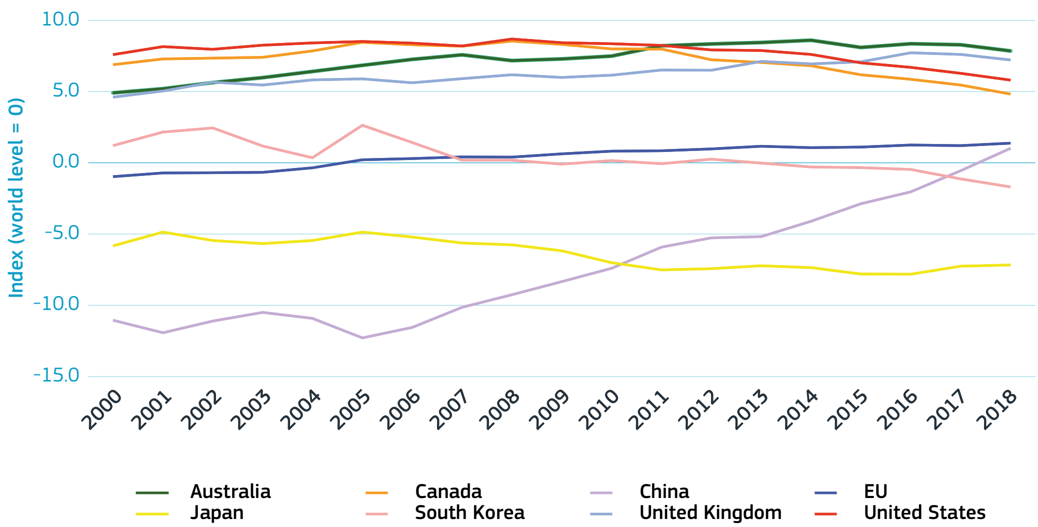
Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Science-Metrix, using the Scopus database

Note: (1)Share of scientific publications within the 1% most-cited scientific publications worldwide by the total number of scientific publications of the country; fractional counting used

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-1-14.xlsx

Evidence from other metrics on the scientific quality and impact, such as the Citation Distribution Index (CDI), the h-index and the Nature index, confirm the lead of the US, the EU's stable position and China's remarkable improvement. The impact of EU publications in terms of citations has been stable over the last two decades and just above the world level. This stability in the CDI [4] (Lando and Bertoli-Barsotti, 2014), (Campbell et al., 2016) is a positive result compared to the decreases in scores observed for countries such as Japan, Canada, South Korea and the United States. The highest growth in CDI score was recorded for China. China had one of the lowest CDI scores in 2000 (-11.0) but managed to improve and become on a par with the world level and to close the gap with the EU in 2018. From these observations, combined with decreasing citation impact scores between 2010 and 2018 for publications from countries such as Canada, South Korea and the United States, it is safe to conclude that Chinese publications are now widely read and used by researchers throughout the world. Chinese gains in citation impact may have come at the expense of these other countries' relative influence (European Commission, 2021b). The evolution of the CDI is shown in Figure 6.1-15.

Figure 6.1-15: Citation Distribution Index, 2000-2018



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Science-Metrix, using the Scopus database

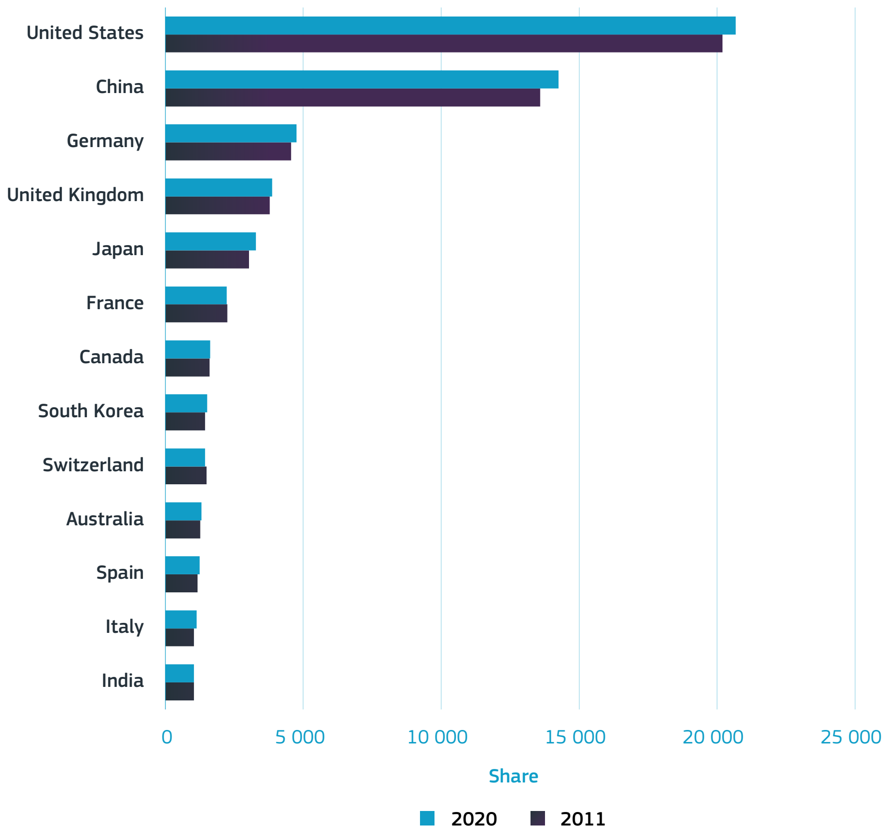
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-1-15.xlsx

4 The principle is to define, for an entity (e.g. a country) with a given number of citations, an ideal citation distribution that represents a benchmark in terms of number of papers and number of citations per publication, and to obtain an index that increases in value when the real citation distribution approaches its ideal form. To prepare this indicator, Science-Metrix divides all publications in a given research area, document type and year into 10 groups of equal size, or 'deciles', based on their normalised citation scores.

The leading position of the United States in scientific performance and impact is confirmed by the h-index. The h-index is a country's number of articles (the value h) that have received at least h citations. It quantifies both a country's scientific productivity and scientific impact and it is also applicable to scientists, journals, etc. The h-index is often used to measure and rank the scientific performance and impact of countries, journals and even researchers. In 2020, the United States was still at the top of the league, followed by the United Kingdom and Germany. In total, four EU countries are in the top ten global positions (Germany, France, Italy and the Netherlands)[5].

The Nature Index also confirms the leading position of the United States in scientific impact. The Nature Index measures publication outputs in 82 selected journals covering life sciences, physical sciences, chemistry, and earth and environmental sciences. The first

Figure 6.1-16: Nature Index 2020 (leading countries)[(1)]



Source: Nature Index

Notes: [(1)]The leading countries by research output are measured by the metric Share in the Nature Index for 2020, compared with their Share for 2019.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-1-16.xlsx

5 Scimago Journal and Country Rank. https://www.scimagojr.com/countryrank.php

year of the COVID-19 pandemic brought an end to China's run of high growth in output[6]. After growing 15.5 % from 2018 to 2019, China's adjusted Share[7] in the Nature Index slowed to a 1.1 % increase from 2019 to 2020, by far its slowest growth since at least 2015. Therefore China remains significantly behind the United States, followed by Germany, the United Kingdom and Japan (Figure 6.1-16). At the same time, the Chinese Academy of Sciences is clearly the leading institution, with a Share of 1 886.71 (number of publications in 2020, using fractional counting), more than twice that of its nearest competitor, Harvard University, with 927.26.

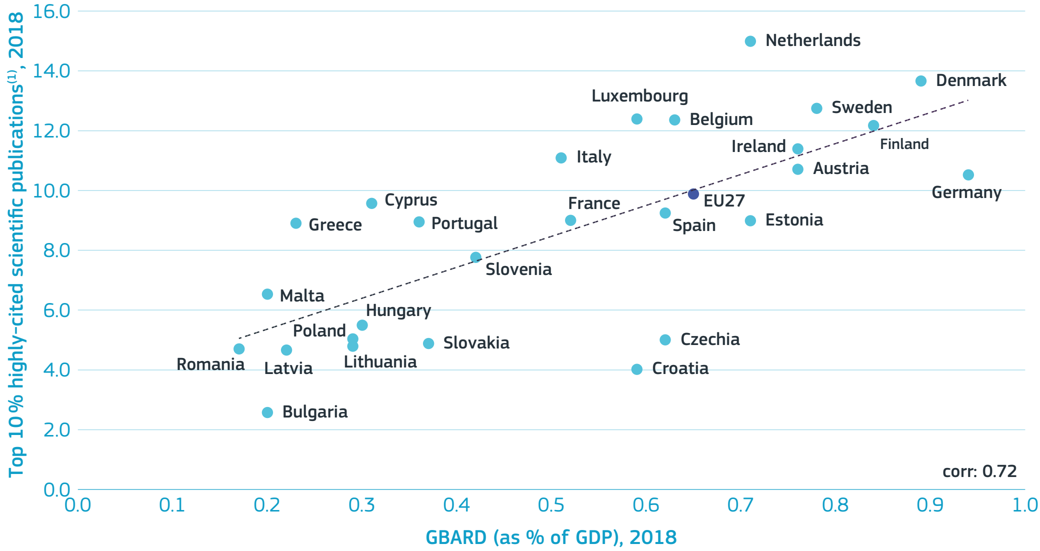
There is a positive correlation between the public budget allocated to R&D and the scientific impact measured by the share of top 10 % most-cited publications, similar to the direct relationship between spending on research and scientific output. For example, the Netherlands, Denmark, Sweden, Finland, Ireland, Austria and Germany enjoy higher levels of public investment in R&D than the EU average, as well as better scientific results (Figure 6.1-17). Although this relationship cannot be interpreted as causal, it is an indicator to be considered in R&I policymaking.

Improvement in the access to excellence and prioritisation of R&D investments are two main priorities of the European Research Area. Horizon Europe, the European Union's research framework programme for 2021 to 2027, supports researchers to carry out basic and applied research and promotes collaborations within the EU to deliver R&I addressing the social and economic challenges of today. Through its Widening Participation and Strengthening the European Research Area part, Horizon Europe supports the less-performing Member States to valorise research findings and connect their ecosystems. Another flagship component of Horizon Europe is the European Research Council (ERC), which encourages the highest quality research in Europe through competitive funding that complements other funding activities in Europe, such as those of national research funding agencies.

6 https://www.natureindex.com/news-blog/nature-index-annual-tables-twenty-twenty-one-country-comparisons-difficult-year

7 Nature Index's metric is Share, a fractional count based on an institution's or location's contribution to an article. Adjusted Share is used when comparing data over time, to take account of a small variation in the number of articles published in the Nature Index journals year by year.

Figure 6.1-17: Government Budget Appropriations to R&D (GBARD) and top 10% most-cited scientific publications, 2018



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Science-Metrix, using the Scopus database

Note: (1) Scientific publications within the 10 % most cited scientific publications worldwide as % of total scientific publications of the country; fractional counting used.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-1-17.xlsx

Box 6.1-2: European Research Council

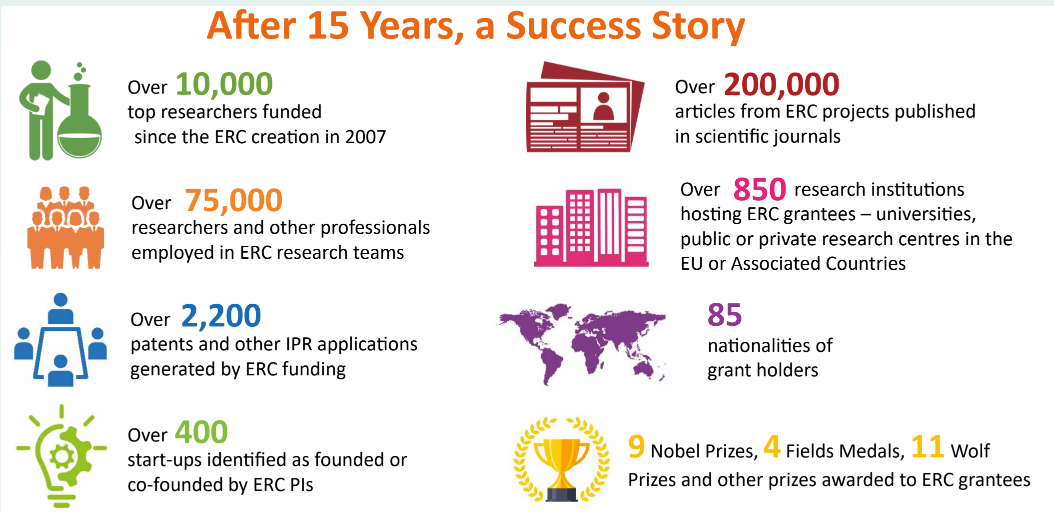
Since the ERC launched its first call in 2007, it has funded over 10 000 of the best scientists in Europe. The aim of the ERC is to allow its grantees to pursue ground-breaking, high-gain/high-risk research leading to advances at the frontiers of knowledge.

Since 2007, ERC-funded researchers have won nine Nobel Prizes, four Fields Medals and eleven Wolf Prizes. In February 2022, two ERC grantees were awarded the latest Wolf Prize in Physics **for pioneering contributions to ultrafast laser science and attosecond physics[8].**

Every year the ERC asks a group of independent experts to look at the results of the projects that the ERC has funded in the past. **The latest such exercise found that 81 % of projects funded by the ERC resulted in a scientific breakthrough or major advance**[9]. Over 200 000 scientific publications have been produced by ERC grantees recording the results of their work. Publications by ERC grantees are cited by other scientists seven times more than average, indicating their significance within their fields.

ERC-funded projects have already generated over 2 000 patent and other IPR applications and created over 400 start-up companies. Out of 42 recipients of the European Innovation Council's new Transition fund, 25 originated from research funded by the ERC[10].

Figure 6.1-18: European Research Council, After 15 Years, a Success Story



Science, Research and Innovation Performance of the EU 2022

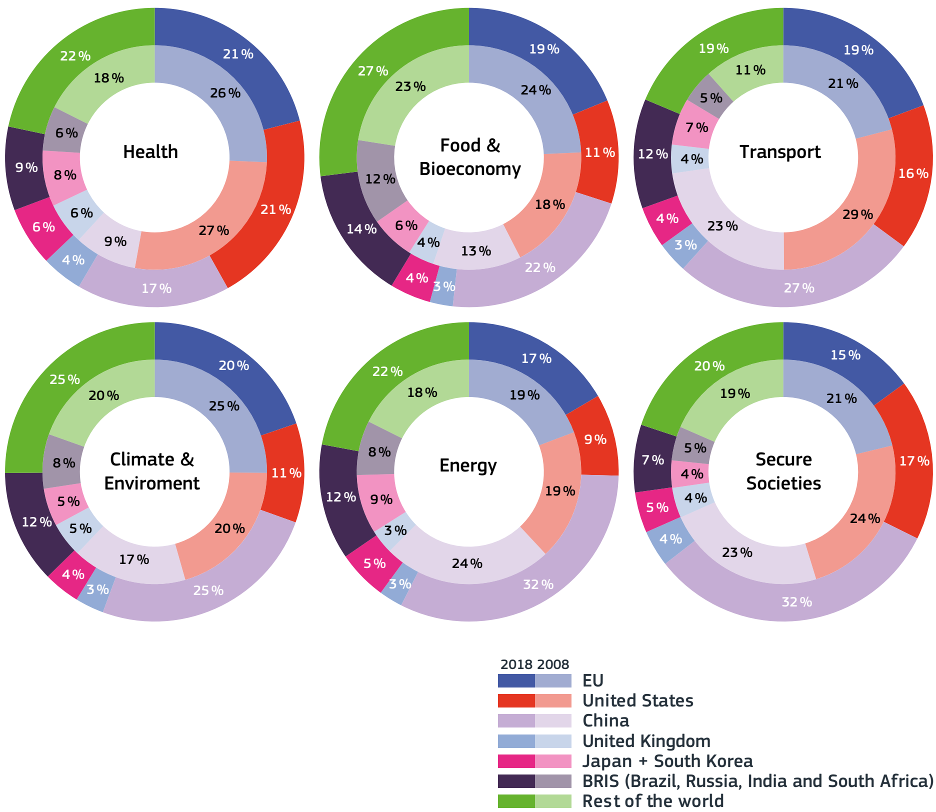
Source: European Research Council
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-1-18.xlsx

8 https://erc.europa.eu/news/wolf-prize-physics-awarded-erc-grantees
9 https://erc.europa.eu/news/impact-erc-funded-frontier-research-again-confirmed
10 https://erc.europa.eu/news/erc-funded-research-wins-most-new-eu-innovation-grants

3. Societal Grand Challenges and Sustainable Development Goals

In terms of scientific output, China is leading in all Horizon 2020 Societal Grand Challenges[11] (SGCs) except for health, where the eight percentage-point increase over 2010-2020 was not sufficient to overtake the United States and the EU. EU researchers are the authors of about 20% of scientific publications for all the SGCs worldwide, except for energy and secure societies, where the shares are lower (17% and 15% respectively). The US's publication share declined substantially for all SGCs in the last 10 years. Other noteworthy findings are the

Figure 6.1-19: World shares (%) of scientific publications(1) by country/region and Horizon 2020 Societal Grand Challenges, 2010 (interior) and 2020 (exterior)



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Science-Metrix, using the Scopus database

Note: (1)Fractional counting methods.

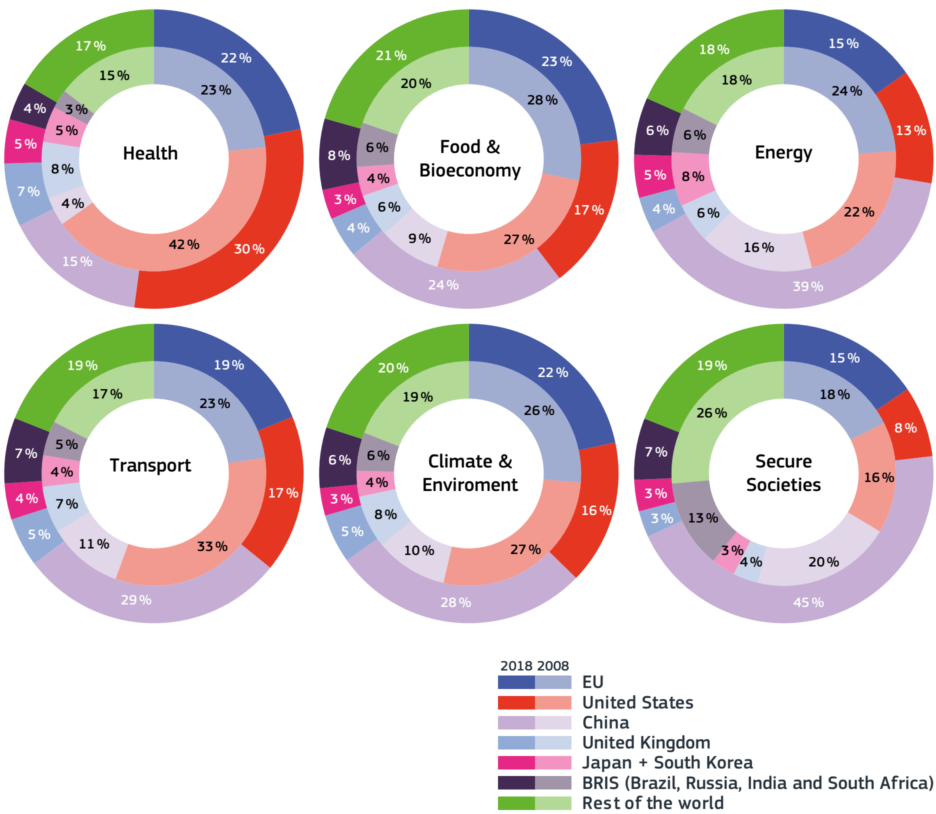
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-1-19.xlsx

11 The six SGCs analysed in this report are: 1) health, demographic change and wellbeing; 2) food security, sustainable agriculture and forestry, marine and maritime and inland water research and the bioeconomy; 3) secure, clean and efficient energy; 4) smart, green and integrated transport; 5) climate action, environment, resource efficiency and raw materials; 6) secure societies – protecting the freedom and security of Europe and its citizens.

increased contribution of the BRIS countries, with an average increase across the six SGCs of 4 percentage points, and the widening of the scientific base of the rest of the world, i.e. countries beyond those analysed individually, with an average increase of 5 percentage points in the publication share.

The EU has the second-highest world share of the top 10% most-cited publications in all Societal Grand Challenges. Ten years ago, the EU was leading in energy and in food and bioeconomy (Figure 6.1-20). The massive improvement in the quantity and quality of the Chinese output in these fields has forced the EU to second position. Chinese researchers are leading as regards the most-cited publications related to energy (with a 39% share). The United States is undoubtedly the global leader in health-related most-cited publications with a 30% share, despite the loss of 12 percentage points since 2008.

Figure 6.1-20: World shares (%) of the top 10% most-cited scientific publications[1] by country/region and Horizon 2020 Societal Grand Challenges, 2008 (interior) and 2018 (exterior)



Science, Research and Innovation Performance of the EU 2022

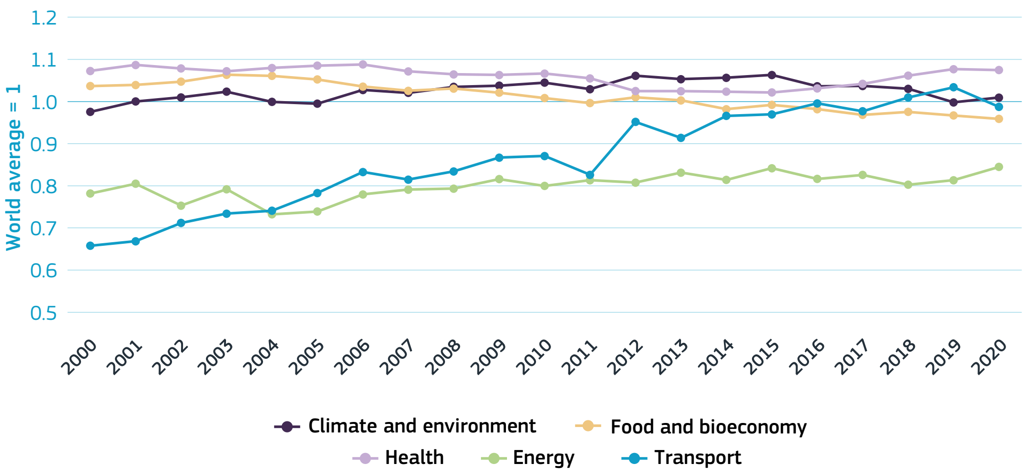
Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Science-Metrix, using the Scopus database

Note: [1]Scientific publications within the 10% most cited scientific publications worldwide; fractional counting method.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-1-20.xlsx

Over the years, the EU has maintained its specialisation in health and, to a large extent, in climate and environment. In contrast, in food and bioeconomy, the EU has progressively become less specialised, scoring below the world average since 2014. On the other hand, transport has shown the opposite pattern, with the EU gradually becoming more specialised. However, as Figure 6.1-21 shows, this upward trend slowed down significantly after 2014. In energy-related publications, the EU is lagging behind and is much less specialised than the world average.

Figure 6.1-21: EU Specialisation Index[(1)] (SI), 2000-2020



Science, Research and Innovation Performance of the EU 2022

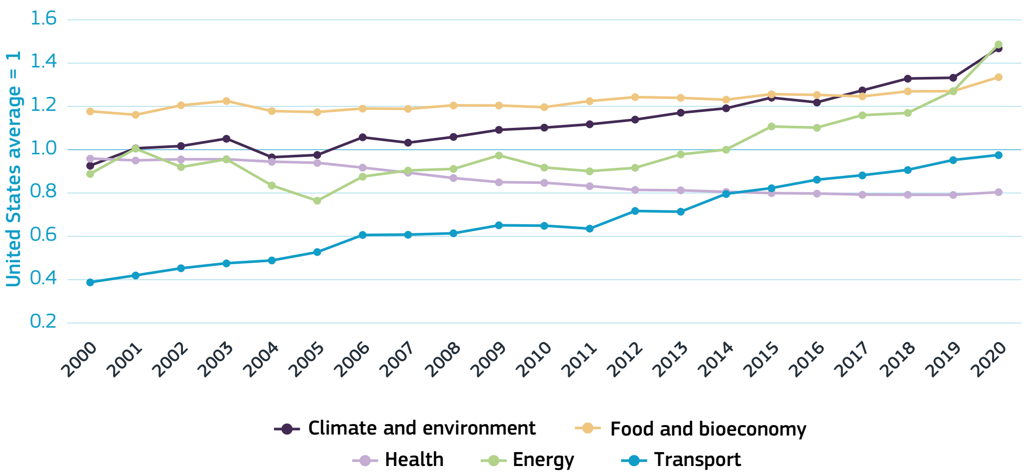
Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Science-Metrix, using the Scopus database

Note: [(1)]The specialisation index (SI) is an indicator of research intensity in a given entity (e.g. a country) for a given research area (e.g. one of the SGCs), relative to the intensity in a reference entity (e.g. the world) for the same research area. In other words, the SI of a country in a given research domain portrays how much emphasis that country allocates to research in that domain relative to the world. Comparisons are meaningful only between countries of similar size.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-1-21.xlsx

Compared to the United States, the EU specialises in publications on climate and environment, food and bioeconomy, and energy. Over time, the EU has improved in transport, and almost reached the specialisation level of the United States in 2020. However, the EU has remained systematically below the United States in health.

Figure 6.1-22: EU Specialisation Index (SI)[1] compared to the United States, 2000-2020



Science, Research and Innovation Performance of the EU 2022

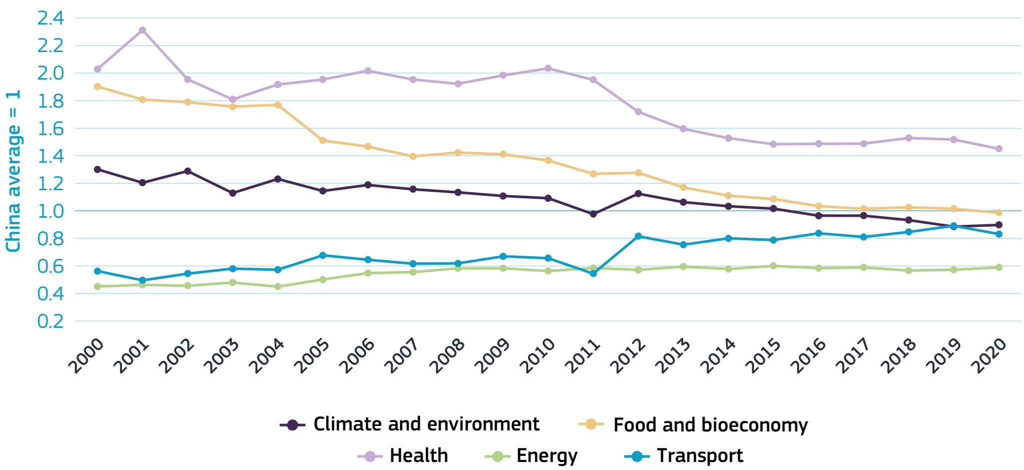
Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Science-Metrix, using the Scopus database

Note: [1]The specialisation index (SI) is an indicator of research intensity in a given entity (a country) for a given research area (e.g. one of the SGCs), relative to the intensity in a reference entity (e.g. the world) for the same research area. In other words, the SI of a country in a given research domain portrays how much emphasis that country allocates to research in that domain relative to the world's equivalent. Comparisons are meaningful only between countries of similar size.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-1-22.xlsx

Compared to China, the EU is more specialised in health-related scientific output and on a par in food and bioeconomy despite the dramatic decline since 2000. In climate and environment, the EU has gradually declined, and it lost its competitive edge over China in 2016. In contrast, the EU has increased its specialisation in transport, particularly in 2011, but has not yet reached Chinese levels. In energy, the EU is significantly less specialised than China, with very little progress in the last 20 years.

Figure 6.1-23: EU Specialisation Index (SI)[(1)] compared to China, 2000-2020



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Science-Metrix, using the Scopus database

Note: [(1)]The specialisation index (SI) is an indicator of research intensity in a given entity (a country) for a given research area (e.g. one of the SGCs), relative to the intensity in a reference entity (e.g. the world) for the same research area. In other words, the SI of a country in a given research domain portrays how much emphasis that country allocates to research in that domain relative to the world's equivalent. Comparisons are meaningful only between countries of similar size.

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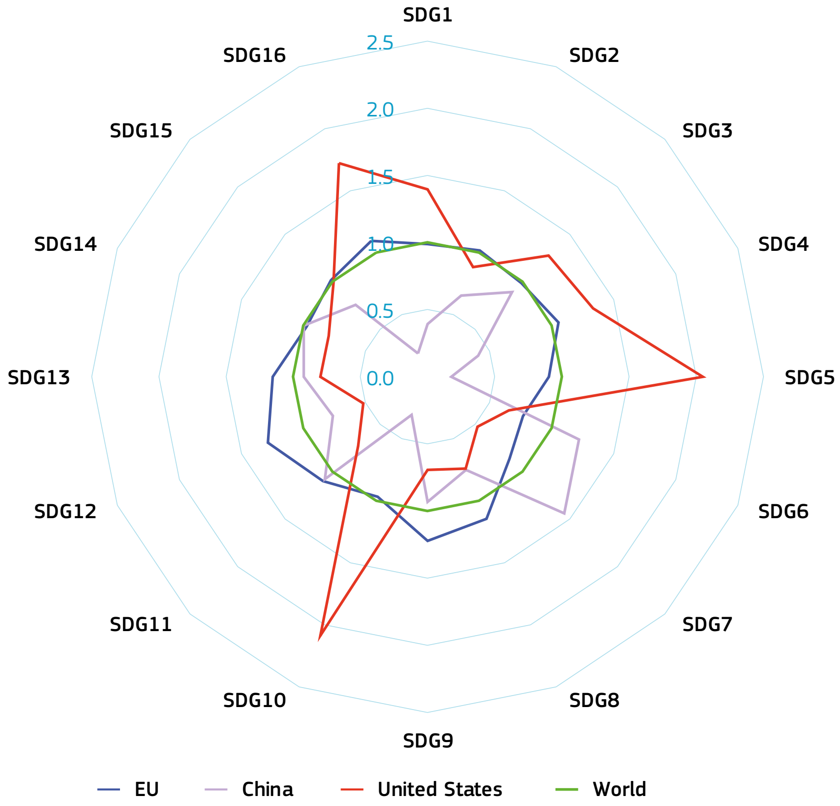
Sustainable development is at the heart of European policy. The European Union through its political leadership took the decision to lead the sustainability transition and accelerate the achievement of the Sustainable Development Goals (SDGs), as outlined in 'The European Green Deal'[12] and the Commission Staff Working Document 'Delivering on the UN's Sustainable Development Goals' (European Commission, 2020). While the Societal Grand Challenges (SGCs), introduced in Horizon 2020, represent complex, multi-level, multi-dimensional problems that require concerted efforts by various actors to be successfully addressed, the SDGs go a step further and offer 'the blueprint to achieve a better and more

Figure 6.1-24: Specialisation Index for each SDG[(1)], 2020



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Science-Metrix, using the Scopus database

Notes: [(1)]SDG 1 – No poverty; SDG 2 – Zero hunger; SDG 3 – Good health and well-being; SDG 4 – Quality education; SDG 5 – Gender equality; SDG 6 – Clean water and sanitation; SDG 7 – Affordable and clean energy; SDG 8 – Decent work and economic growth; SDG 9 – Industry, innovation and infrastructure; SDG 10 – Reduced inequality; SDG 11 – Sustainable cities and communities; SDG 12 – Responsible consumption and production; SDG 13 – Climate action; SDG 14 – Life below water; SDG 15 – Life on land; SDG 16 – Peace, justice and strong institutions.

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12 https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1576150542719&uri=COM%3A2019%3A640%3AFIN

sustainable future for all'[13]. They also address global challenges, including poverty, energy, climate change, inequality, economic growth, environmental degradation, peace and justice.

In 2020, publications covering SDG 3, on health, and SDG 7, on energy, accounted for the largest share of SDG-related publications in the world, 49% and 14% respectively. The effect of the pandemic on scientific output worldwide is again demonstrated by the increase in the share of health-related publications by 6 percentage points compared to 2019. The EU has been involved in roughly 20% of the world's total publications in each SDG. China has the lead in energy-related publications, confirming previous findings when using different classifications.

The EU is more specialised in terms of scientific output in SDGs 8 – Decent work and economic growth, 9 – Industry, innovation and infrastructure, 12 – Responsible consumption and production, and 13 – Climate action. The US has the lead in SDG 1 – No poverty, SDG 3 – Good health and well-being, SDG 4 – Quality education, SDG 5 – Gender equality, SDG 10 – Reduced inequalities and SDG 16 – Peace, justice and strong institutions. Finally, China is more specialised in SDG 6 – Clean water and sanitation and SDG 7 – Affordable and clean energy.

Between the EU countries, the levels and areas of specialisation vary significantly. Table 6.1-2 presents the Specialisation Index for each SDG by EU Member State. The Member States have been sorted and grouped by their overall volume of scientific publications related to the SDGs. The first group includes countries with less than 1 000 publications, the second with 1 000 to less than 5 000, the third with 5 000 to less than 15 000, and the last group includes the countries with the most SDG-related publications.

Compared to the world averages, almost all EU countries are specialised in SDG 8, SDG 9 and SDG 12, followed by SDG 11, SDG 13 and SDG 4[14] (Table 6.1-2). In contrast, only a few countries are specialised in SDG 6 – Clean water and SDG – 7 Affordable and clean energy. As expected, the largest countries in terms of scientific output show low specialisation levels across most categories, with only a few categories having high specialisation scores. For example, France is specialised only in two SDGs, SDG 3 – Health and well-being and SDG 14 – Life below water. Similarly, Germany shows specialisation in SDG 9 – Industry, innovation and infrastructure and SDG 13 – Climate action.

13 https://www.un.org/sustainabledevelopment/sustainable-development-goals/

14 SDG 8 – Decent work and economic growth, SDG 9 – Industry, innovation and infrastructure, SDG 12 – Responsible consumption and production, SDG 11 – Sustainable cities, SDG 13 – Climate action and SDG 4 – Quality education.

Table 6.1-2: Specialisation index per EU Member State and SDG[1], 2020

	Sustainable Development Goals															
Member States	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Malta	1.24	0.65	1.19	2.13	0.70	0.21	0.72	2.52	0.85	2.00	1.89	2.12	1.42	2.23	0.98	1.59
Luxembourg	3.23	0.56	0.54	1.33	0.64	0.43	0.90	1.88	1.35	2.92	1.64	1.67	1.02	0.22	0.50	1.99
Latvia	0.61	1.18	0.50	2.26	0.56	0.82	1.86	2.36	2.23	0.49	1.60	3.06	2.33	1.26	1.91	0.62
Estonia	1.17	1.50	0.42	2.08	1.45	0.94	1.51	1.68	1.38	1.43	1.25	1.75	1.67	1.53	1.91	2.48
Cyprus	1.87	1.14	0.83	4.31	1.74	1.37	1.18	2.41	1.31	2.54	1.90	2.45	1.94	1.03	0.86	1.95
Lithuania	1.44	1.59	0.66	1.92	0.98	0.62	1.30	2.48	1.84	1.30	1.41	2.70	1.64	1.04	1.14	1.19
Bulgaria	0.21	1.02	0.64	1.30	0.32	0.82	1.03	0.99	1.18	0.20	1.07	1.05	0.82	0.82	1.14	0.39
Slovenia	0.81	0.93	0.73	1.21	0.73	0.94	0.76	1.14	1.41	0.80	1.01	1.48	0.72	0.65	1.37	1.01
Slovakia	0.97	0.84	0.62	1.31	0.47	0.83	0.64	1.75	2.02	0.82	1.48	1.88	0.84	0.30	1.71	0.91
Croatia	0.67	1.17	0.76	2.21	0.98	0.77	0.86	1.65	1.13	0.87	1.51	1.58	1.20	1.92	1.05	1.33
Hungary	0.96	1.00	0.81	1.05	0.53	0.95	0.65	1.24	1.26	0.99	1.16	1.10	0.97	0.39	1.56	0.89
Ireland	1.57	0.91	1.04	1.72	1.81	0.73	0.75	1.10	1.09	1.70	0.82	1.04	1.10	1.15	0.84	2.52
Romania	0.82	0.88	0.75	1.97	0.45	1.34	1.10	1.91	1.91	0.79	1.64	1.75	1.12	0.71	0.91	0.76
Austria	1.08	0.86	0.86	0.82	0.73	0.41	0.65	1.19	1.46	0.99	0.93	1.30	1.28	0.48	0.84	0.98
Czechia	0.57	0.96	0.67	0.71	0.46	0.83	0.69	1.05	1.40	0.59	1.11	1.60	1.04	0.52	1.71	0.78
Finland	1.56	0.83	0.83	2.15	1.31	0.88	0.97	1.36	1.43	1.33	1.10	1.99	1.74	0.95	1.84	1.73
Greece	0.94	1.44	1.15	1.40	0.57	1.23	1.10	1.45	1.25	1.05	1.84	1.92	1.44	1.53	1.03	0.85
Belgium	1.34	1.22	0.96	1.06	1.11	0.63	0.72	0.99	1.02	1.25	0.85	1.03	1.02	0.78	0.98	1.42
Denmark	1.04	0.99	1.25	0.91	0.77	0.72	1.36	1.05	1.04	1.15	0.72	1.07	1.34	1.28	0.80	1.22
Portugal	1.03	1.12	0.89	1.74	1.03	1.35	1.07	1.92	1.84	1.01	1.63	2.38	1.63	2.40	1.46	1.22
Sweden	1.69	0.98	1.10	1.60	2.02	0.73	0.97	1.31	1.46	1.51	1.14	1.64	1.51	0.97	1.05	1.84
Poland	0.65	0.93	0.84	0.59	0.43	1.18	0.84	1.14	1.22	0.47	1.37	1.46	0.89	0.66	1.18	0.62
Netherlands	1.39	1.10	1.18	1.12	1.30	0.79	0.64	1.17	0.87	1.35	1.15	0.89	1.24	0.80	0.81	1.82
France	0.61	0.99	1.01	0.40	0.60	0.55	0.69	0.61	0.79	0.65	0.66	0.71	0.88	1.09	0.85	0.60
Spain	1.18	1.13	0.95	1.99	1.73	1.03	0.86	1.50	1.16	1.31	1.18	1.76	1.26	1.17	1.17	1.56
Germany	0.92	0.78	0.86	0.70	0.61	0.48	0.93	0.84	1.22	0.84	0.65	0.78	1.10	0.63	0.79	0.83
Italy	0.88	1.21	1.30	0.65	0.67	0.71	0.86	1.16	1.36	0.85	1.60	1.42	1.11	1.18	0.94	0.96

Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Science-Metrix, using the Scopus database

Note: [1] SDG 1 – No poverty; SDG 2 – Zero hunger; SDG 3 – Good health and well-being; SDG 4 – Quality education; SDG 5 – Gender equality; SDG 6 – Clean water and sanitation; SDG 7 – Affordable and clean energy; SDG 8 – Decent work and economic growth; SDG 9 – Industry, innovation and infrastructure; SDG 10 – Reduced inequality; SDG 11 – Sustainable cities and communities; SDG 12 – Responsible consumption and production; SDG 13 – Climate action; SDG 14 – Life below water; SDG 15 – Life on land; SDG 16 – Peace, justice and strong institutions.

Only 16 of the top 100 universities included in the Times Higher Education University Impact Ranking 2021 are located in the EU[15]. The Times Higher Education Impact Rankings measure universities' overall success in delivering the United Nations Sustainable Development Goals. It uses indicators across four areas: research, stewardship, outreach and teaching. In 2021, 1 239 institutions across 98 countries submitted data, compared to 859 institutions in 2020. This shows that the Times Higher Education University Impact Ranking has gradually become an important tool for universities to monitor their progress in delivering the SDGs. The European university with the highest position is Aalborg from Denmark, and the overall leader is Manchester University (UK). Ireland is the EU Member State with the largest number of universities (5) in the top 100, followed by Spain with 4. Portugal, Italy and Sweden are the remaining EU Member States with universities represented in the top 100. Outside the EU, the United Kingdom is the single country with the most universities in the top 100 (20), followed by Australia (17). The United States is lagging with only 9 universities but improving compared to the 2020 ranking.

Table 6.1-3: Global performance of EU universities against the UN SDGs in the Times Higher Education University Impact 2021

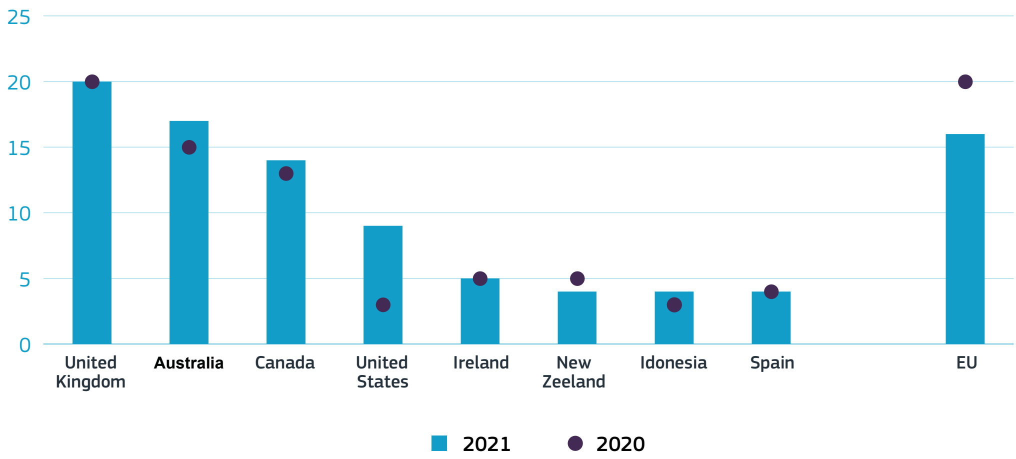
Position in ranking	Name	Country	Comparison with 2019
6	Aalborg University	Denmark	up from rank 97
8	University College Cork	Ireland	up from rank 21
20	University of Bologna	Italy	down from rank 9
21	University of Coimbra	Portugal	new
22	University College Dublin	Ireland	up from rank 58
23	University of Southern Denmark	Denmark	new
41	KTH Royal Institute of Technology	Sweden	down from rank 7
49	University of Gothenburg	Sweden	down from rank 6
50	University of Limerick	Ireland	down from rank 35
53	NOVA University of Lisbon	Portugal	new
57	Trinity College Dublin	Ireland	down from rank 28
82	National University of Ireland, Galway	Ireland	new
83	Polytechnic University of Valencia	Spain	new
90	University of Barcelona	Spain	down from rank 34
92	University of Jaén	Spain	new
98	Comillas Pontifical University	Spain	down from rank 86

Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Times Higher Education

15 https://www.timeshighereducation.com/impactrankings#!/page/1/length/25/sort_by/rank/sort_order/asc/cols/undefined

Figure 6.1-25: Number of universities by country/region in the top 100 Times Higher Education University Impact Rankings, 2020 and 2021



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Times Higher Education

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4. Conclusions: the European Union remains a scientific powerhouse

The EU, with almost 620000 publications in 2020, has the second highest share of scientific output worldwide. The EU is leading globally in the domains[16] of economics and social sciences, and arts and humanities, which comprise significantly fewer publications than other domains, such as health science, led by the US, or applied and natural science, where China has the lead. Due to this specialisation in less-technological fields, the EU has been less affected by the incredible increase in Chinese scientific output, which has cost the United States 13 percentage points since 2000 and the EU only 7 percentage points Within the EU, the shares of scientific publications vary significantly, and to a large extent depend on the size of the country, although southern and eastern European countries have increased their share over 2000-2020.

Over the last 10 years, the EU has emerged as the leading promoter of open science. With over 39% of publications freely available under at least one open-access publishing pathway (gold, green or other), the EU is ahead of its global competitors. Despite the differences in the shares between the Member States, open-access scientific publications have increased for 22 of the 27 Member States over the last decade. Recent studies showed that countries increased their proportion of international collaboration and open-access publications during the pandemic, especially countries with lower GDP and, predictably, smaller-sized science systems (Lee and Haupt, 2020). Therefore it is essential for the EU to continue efforts to make the European scientific system more open, which will allow researchers across Europe unrestricted access to knowledge.

China's rapid improvement in the quality of scientific output has forced the EU to third place in the global share of the top 10% and top 1% most-cited publications. Still, the EU's scientific publications account for 21% and 18.4% of the top 10% and the top 1% most-cited worldwide, respectively. Similarly to scientific volume, China's remarkable improvement in the quality of the scientific publications has primarily affected the United States, which, however, preserved its leading position in the top 1% most-cited publications. The leading position of the United States in scientific quality and impact is particularly evident in health-related scientific fields, where the EU is also strong. Between the EU Member States, the share of their publications included in the top 10% most-cited worldwide varies between 15 and 2%, with the Netherlands leading globally, ahead of Switzerland, the United Kingdom and the United States.

The EU's contribution to the scientific publications in each of the Societal Grand Challenges worldwide is about 20%, except for energy and for secure societies, where the shares are lower. In terms of quality, the EU has the second-highest world share of the top 10% most-cited publications in all Societal Grand Challenges. China is leading in both scientific output and quality in all SGCs except for health, where the United States remains at the top, despite a significant decline over the last ten years. Moreover, the EU is showing specialisation in health-related scientific publications at the world level compared to China, although not to the United States, which dominates the scientific output in this domain.

16 Each domain includes several scientific fields.

References

Campbell, D., Tippett, C., Côté, G., Roberge, G., & Archambault, É. i.e. (2016), '*An approach for the condensed presentation of intuitive citation impact metrics which remain reliable with very few publications. In I. Rafols, J. Molas-Gallart, E. Castro-Martínez, & R. Woolley (Eds.)*', Proceedings of the 21st International Conference on Science and Technology Indicators, pp. 1229-1240. Valencia, Spain. doi:10.4995/STI2016.2016.4543.

European Commission (2020), *Delivering on the UN's Sustainable Development Goals – A comprehensive approach*, SWD(2020) 400 final.

European Commission (2021a), *Monitoring the open access policy of Horizon 2020: final report*, Publications Office of the European Union, Luxembourg.

European Commission, Directorate-General for Research and Innovation (2021b), *Provision and analysis of key indicators in R&I: final study report covering work packages 1-6*, Publications Office of the European Union, Luxembourg. https://data.europa.eu/doi/10.2777/587466

Holly Else (2020), 'How a torrent of COVID science changed research publishing – in seven charts', *Nature*, pp. 588 (24/31): pp. 553.

Jian Gao et al. (2021), 'Potentially long-lasting effects of the pandemic on scientists'. *Nature Communications,* 12, 6188. https://doi.org/10.1038/s41467-021-26428-z

Lando, T., Bertoli-Barsotti, L. (2014), 'A New Bibliometric Index Based on the Shape of the Citation Distribution'. *PLoS ONE 9(12): e115962*. https://doi.org/10.1371/journal.pone.0115962

Lee, J.J, and Haupt J.P, (2020), 'Scientific globalism during a global crisis: research collaboration and open access publications on COVID-19', *Higher Education* 81, pp. 949-966, https://doi.org/10.1007/s10734-020-00589-0

Nature editorial (2020), 'China's research-evaluation revamp should not mean fewer international collaborations', *Nature*, 579, 8(2020) https://doi.org/10.1038/d41586-020-00625-0

Sloane, P., Zimmerman, S. (2021). The Impact of the COVID-19 Pandemic on Scientific Publishing. *Journal of the American Medical Directors Association*, 22(3), pp. 484-488

UNESCO (2021), *UNESCO Science Report: the Race Against Time for Smarter Development*, S. Schneegans, T. Straza and J. Lewis (eds), UNESCO Publishing: Paris.

CHAPTER 6.2

KNOWLEDGE FLOWS

KEY FIGURES

7 %
of human resources in S&T in the EU changed jobs from one year to the next in 2020

9.1 %
of public-private scientific co-publications are in the EU

12 %
of innovative enterprises in the EU cooperated with universities or other HEI on R&D

50 %
or more share of international scientific co-publications are in most EU Member States

KEY QUESTIONS WE ARE ADDRESSING

- How good is researchers' mobility in the EU?
- How well-represented is the EU in public-private collaborations?
- How is international collaboration developing?

KEY MESSAGES

What did we learn?

- At the EU level, the share of job-to-job mobility remains low at almost 7 %. However, there has been an increase in mobility in the last 10 years in all Member States except Czechia, Sweden and Romania.
- Between 2010 and 2020, the EU share of public-private co-authored scientific publications increased from 8.5 % to 9.1 %, placing the EU above the United States and behind only Japan.
- In 2020, international co-publications accounted for more than 50 % of scientific publications in most EU Member States. Between 2010 and 2020, the share of international scientific co-publications increased in all Member States, except Bulgaria.
- The EU and the United States were each other's primary partners for patent applications filed under the Patent Cooperation Treaty (PCT) with a foreign co-inventor in 2018.

What does it mean for policy?

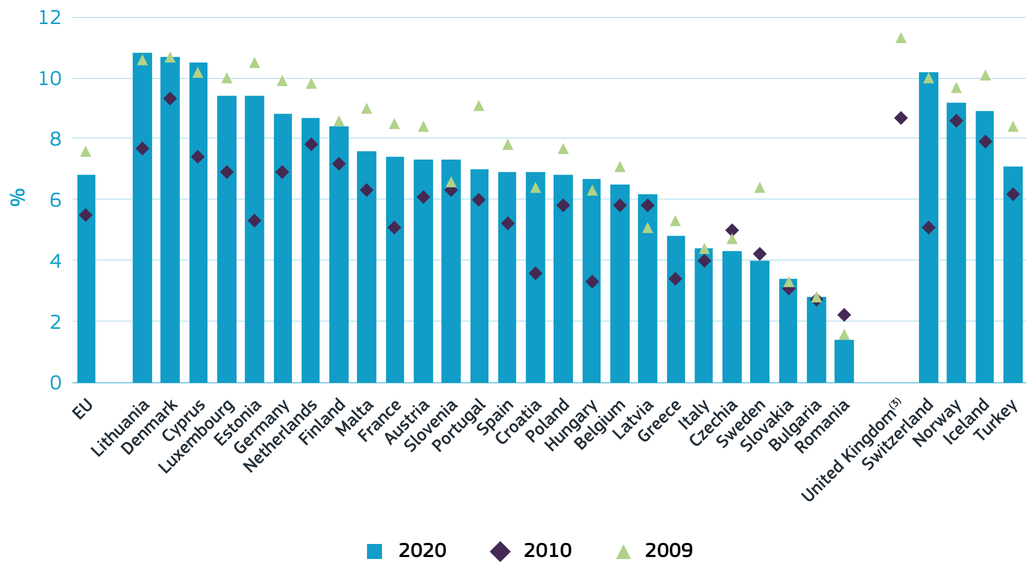
- Continuing divergence between the EU Member States on researcher mobility patterns calls for a better understanding of drivers and barriers to international and job-to-job mobility, as well as the implementation of policies to foster brain circulation.
- To increase scientific productivity and knowledge transfer, there is a need to reinforce international scientific collaboration and promote further collaboration in patenting.
- There is a need to strengthen the capacity of the business sector to engage in R&I collaborations with academia and research centres, in particular in high-tech sectors, and in countries with less-performing research systems.

1. Researchers' mobility

Mobility of researchers across jobs can be an important driver for knowledge transfer and knowledge diffusion. More generally, inventors' mobility has been deemed central to knowledge transfer and is an important source of learning for hiring organisations (Lenzi, 2013). At the EU level, the share of job-to-job mobility has remained small at almost 7 %, despite an increase between 2010 and 2020. Within the EU, there are significant differences in the mobility patterns of human resources in science and technology (Figure 6.2-1). While Lithuania, Denmark and Cyprus registered more than 10 % of human resources in science and technology (HRST) changing jobs from one year to the next in 2020, less than 2 % did so in Romania.

Except for Czechia, Sweden and Romania, all other Member States reported an increase in job-to-job mobility in the last 10 years. Mobility increased the most in Estonia, Croatia and Hungary. Despite the increase in the 10-year period, most Member States experienced a decline between 2019 and 2020, in particular Sweden and Portugal. This drop could be partly explained because of people preferring to remain in their current

Figure 6.2-1: Job-to-job mobility[1] of human resources in science and technology[2] as a % of total HRST, 2010, 2019 and 2020



Science, Research and Innovation Performance of the EU 2022

Source: Eurostat (online data code: hrst_fl_mobsex)

Notes: [1]The movement of individuals between one job and another from one year to the next. This does not include inflows into the labour market from a situation of unemployment or inactivity. [2]HRST: Persons with tertiary education and/or employed in science and technology. [3]No data available for UK 2020. [4]Figures for Ireland not available.

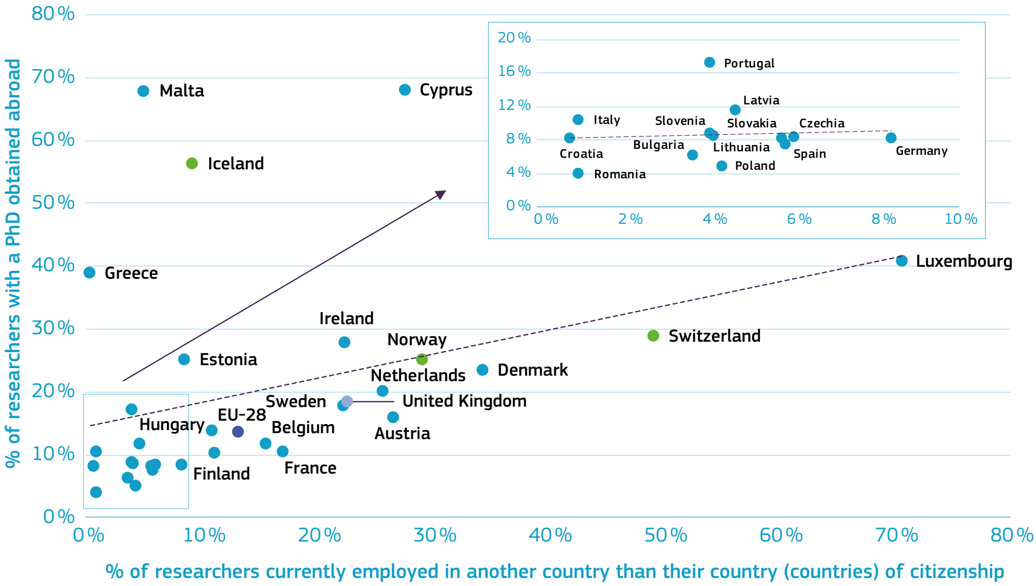
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-2-1.xlsx

jobs rather than moving, due to the COVID-19 pandemic, and the related reduction in job openings. According to the results of the OECD Science Flash Survey 2020[1] (OECD, 2021), COVID-19 has also limited the international mobility of researchers, who expected the crisis to negatively affect their job security and career opportunities.

Another important channel of knowledge diffusion concerns the mobility of researchers across countries. Data from the MORE study (European Commission, 2021) suggests the presence of strong differences between EU Member States in terms of inflow of researchers, measured by the number of foreign researchers working in a country, and the share of researchers having obtained their PhDs abroad (Figure 6.2-2). These indicators are also proxies for the attractiveness of the national research system to researchers. It is important to highlight that several factors can impact the mobility of researchers, such as working conditions, career prospects and cultural and linguistic aspects. Several studies (Franzoni et al., 2012; Geuna, 2015; IDEA Consult, 2013a, 2013b; Janger et al., 2019) confirm these reasons.

Overall, smaller countries and/or those performing better in R&I show a relatively high inflow of researchers and a higher share of researchers who obtained a PhD abroad. Among this group of countries, Luxembourg, Switzerland and Cyprus display the highest percentages (Figure 6.2-2). On the other hand, other small countries, such as Malta and Iceland, report a relatively high

Figure 6.2-2: International mobility of researchers



Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit based on European Commission, MORE4 study (2019)

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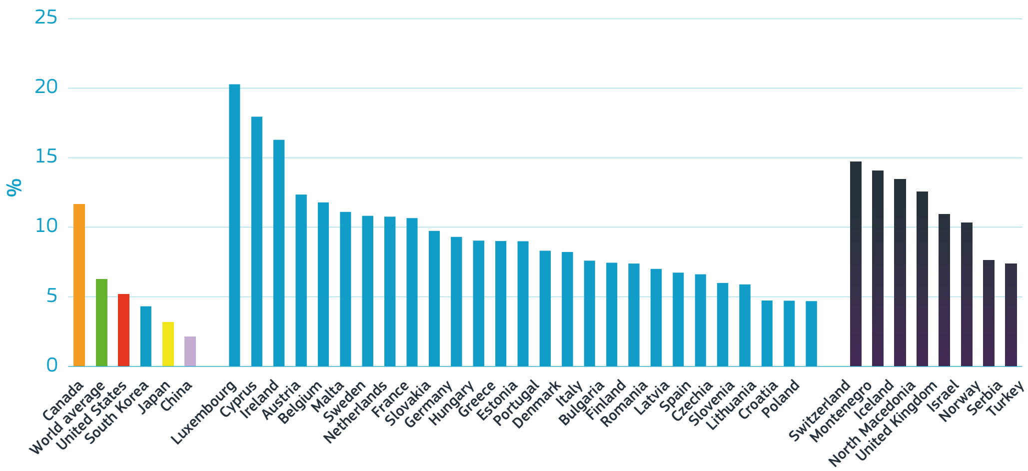
1 https://oecdsciencesurveys.github.io/2020flashsciencecovid/

share of researchers with PhD obtained abroad but a much lower share of foreign employed researchers. An extreme case is Greece, which shows a relatively high share of researchers who obtained a PhD abroad but has a very small share of foreign researchers. At the same time, a group of more innovative European countries such as Denmark, Norway, Netherlands, Ireland and Austria are characterised by relatively high influx of researchers, as well as a relatively high share of mobile PhDs. However, given the survey-based nature of the data and the cultural and local specificities of each national research system, the results must be interpreted with caution.

The analysis of scientific publications over a 15-year period shows a similar trend in the outflow of researchers. Using scientific publications data (Figure 6.2-3), it is possible to calculate the share of researchers that left the country at some point. Similarly to the trend observed for researchers' inflows, smaller and/or more innovative countries, such as Luxembourg, Switzerland, Cyprus and Ireland, report the highest shares of researchers who left the country over 2005-2020. Given the high level of performance of some of those countries' research systems, this pattern should not be seen simply as a brain drain phenomenon, but as a way for researchers to improve their research careers by moving to another country. Within the EU, the eastern countries have the lowest shares of researchers that were mobile in the last 15 years. Outside the EU, Canada has the highest share, while China reports the lowest performance. Once again, the method applied demands a cautious interpretation of the results.

Figure 6.2-3: Share of researchers leaving the country[1] at some point during the period 2005-2020



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit based on Science-Metrix using Scopus database

Note: [1]To investigate the mobility of individual researchers, Scopus author IDs (AUIDs) were selected as unique identifiers for individual researchers. AUIDs are generally quite precise and allow for the identification of sets of publications related to unique researchers. One drawback is that they are not as precise for common names, which mostly affects Chinese and Korean researchers, as well as researchers with highly frequent English names. In addition, because an AUID relies partially on institutional affiliations, mobility may cause a rupture in the portfolio of publications of researchers, resulting again in a split of the output between the original AUID and a new distinct AUID assigned after moving, again impacting the measurement of mobility. Therefore, the indicator will tend to underestimate mobility because of the aforementioned issues.

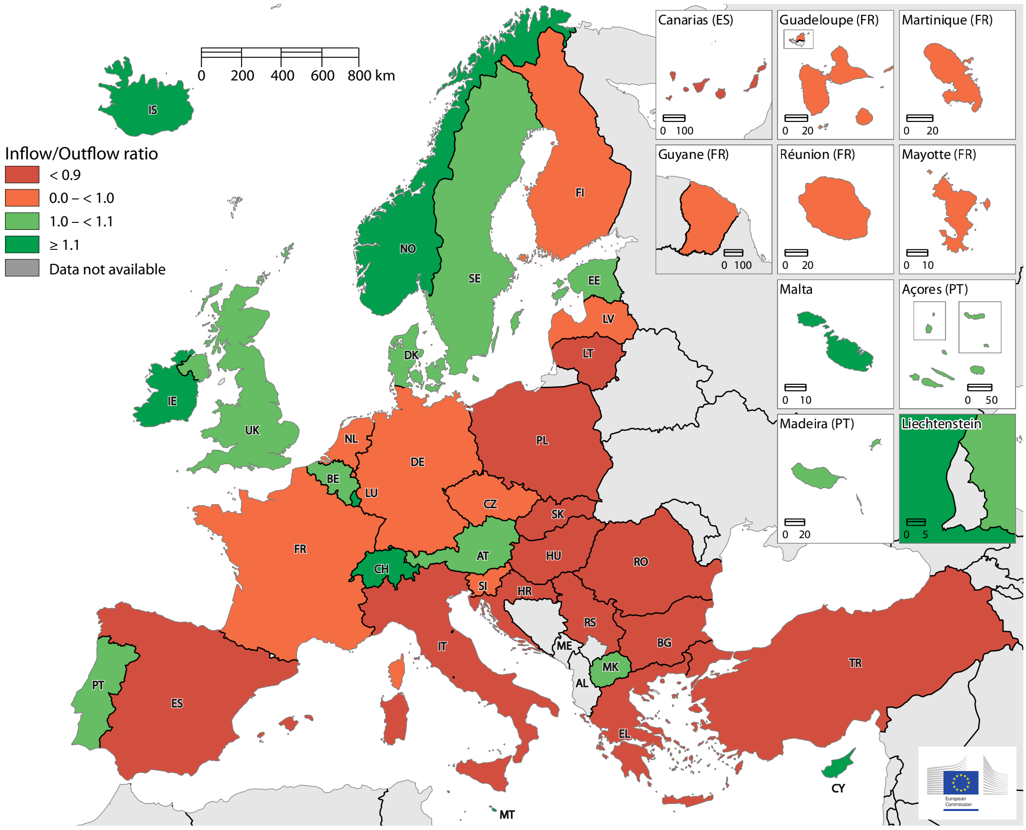
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-2-3.xlsx

The mobility of researchers, based on bibliometric data, suggests that many European countries are suffering a brain drain. This is particularly the case of most eastern and southern European countries, such as Italy, Greece, Hungary and Poland, for which the outflow of researchers outstrips the inflow when calculating the ratio between the inflow and outflow of researchers in Europe during the last 20 years to and from the rest of the world (Figure 6.2-4). These results might be explained by poor career conditions and unattractive research systems that have led researchers to look for better conditions abroad. In contrast, the inflow of researchers outpaces the outflow in most northern and western European countries (including Switzerland, Luxembourg, Norway and the United Kingdom). As regards EU countries only, most Member States report a ratio of researcher inflow over outflow below 1, suggesting that the number of researchers who left the country over the period considered was lower than the number of researchers who entered it. This might be explained by the fact that in most EU Member States, the top destination for European researchers is not another Member State but a country outside the EU such as the United States, which is a top destination (data not shown). In addition, the outflow of European researchers to the United States is higher than the inflow of American researchers to the EU. These results are confirmed by other studies such as Khan (2021).

Mobility patterns are influenced by several factors, such as the dynamics of labour markets, security of research careers and ease of changing jobs, as well as other external factors (e.g. a pandemic or an economic crisis). The report on researchers' mobility flows in Marie Skłodowska-Curie Actions (MSCA) investigates mobility determinants, looking at push and pull factors at three levels: individual (such as career prospects and conditions), organisational (such as peer support and infrastructure), and systemic (such as level of openness/closedness of the research systems). The study shows that the most advanced R&I systems remain the most attractive for researchers but also that the MSCA are effective at attracting and retaining European talent, as well as attracting European researchers back to Europe and supporting return mobility, particularly towards widening countries. Based on these findings, the study does not recommend reintroducing return grants for researchers. Instead, it provides a set of policy recommendations aimed at enhancing the quality and attractiveness of the less advanced R&I systems, including their capacity to support more balanced flows of researchers (PPMI, 2022).

The mobility of researchers is positively correlated with the share of international scientific co-publications. As reported in Figure 6.2-5, a high level of researcher mobility can lead to a higher level of international collaboration. When researchers move to other countries, they usually keep ties with their place of origin, increasing the level of collaboration between home and reception countries. At the same time, a high level of international collaboration might lead to a more attractive research system, thereby attracting more researchers and promoting mobility.

Figure 6.2-4: Map of inflow and outflow ratio of researchers[1] during the period 2001-2020[2] by country



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit based on Science-Metrix using Scopus database

Note: [1]To investigate the mobility of individual researchers, Scopus author IDs (AUIDs) were selected as unique identifiers for individual researchers. AUIDs are generally quite precise and allow for the identification of sets of publications related to unique researchers. One drawback is that it is not as precise for common names, which mostly affects Chinese and Korean researchers, as well as researchers with highly frequent English names. In addition, because an AUID relies partially on institutional affiliations, mobility may cause a rupture in the portfolio of publications of researchers, resulting again in a split of the output between the original AUID and a new distinct AUID assigned after moving, again impacting the measurement of mobility. Therefore, the indicator will tend to underestimate mobility because of the aforementioned issues. [2]RO: period corresponds to 2001-2019.

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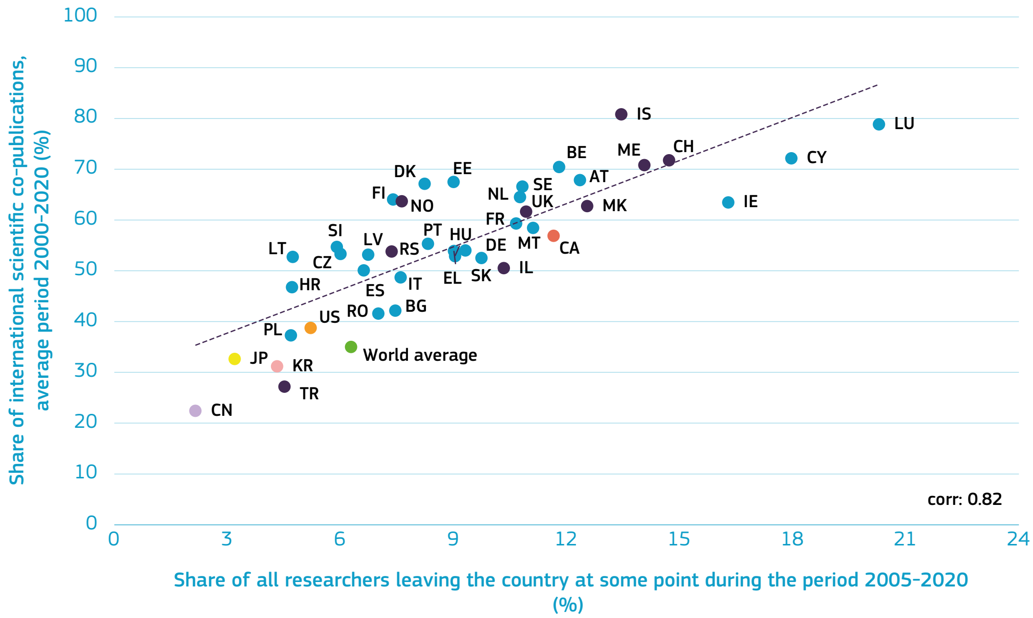
Figure 6.2-5: Share of mobile researchers vs share of international co-publications



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit based on Science-Metrix using Scopus database

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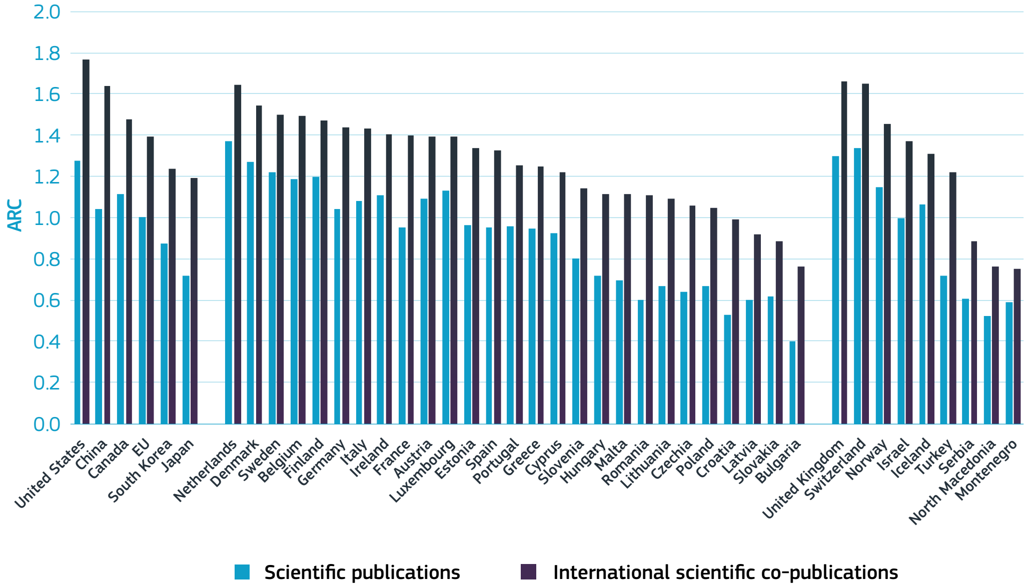
Overall, international scientific co-publications have a higher citation impact than scientific publications. The higher the citation impact of international scientific co-publications, the higher the quality of the scientific production. Several studies have examined the effect of international mobility on scientific productivity, providing evidence that international mobility increases the number of publications (Netz et al., 2020). Another study suggests substantial gains from mobility on scientific output, with mobility inducing a long-lasting increase in a researcher's publications by 32% and citations by 63% (Ejermo et al., 2020). In 2018, the United States had the highest average relative citations of international co-publications, followed by China, Canada and the EU (Figure 6.2-6). Within the EU, the Netherlands, Denmark and Sweden topped the ranking, while Bulgaria, Slovakia and Latvia were the worst performers.

Figure 6.2-6: Average of relative citations (ARC)[1], 2018 (citation window 2018-2020)



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit based on Science-Metrix using Scopus database

Note: [1]The average of relative citations uses a variable citation window, fractional counting and corresponds to the total relative citations/total valid publications for impact indicators.

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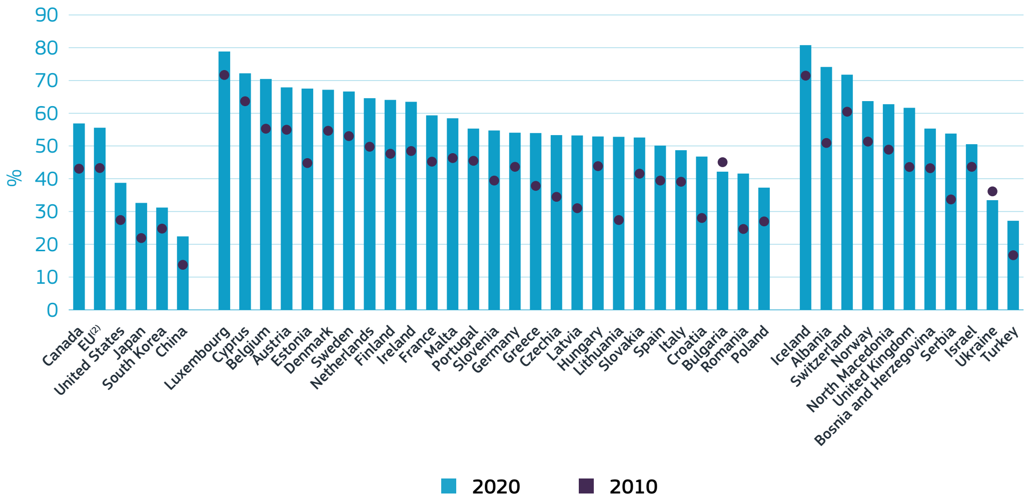
2. International collaboration

Cross-border research and collaboration among researchers are important channels of knowledge flow and knowledge transfer. International collaboration via scientific co-publications improves scientific quality since researchers achieve greater impact and citations from their international collaborations. International co-publications gain, on average, more citations than domestic co-publications (Puuska et al., 2014).

In 2020 in most EU Member States, more than 50 % of scientific publications were international co-publications. (Figure 6.2-7) The share increased between 2010 and 2020 in all selected countries, except Bulgaria and Ukraine. This growth was significant in the three Baltic countries, Estonia, Lithuania and Latvia, where the share increased by more than 20 percentage points. Countries such as Luxembourg and Iceland, due to their small but innovative research systems, show the highest shares, with around 80 % of their publications being international. As seen previously, these results might also be linked to the internationalisation of universities measured as the share of foreign researchers, which for these two countries is very high.

Among the international partners, Canada tops the list of selected countries with a share of 57 %, followed by the EU with 56 %.

Figure 6.2-7: Share of international scientific co-publications per total scientific publications(1), 2010 and 2020



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit based on Science-Metrix using Scopus database

Note: (1)Full counting method used. (2)The EU average includes intra-EU collaborations. The EU figure without intra-EU collaborations is 37 % for 2020.

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China comes last, with around 22 % of its scientific co-publications being international. When excluding intra-EU publications, the EU is at 37 %, which is slightly below the share of the United States (39 %) but above that of Japan and South Korea. Even though big countries tend to collaborate less with international partners due to their internal large research systems, there are still some exceptions such as Canada, the United Kingdom, France and Germany, for whom more than 50 % of their publications are international co-publications (Figure 6.2-7).

European-level funding programmes and initiatives such as MSCA contribute to the high figures and trends. These programmes also have an important role in promoting international cooperation to tackle societal challenges[2]. A recent report on the contribution of EU R&I funding to COVID-19-related research shows that out of the analysed publications (1 419), 56 % were internationally co-authored (European Commission, 2021). Furthermore, earlier framework-programme evaluations show that international cooperation in MSCA projects significantly contributes to the advancement of certain new and emerging research areas that are highly relevant for tackling particular global challenges common to Europe and its neighbouring countries (European Commission, 2019). However, some eastern EU countries, such as Poland, Romania and Bulgaria, can improve further.

2 In Horizon 2020, 39 % of all researchers involved in MSCA were from third countries, accounting for nearly 50 % of all international participations in Horizon 2020. This translated into funding 13 420 researchers from 1 300 organisations in more than 100 countries.

Box 6.2-1: Research trends on the Sustainable Development Goals and alignment with SDG 17 on international partnerships

Paul Khayat, Simon Provençal and David Campbell
Science-Metrix

The 17 Sustainable Development Goals (SDGs), part of the United Nations' 2030 Agenda for Sustainable Development, are interconnected goals that aim at achieving a better and more sustainable future for all. Given the increasing emphasis placed by the European Commission on achieving the SDGs (e.g. through Horizon 2020 and Horizon Europe), three policy briefs examined how European research, at the level of the European Union (EU) and the ERA, in comparison to key international comparators (the United States, China, Japan and South Korea), contributed to research for the SDGs. This was achieved by relying on sets of scientific publications covering each of the SDGs (except SDG 17) in Scopus database. These data sets were constructed by Science-Metrix using advanced keyword-based queries designed to capture literature relevant to each SDG's underlying target. They were then grouped by the People (SDGs 1–5, Brief H), Prosperity (SDGs 7–11 and 16, Brief I) and Planet (SDGs 6 and 12–15, Brief J) thematics.

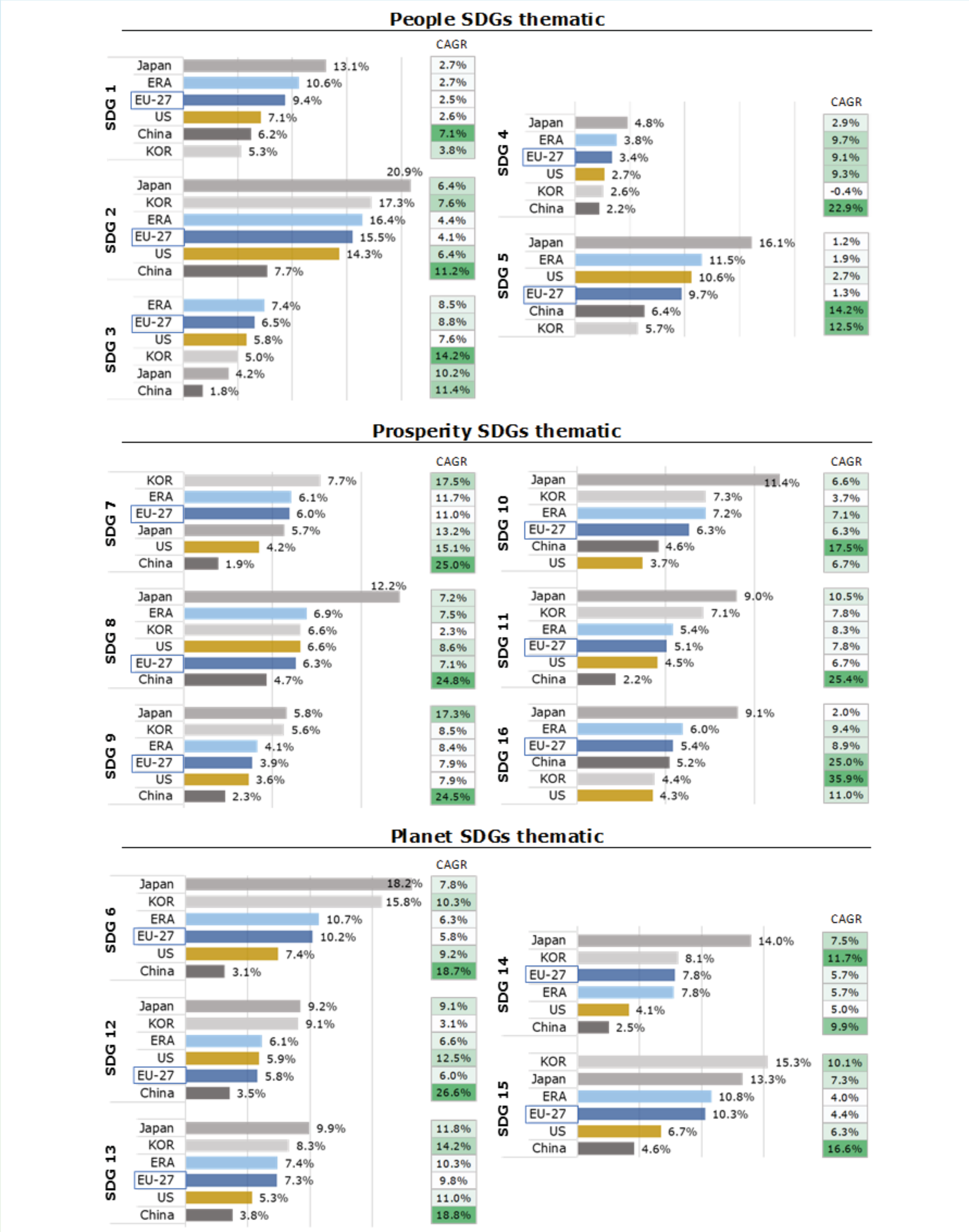
Among the seventeen SDGs, SDG 17 on 'partnerships for the goals' cuts across all other SDGs and is intended, in part, to promote inclusive collaborations among a broad range of actors (e.g. North–South co-publications) –To assess whether SDG-related research at the level of the EU/ERA (and comparators) is aligned with SDG 17 on 'partnerships for the goals' the policy briefs examined the evolution in the proportion of international co-publications along North–North and North–South axes in research related to the SDGs. Here, North and South were interpreted in terms of income level rather than geographic distribution, with North corresponding to high income (according to the World Bank) and South corresponding to low income. Two indicators based on co-publications were used: (1) share of co-publications with high- or low-income countries, and (2) diversity of international partners, particularly among low-income countries.

Given the much larger research output of high-income versus low-income economies, the international co-publication rates of all presented regions/countries in 2019 were much higher with the former than the latter group in all SDGs. Among international comparators, the EU and the ERA were the most active in co-publication with high-income countries (which includes co-publications between EU or ERA members), having comparable co-publication shares of 40% to 60%. These co-publications predominantly involved collaborations with major European scientific contributors such as the United Kingdom, Germany, Italy, Spain, France and the Netherlands, as well as the United States and China.

In parallel, the EU and the ERA co-published 16% or less of their SDG-related publications with low-income countries (Figure 6.2-8). Among the top 10 largest EU scientific contributors, France and Belgium were consistently among the top countries having the highest shares of co-publications with low-income countries in all SDGs.

Relative to the selected international comparators, the EU and ERA were leading in co-publication activity with low-income countries in SDG 3 (Figure 6.2-8). In the other SDGs, the smallest contributors to the SDGs in output size among selected comparators (i.e. Japan and

Figure 6.2-8: Share of co-publications and annual growth (CAGR) of the EU and selected comparators with the low-income countries



Source: Science-Metrix using Scopus (Elsevier) data, European Commission (2021)

Note: The share of co-publication is calculated for the period 2017–2019, and the CAGR estimates the annual growth between the period 2011–2013 and the period 2017–2019.

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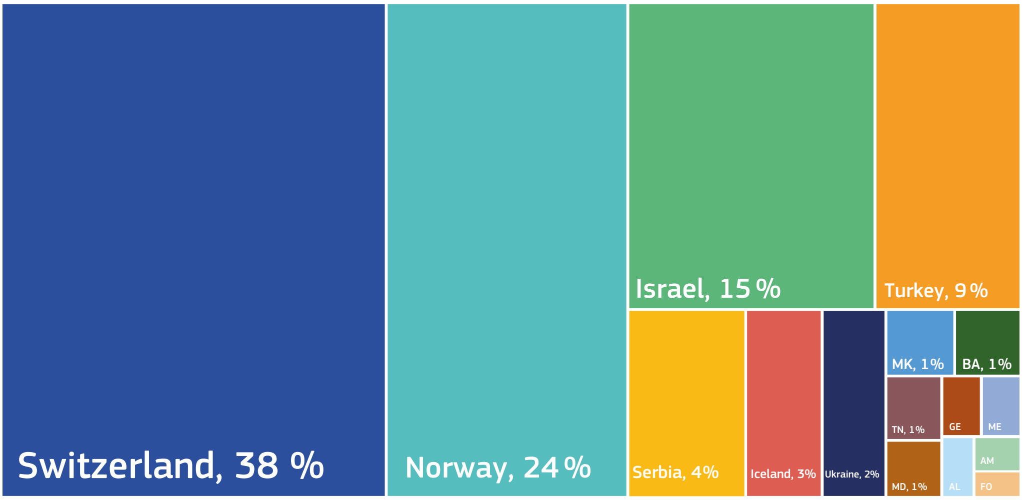
South Korea) displayed the highest co-publication shares with low-income partners – Japan led in 13 SDGs and South Korea in 2 SDGs (SDG 7 and SDG 15). The EU's share of co-publication with low-income countries was higher than that of the other major scientific contributors – China in all SDGs, and the United States in most SDGs (except in SDGs 5, 8 and 12).

Over the past decade (since 2011-2013), the growth in co-publication shares of each presented region/country has generally evolved at a faster pace with low-income compared to high-income countries. At the level of the EU, the co-publication growth with low-income countries has been particularly dynamic in some SDGs, reaching about 8% to 11% in SDGs 3 and 4 (People), SDGs 7, 9, 11 and 16 (Prosperity) and SDG 13 (Planet) (Figure 6.2-8). However, despite the relatively good placement of the EU along the collaboration dimension with low-income countries, it did not exhibit the fastest annual growth since 2011–2013. Instead, China experienced the sharpest growth in most SDGs, as did South Korea in SDGs 3, 16 and 14. Given China's co-publication growth, it may also soon become a key figure in scientific collaborations with low-income countries in these SDGs.

The growth in co-publication activity with the low-income group over the past decade was largely due to an increase in the proportion of new, low-income countries active in SDG research (from 55 to 60 countries on average in the period 2011–2013, to about 70 countries in 2017–2019). It was also influenced by an increase in the intensity of co-publication links with developing countries. In general, the co-publication activity of EU Member States was not distributed evenly across the low-income countries but was instead dominated by a handful of countries. It is not surprising that, in all SDGs, India was consistently the leading (or a top leading) partner with most individual EU countries. Apart from India, other low-income countries had large bilateral links with EU countries in specific SDGs, including Kenya, Ethiopia, Vietnam, Ukraine, Pakistan, Morocco, Egypt, Tunisia, Algeria, Nigeria and Ghana (data not shown; for further details, see the full Policy Briefs H, I and J).

Figure 6.2-9: Share of participations from associated countries in Horizon 2020 as % of all associated countries' participation



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Horizon Dashboard data (data extracted April 2022)

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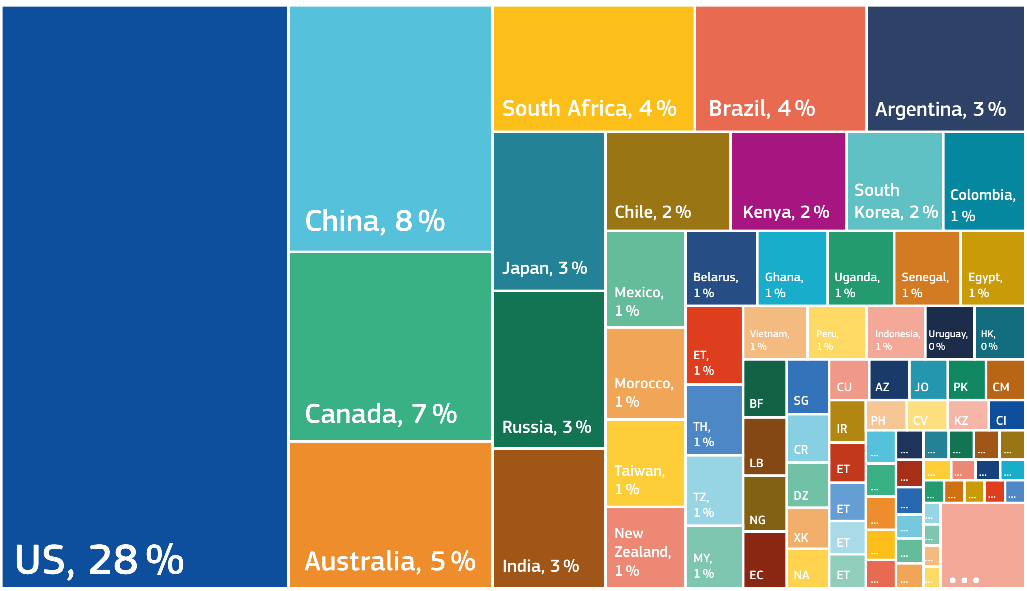
Figure 6.2-10: Share of participations from non-associated third countries in Horizon 2020 as % of all non-associated third countries' participation



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Horizon Dashboard data (data extracted April 2022)

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With applicants from 147 countries, Horizon 2020 promoted broad international collaboration. Concerning the associated countries (Figure 6.2-9), Switzerland, with its strong R&I system, was the most active associated country, with 5 137 participations – i.e. a share of 38 % of all associated countries. Norway, Israel and Turkey, followed, accounting for 23 %, 17 % and 9 %, respectively. The associated countries with the lowest participation (equal or less than 1 %) were Tunisia, Moldova, Georgia, Montenegro and Albania. Concerning the non-associated third countries (Figure 6.2-10), the United States came on top, accounting for 28 %. In far second place came China with 9 %, followed by Canada (7 %), Australia (5 %), South Africa (4 %) and Brazil (4 %). Overall, the top 10 participating non-associated third countries, which also includes Japan, India, Russia and Argentina, gathered 68 % of these participations, with a low level of participation from many developing economies.

Albeit at a lower extent than scientific publications, international collaboration can also occur in patent applications. Patent applications with a foreign co-inventor are also an important vehicle of knowledge diffusion, which in this case, is much closer to the market and allows the diffusion of new technologies. Motives to collaborate are access to complementary knowledge or access to research facilities, instruments or results, allowing international knowledge flows in co-patents (Frietsch et al., 2009).

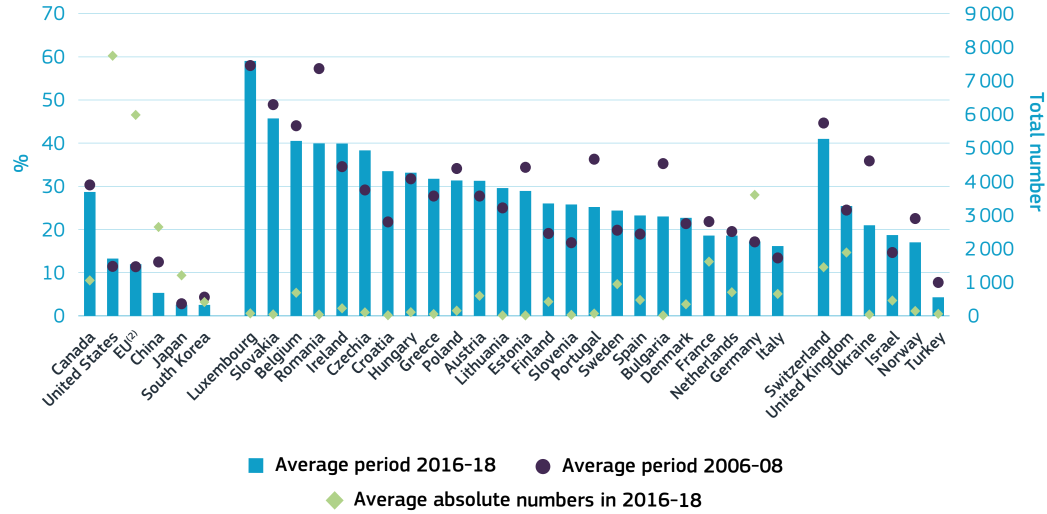
With an average of 7 747 patent applications, the United States had the highest number of patent applications filed with a foreign co-inventor under the PCT in 2016-2018. The EU came second, with an average of 5 988 patent applications, followed far behind by China (2 649) and Japan[3] (1 206). In relative terms (as a share of the total number of patents), Figure 6.2-11 shows that despite having a lower absolute number of co-patent applications, Canada has the highest share (an average of almost 30 % during 2016-2018) among the selected international competitors . The United States came second, with an average of 13 %, and the EU third, with 12 %. China, Japan and South Korea all come next with shares of 5 % or less.

Within the EU, there is significant variability, both in terms of shares, absolute figures and variations over time. In relative terms, Luxembourg came top, with almost 60 % of its patent applications taking place with a foreign co-inventor. Conversely, Italy had the lowest share, with an average of 16 % in 2016-2018. Generally, the countries with highest absolute numbers, such as Germany, France or United Kingdom, had the lowest shares, while the countries with low absolute numbers had the highest shares. However, Switzerland and Belgium, which have relatively high figures of both absolute numbers and shares of patent applications with a foreign co-inventor, are notable exceptions.

Over time, most EU countries have increased their shares, in particular Croatia and Slovenia. However, some countries recorded significant declines, such as Romania, Portugal and Bulgaria. It is important to highlight that for some countries the absolute number of patents is very small, which consequently increases their volatility. Among the selected competitors, all countries showed stable performance. China was the only exception, with a significant decline in its share between the two periods considered.

3 Although Japan is one of the main patent applicants, as shown in Chapter 6.3.

Figure 6.2-11: Share (%) of PCT patents with foreign co-inventor(s) in total number of patents[1], 2006-08 and 2016-18, and total number of patents with foreign co-inventor(s), 2016-18



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on OECD (international co-operation in patents) data

Notes: [1]PCT patents at the international phase designating the European Patent Office. Full counting and priority date used. Countries with fewer than 10 patent applications were excluded. Average of 3 years used to reduce volatility. [2]EU figures

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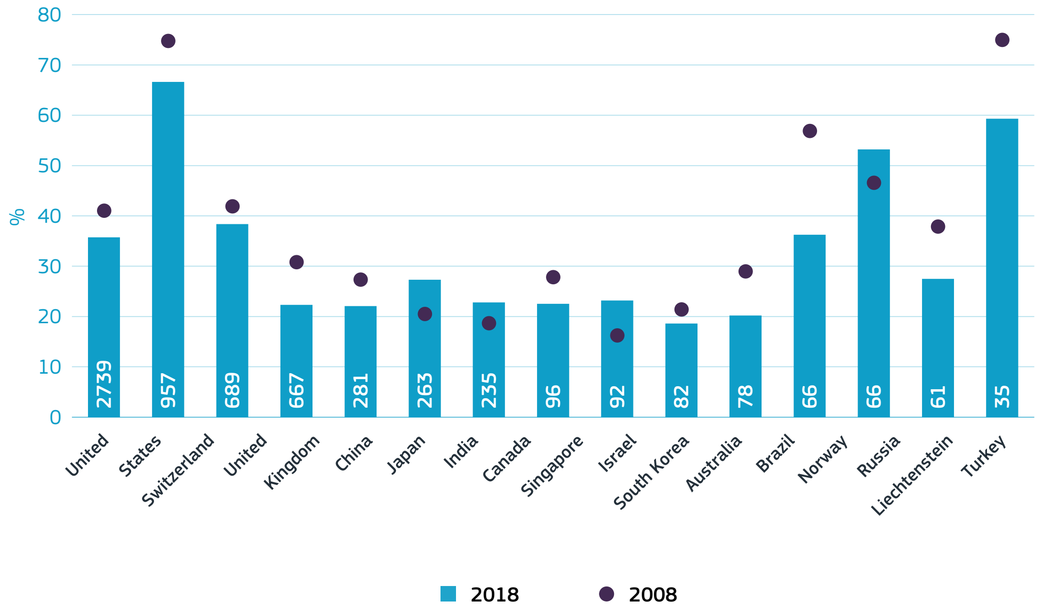
In 2018, the United States had the highest absolute number of patent applications filed under PCT with a foreign co-inventor from the EU. In relative terms, however, this accounted for only 36% of the total patent applications with a foreign co-inventor for the United States. Figure 6.2-12 shows the top 15 countries with the highest absolute number of patent applications filed under the PCT with an EU foreign co-inventor. Out of the 15 countries, the EU was co-inventor for more than 50% of patent applications in 2018 for only Switzerland (67%), Norway (53%) and Liechtenstein (59%). Over time, the share of the EU as foreign co-inventor declined for most of the countries selected and increased only for Norway, Canada, Israel and India.

Figure 6.2-12: Share of patent applications filed under the PCT[1] with the EU as foreign co-inventor, top 15 countries, 2008 and 2018



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on OECD (International co-operation in patents) data

Notes: [1]PCT patents at the international phase designating the European Patent Office. Full counting method and priority date used. Countries ordered by the absolute number of patent applications with the EU as foreign co-inventor (figures at the bottom).

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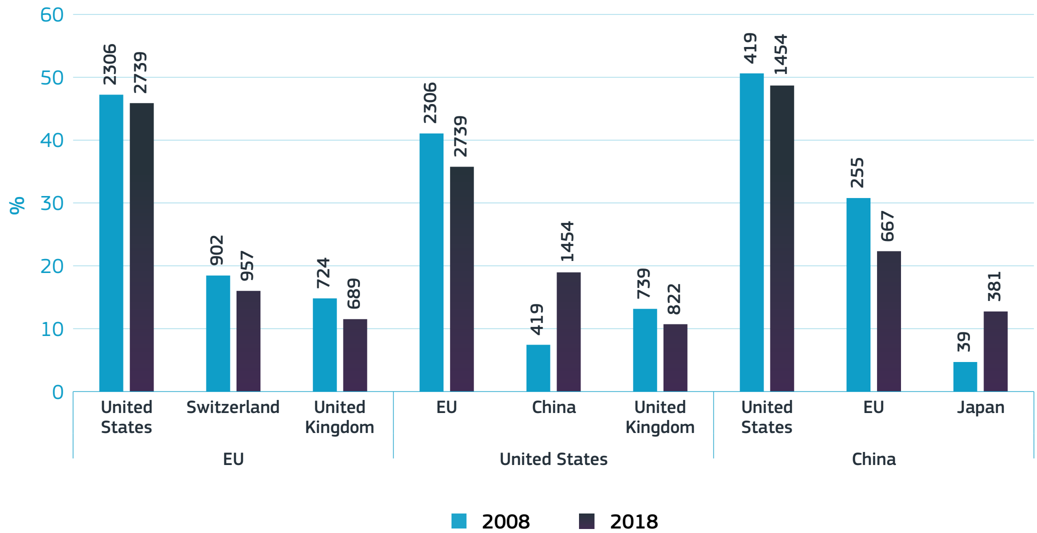
The EU and United States were each other's primary partners for patent applications filed under PCT with a foreign co-inventor in 2018. However, the EU represented less than 40% of patent applications with a foreign co-inventor for the United States, while the United States co-inventors accounted for 46% of EU patent applications (Figure 6.2-13). For the EU, the second main partner was Switzerland, with 16%, followed by the United Kingdom with 12%. For the United States, China was the second main partner, with a share of almost 20% and an impressive increase since 2008, followed by the United Kingdom with 11%. For China, the picture is slightly different: the United States was its main partner in 2018, with a share of 49%, while the EU came far behind with 22%, followed by Japan with 13%.

Figure 6.2-13: Top three main partners of patent applications filed under PCT[1] with a foreign co-inventor (%) for the EU, United States and China, 2008 and 2018



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on OECD (International co-operation in patents) data

Notes: [1]PCT patents at the international phase designating the European Patent Office. Full counting and priority date used. Absolute numbers shown on top of the bars.

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In absolute terms, with the exception of the EU-United Kingdom pair, all remaining pairs increased patenting collaboration during 2008-2018. The decline in collaboration between the EU and the United Kingdom was compensated by an increase in collaboration between the EU and the United States and Switzerland, as well as with China, Japan and India (data not shown). Collaboration improved the most between China and the United States, with an increase of 247 %, and between China and Japan, with an increase of 877 %. In relative terms, only China became more important to the United States, and Japan became more important to China.

3. Public-private cooperation

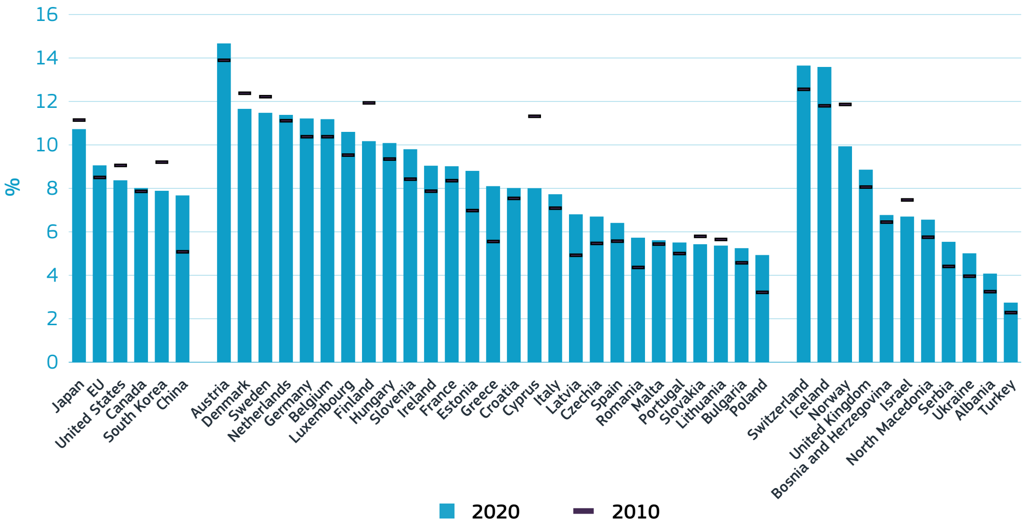
Collaboration between public research-performing institutions and the business sector is one of the most important channels for knowledge diffusion and valorisation. Motivations among companies for engaging in industry-university cooperation are: access to key research staff, complementary research activity and relevant results; providing promising new areas of applied R&D; avoiding wasteful experimentation; offering an understanding of novel directions on inventions and technological innovations; and augmenting the capacity to solve complex problems (e.g. Rosenberg, 1990; Fleming and Sorensen, 2004; Tijssen, 2012). The number of public-private co-authored scientific publications is an indicator to assess the level of collaboration between public research institutions and companies. A public-private co-publication involves several actors, including businesses' R&D departments (or R&D staff in other private-sector organisations), and offers several opportunities, such as co-authoring a research publication with partners in a public-sector organisation, including the academia. This type of collaboration represents a successful channel for knowledge transfer ('knowledge spillover').

Between 2010 and 2020, the share of public-private co-authored scientific publications increased from 8.5 % to 9.1 % in the EU. As reported in Figure 6.2-14, this small growth enabled the EU to overtake the United States in this period. However, the increase was not enough to overtake Japan, which remains the best-performing country among the selected international competitors, with a share of 10.7 %. Although China continues to lag, it showed a significant improvement (from 5.1 % to 7.7 %) during the same period.

Within the EU, there are significant differences between the Member States. Austria ranks first, with a share of 14.7 %, while Poland is the least-performing Member State, reporting a share of 4.9 %. Outside the EU, Switzerland and Iceland stand out with shares above 13 %, whereas Turkey falls behind with a share of less than 3 %. Countries with higher business R&D expenditure tend to have a higher share of public-private co-publications (as shown by the high correlation between the two variables), as enterprises procure public research-oriented institutions to perform research, leading to more scientific publications. This research is then applied by the enterprises to develop new products or processes.

Over time, most EU Member States have seen a rise in the share of public-private co-authored scientific publications. Greece and Latvia showed the biggest improvements, whereas Cyprus and Finland experienced the biggest declines. In absolute terms, all countries except Japan reported an increase in the number of public-private co-publications between 2010 and 2020. However, this growth was smaller than the overall growth in scientific production in countries such as Cyprus, Denmark, South Korea and Norway, explaining the declines reported in Figure 6.2-14.

Figure 6.2-14: Share of public-private co-authored scientific publications in total scientific publications[1], 2010 and 2020



Science, Research and Innovation Performance of the EU 2022

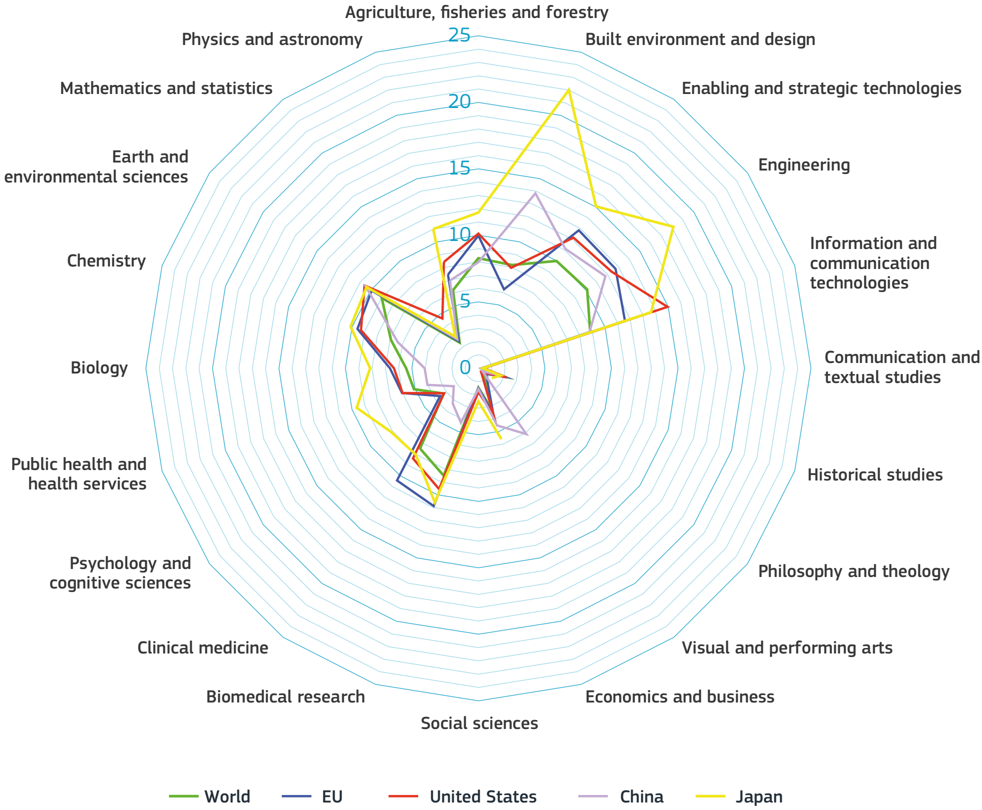
Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit based on Science-Metrix using Scopus database

Note: [1]Full counting method used. Accordingly, weighted averages are used for computing the share country aggregates. Both public and private entities are counted.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-2-14.xlsx

Generally, public-private cooperation is more frequent in the fields of applied sciences, natural sciences and health sciences. Figure 6.2-15 shows the share of public-private co-publications by fields of science and technology. Overall, natural and applied sciences are the areas characterised by the highest shares of collaboration, in particular in the fields of engineering and technologies. Japan is leading public-private collaboration in most fields but mainly in built environment and design, with 22%, and engineering, with 18%. The EU stands out in the health sector, while the United States is the strongest in ICT.

Figure 6.2-15: Share (%) of public-private co-authored scientific publications (in total scientific publications) per field of science and technology(1), 2020



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit based on Science-Metrix using Scopus database

Note: (1)Full counting used. Accordingly, weighted averages are used for computing the share country aggregates. Both public and private entities are counted.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-2-15.xlsx

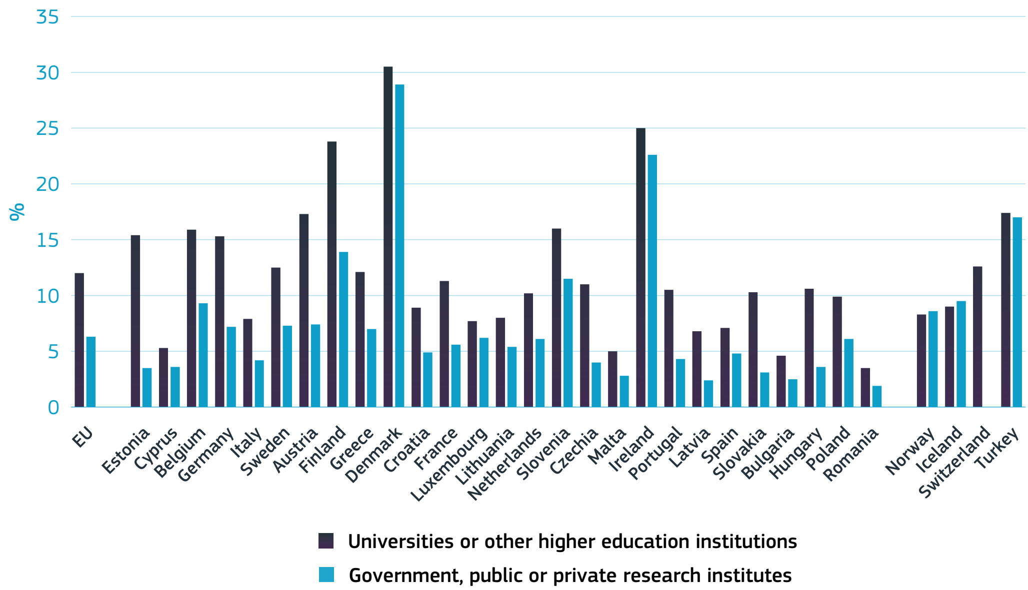
EU innovative enterprises tend to collaborate more with universities than with research institutes. A different indicator to assess the level of collaboration between the business sector and public research-oriented institutions is the share of innovative enterprises that co-operated on R&D and other innovation activities with universities (or other higher education institutions, HEI) and government, public or private research institutes[4]. Results from the Community Innovation Survey (CIS) suggest that 12 % of EU innovative enterprises cooperate on R&D with universities or other HEI, while only 6.3 % cooperate with government, public or private research institutes.

There are significant differences in the level of collaboration across the EU Member States. During 2016-2018, Denmark reported the highest level of cooperation

4 In the available data, it is not possible to separate private research institutes from other public research institutions. However, the number of private research institutes is relatively small in the EU.

between innovative enterprises and universities, with a percentage of 31%. Conversely, Romania performed very poorly, with a share of less than 2% (Figure 6.2-16). The data also suggests that a higher share of innovative enterprises does not necessarily lead to higher collaboration. For instance, Ireland, which ranks low in terms of innovative enterprises, has the second-best performance in terms of cooperation, both with universities and research institutes. On the other hand, Cyprus, reporting the second highest share of innovative enterprises, is a country where they cooperate the least.

Figure 6.2-16: Share of innovative enterprises that co-operated on R&D and other innovation activities, 2016-2018

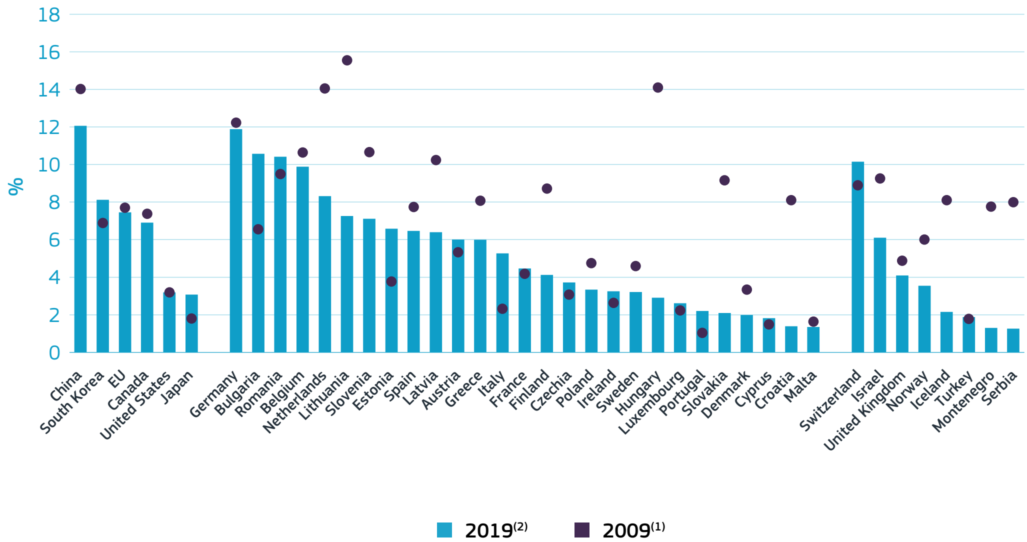


Science, Research and Innovation Performance of the EU 2022

Source: Eurostat – Community Innovation Survey 2018 (online data code: inn_cis11_coop)
Note: Countries ranked by their share of innovative enterprises
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-2-16.xlsx

China has the highest percentage of public R&D expenditure financed by the private sector, i.e. 12%. Despite the decline between 2009 and 2019, China remains the country accounting for the highest share of public R&D expenditure financed by business enterprises, followed by South Korea, with 8%, and the EU with 7.5% (Figure 6.2-17). The United States and Japan fell behind, with shares below 4%. Within the EU, only five countries perform above the EU average, notably Germany (reporting the same share as China), Bulgaria, Romania, Belgium and Netherlands, while important differences persist between the remaining EU countries. While most Member States experienced sharp declines over 2009-2019 (in particular Hungary, Lithuania and Slovakia), other Member States such as Bulgaria, Italy and Estonia saw significant increases. At the EU level, the share remained roughly stable (Figure 6.2-17).

Figure 6.2-17: Public expenditure (GOVERD + HERD) on R&D financed by business enterprise sector as % of total public expenditure on R&D



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit based on Eurostat (online data code: rd_e_gerdfund) and OECD

Note: (1)Greece, Montenegro: 2011. Switzerland: 2010. (2)Israel, UK, Montenegro: 2018

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-2-17.xlsx

MSCA support for university-business cooperation impacted positively on both participating businesses (SMEs and large businesses) and individual MSCA fellows' career development, according to a study linked to the ex-post and mid-term evaluation of the FP7 and H2020 R&I programmes. Additionally, MSCA support was found to have a broader impact on R&I ecosystems and inter-sectoral cooperation (European Commission, 2017). In particular:

- around 47% of all business beneficiaries indicated that as a result of their project at least one job (FTE equivalent) was created in their organisation;
- business participation significantly increased the chance of a patent application being registered as a result of the MSCA project;
- as a result of the MSCA, the vast majority (89%) of businesses started to collaborate with at least one new academic organisation.

4. Conclusions: mobility of researchers and collaboration are essential engines for knowledge flows

There is a divergent pattern in researcher mobility observed across Member States both in terms of geographical mobility and across jobs. At the EU level, the share of job-to-job mobility of human resources in science and technology from one year to the next has remained small at almost 7% in 2020, despite an increase between 2010 and 2020. Across the EU, the share varies from more than 10% in Lithuania, Denmark and Cyprus to less than 2% in Romania. Except for Czechia, Sweden and Romania, all other Member States had an increase in mobility in the last 10 years.

Smaller countries and/or those with better-performing R&I tend to show higher levels of researcher mobility. Using survey-based data, Luxembourg, Switzerland and Cyprus display the highest percentages of both inflow of researchers and researchers who obtained a PhD abroad. Using bibliometric data, the same countries report the highest shares of researchers who left the country over 2005-2020. However, many European countries appear to be suffering a brain drain, with the outflow of researchers outstripping the inflow of researchers from the rest of the world.

Collaboration between public research-performing institutions and the business sector is one of the most important channels for knowledge diffusion and valorisation. Between 2010 and 2020, the EU share of public-private co-authored scientific publications increased from 8.5% to 9.1%, placing the EU above the United States and only behind Japan. Within the EU, there are strong differences, from 14.7% in Austria to 4.9% in Poland. Results from the CIS suggest that EU innovative enterprises tend to collaborate more with universities than research institutes, with significant differences in the level of collaboration across the EU Member States. Denmark reported the highest level of cooperation between innovative enterprises and universities, with a percentage of 31%; while Romania performed very poorly, with a share of less than 2%. In terms of public R&D expenditure financed by the private sector, China has the highest share at 12%, compared to 7.5% in the EU.

Cross-border research and collaboration among researchers are important channels of knowledge flow and result in higher citation impacts. In 2020, more than 50% of the scientific publications in most EU Member States were international co-publications, with Luxembourg as the top performer. Between 2010 and 2020, this share increased in all Member States, except Bulgaria. This growth was quite important in the three Baltic countries, Estonia, Lithuania and Latvia, where the share increased by more than 20 percentage points.

With an average of 7747 patent applications, the United States had the highest number of patent applications filed under the PCT with a foreign co-inventor in 2016-2018. The EU came second, with an average of 5 988 patent applications, followed far behind by China (2649) and Japan (1206). In relative terms, however, Canada had the highest share (an average of almost 30% during 2016-2018). Second came the United States, with an average of 13%, and third the EU with 12%. In 2018, both the EU and the United States were each other's primary partners for patent applications filed under PCT with a foreign co-inventor. The EU was also the main partner for Switzerland (67%), Norway (53%) and Liechtenstein (59%). Over time, the share of the EU as a source of a foreign co-inventor increased for Norway, Canada, Israel and India.

References

Lenzi, C. (2013), 'Job Mobility, Patent Ownership and Knowledge Diffusion: Evidence on a Sample of Italian Inventors', *Industry and Innovation*, 20:4, pp. 297-315, DOI: 10.1080/13662716.2013.805930

Ejermo, O., Fassio, C., & Källström, J. (2020), 'Does mobility across universities raise scientific productivity?', *Oxford Bulletin of Economics and Statistics* 82.3, pp 603-624.

European Commission, Directorate-General for Research and Innovation (2021), *MORE4: support data collection and analysis concerning mobility patterns and career paths of researchers,* Publications Office of the European Union, Luxembourg. https://data.europa.eu/doi/10.2777/645537

European Commission, Directorate-General for Education, Youth, Sport and Culture (2017), *Study of business participation and entrepreneurship in Marie Skłodowska-Curie actions (FP7 and Horizon 2020): executive summary*, Publications Office of the European Union, Luxembourg. https://data.europa.eu/doi/10.2766/46752

European Commission, Directorate-General for Education, Youth, Sport and Culture (2019), *Study on international cooperation in the Marie Skłodowska-Curie actions: final report*, Publications Office of the European Union, Luxembourg. https://data.europa.eu/doi/10.2766/621682

European Commission, Directorate-General for Research and Innovation (2021), *Provision and analysis of key indicators in R&I: final study report covering work packages 1-6*, Publications Office of the European Union, Luxembourg. https://data.europa.eu/doi/10.2777/587466

Fleming L, Sorensen O. (2004), 'Science as a Map in Technological Search', *Strategic Management Journal*, vol. 25, pp. 909-928.

Franzoni, C., Scellato, G., & Stephan, P. (2012), 'Foreign-born scientists: mobility patterns for 16 countries', *Nature Biotechnology*, 30(12), pp. 1250.

Frietsch, Rainer, and Taehyun Jung (2009), *The internationalisation of international co-inventions*, Georgia Institute of Technology.

Geuna, A. (2015), Global Mobility of Research Scientists: The Economics of Who Goes Where and Why, Amsterdam: Academic Press.

IDEA Consult. (2013a), *Mobility of Researchers 2. Brussels: Report on survey of researchers in EU HEI.*

IDEA Consult. (2013b), *Mobility of Researchers 2. Brussels: Report on survey of researchers outside EU.*

Janger, J., Campbell, D.F.J. & Strauss, A. (2019), 'Attractiveness of jobs in academia: a cross-country perspective', *High Education*, 78, 991-1010. https://doi.org/10.1007/s10734-019-00383-7

Khan, J. (2021), 'European academic brain drain: A meta-synthesis', *European Journal of Education* 56.2, pp. 265-278.

tKhayat, P., Campbell, D., Provençal, S. (2021), *Provision and analysis of key indicators in research and innovation. Policy brief I, Research trends on the Sustainable Development Goals (SDGs) and alignment with SDG 17 on international partnerships: focusing on SDGs 7–11 plus 16 (prosperity),* European Commission, Directorate-General for

Research and Innovation, Publications Office of the European Union, Luxembourg. https://data.europa.eu/doi/10.2777/291062

Mugabushaka, A. (2021), *Meeting the pandemic challenges: contribution of EU R&I funding to COVID-19 related research*, European Commission, Directorate-General for Research and Innovation, Working Paper 2021/01, Publications Office of the European Union, Luxembourg. https://data.europa.eu/doi/10.2777/616617

Netz, N., Hampel, S., & Aman, V. (2020), 'What effects does international mobility have on scientists' careers? A systematic review', *Research Evaluation*, Volume 29, Issue 3, pp. 327-351. https://doi.org/10.1093/reseval/rvaa00

OECD (2021), *Reducing the Precarity of Academic Research Careers,* OECD Science, Technology and Industry, No. 113.

PPMI (2022), *Study on mobility flows of researchers in the context of the Marie Skłodowska-Curie Actions: analysis and recommendations towards a more balanced brain circulation across the European Research Area Final report*, European Commission (forthcoming).

Provençal, S., Campbell, D., Khayat, P. (2021), *Provision and analysis of key indicators in research and innovation. Policy brief H, Research trends on the Sustainable Development Goals (SDGs) and alignment with SDG 17 through international co-publications: focusing on SDGs 1-5 (People)*, European Commission, Directorate-General for Research and Innovation, Publications Office of the European Union, Luxembourg. https://data.europa.eu/doi/10.2777/70734

Provençal, S., Campbell, D., Khayat, P. (2021), *Provision and analysis of key indicators in research and innovation. Policy brief J, Research trends on the Sustainable Development Goals (SDGs) and alignment with SDG 17 through international co-publications: focusing on SDGs 12-15 plus 6 (Planet)*, European Commission, Directorate-General for Research and Innovation, Publications Office of the European Union, Luxembourg. https://data.europa.eu/doi/10.2777/03227

Puuska, H. M., Muhonen, R., & Leino, Y. (2014), 'International and domestic co-publishing and their citation impact in different disciplines', *Scientometrics*, 98. 10.1007/s11192-013-1181-7.

Rosenberg N. (1990), 'Why do Firms do Basic Research (with their Own Money)?', *Research Policy*, vol. 19, pp. 165-174.

Robert J. W. Tijssen (2012), 'Co-authored research publications and strategic analysis of public-private collaboration', *Research Evaluation,* Volume 21, Issue 3, pp. 204-215. https://doi.org/10.1093/reseval/rvs013

CHAPTER
6.3

INNOVATION OUTPUT AND SOCIETAL AND MARKET UPTAKE

KEY FIGURES

50%
of companies in the EU are innovative

1 in 5
worldwide patent applications filed under PCT come from the EU

23%
of patent applications in climate & environment are from the EU

62%
total EU exports are medium-and-high-technology products

KEY QUESTIONS WE ARE ADDRESSING

- How is the EU performing in terms of innovation output?
- What is the economic impact of innovation in the EU?

KEY MESSAGES

What did we learn?

- Among European businesses, the ability to innovate is related to firm size. Large companies have a higher propensity to innovate than SMEs, especially regarding the development of innovative products.
- The EU continues to lag behind Japan and the United States in the innovation output indicator. One of the main drivers is patent intensity, for which the EU also falls behind China and South Korea.
- The innovation divide persists across Member States, with Germany accounting for more than 40% of patent applications filed under the PCT in the EU in 2018.
- The EU was the top patent applicant in the fields of climate and environment (23%), energy (22%) and transport (28%) worldwide in 2018.
- The share of exports of medium and high-technology products in the EU remained stable over the years, while the share of exports of knowledge-intensive services declined.

What does it mean for policy?

- It is important to continue supporting European IP policy and foster a stronger knowledge-valorisation policy for societal, environmental and economic impact. In addition to improving innovation systems, the EU must encourage structural reforms that upgrade the technology profiles of Member States and address the persistent innovation divide.
- The EU needs to strengthen innovation capacity across Member States, especially in the high-tech economic sectors.
- The EU has the human capital and science base, but can be more effective in translating it into innovations and commercialising innovation output.

1. Innovation Performance

Measuring the innovation performance of the EU is essential for improving existing and designing new R&I policies for economic growth and sustainable development. A key principle of the Oslo Manual (OECD/Eurostat 2018) is that innovation can and should be measured. To this end, the manual provides guidelines for collecting and interpreting data on innovation to facilitate international comparisons. The Community Innovation Survey (CIS)[1], which is the reference survey on innovation in enterprises in the EU, EFTA and the EU Candidate Countries, is based on the Oslo Manual. The survey was introduced in 1992 and has become a regular biennial data collection.

EU innovation performance has increased. According to the 2021 European Innovation Scoreboard (EIS), all EU countries improved their innovation performance in 2020[2]. However, most of the underlying data refers to the pre-pandemic period and does not account for the COVID-19 shock. Sweden is the most innovative country in the EU, followed by Finland, Denmark and Belgium. The distribution of EU countries in the four performing groups[3] clearly indicates the persistent innovation gap between north-west and south-east Europe (Figure 6.3-1).

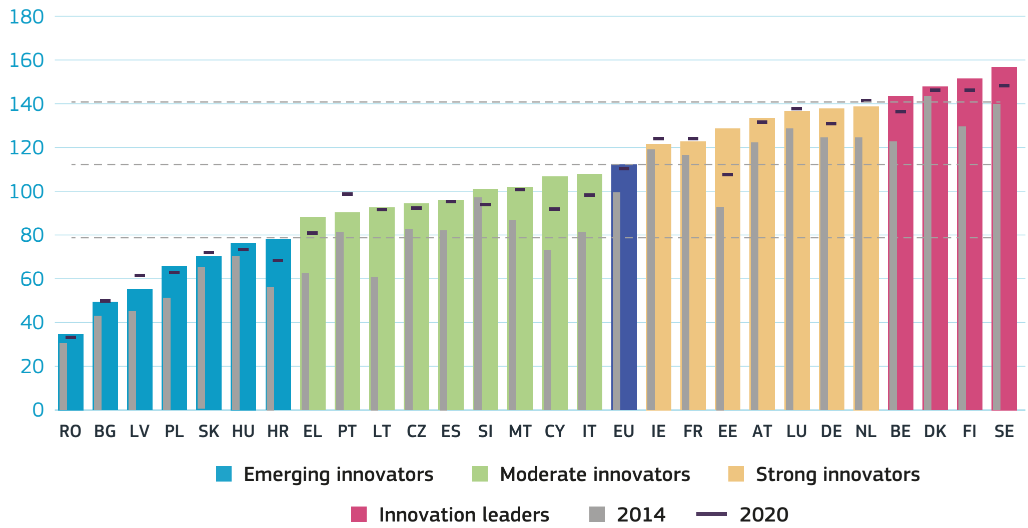
The Global Innovation Index (GII) 2021 finds that investment in innovation has shown remarkable resilience during the COVID-19 pandemic, but varies across sectors and regions (WIPO, 2021). As discussed in other parts of this report, scientific output, public R&D support, IP filings and venture capital (VC) deals continued to grow in 2020. According to the GII 2021, the majority of the top 25 most innovative economies continue to be from Europe. Switzerland, Sweden, and the United Kingdom are among the top five.

1 https://ec.europa.eu/eurostat/web/microdata/community-innovation-survey

2 For most indicators, the reference year lags one or two years behind the year to which the EIS refers.

3 **Innovation Leaders** are all countries with a relative performance in 2021 above 125 % of the EU average in 2021. **Strong Innovators** are all countries with a relative performance in 2021 between 100 % and 125 % of the EU average in 2021. **Moderate Innovators** are all countries with a relative performance in 2021 between 70 % and 100 % of the EU average in 2021. **Emerging Innovators** are all countries with a relative performance in 2021 below 70 % of the EU average in 2021

Figure 6.3-1: European Innovation Scoreboard 2021 – Performance of EU Member States' innovation systems



Science, Research and Innovation Performance of the EU 2022

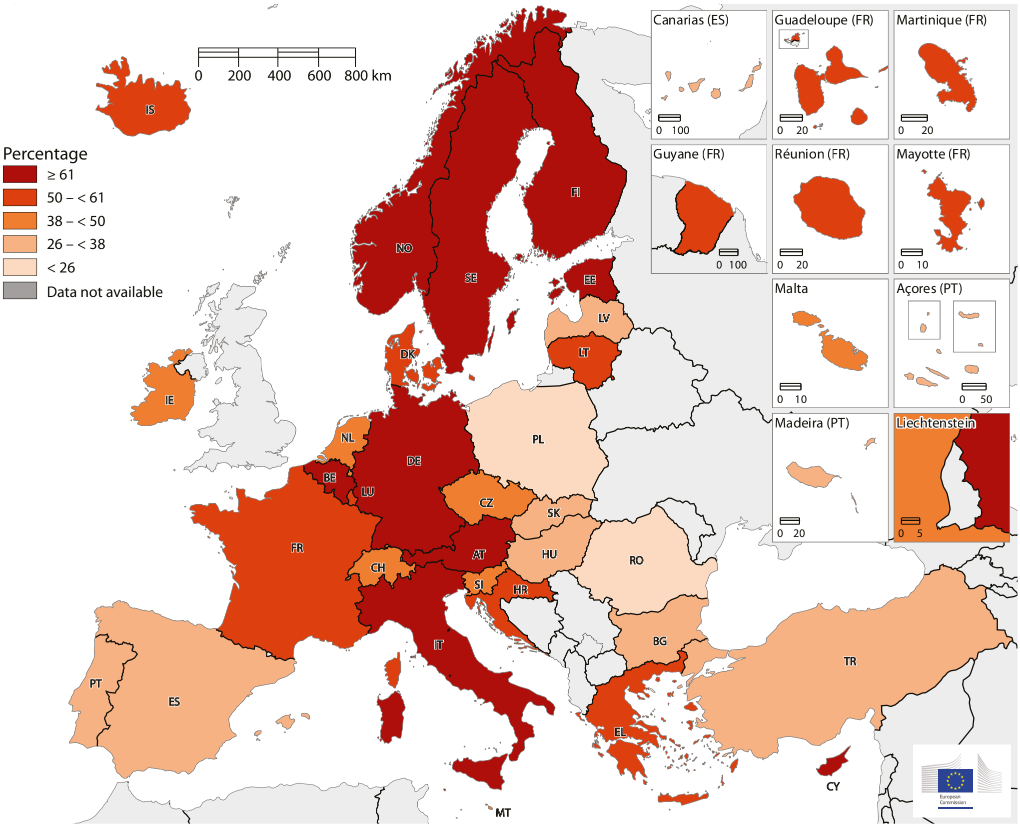
Source: European Innovation Scoreboard 2021, European Commission (2021)

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-3-1.xlsx

The propensity to innovate is higher for large companies than for SMEs. This pattern is observable in all EU and neighbouring countries (Figure 6.3-3). Estonia, Belgium and Greece report the highest share of innovative large enterprises (more than 90%), performing well above the EU average of 78%. The highest shares of innovative SMEs (above 65%) can be found in Estonia, Cyprus, Belgium and Germany.

Intra-country differences in the shares of innovative large companies and SMEs varies significantly within the EU, ranging between 48 p.p. in Bulgaria and 8 p.p. in Ireland. Large differences suggest that innovation is performed by a few large, possibly multinational companies, while the majority of the SMEs are not innovative.

Figure 6.3-2: Map of share of innovative enterprises (number of innovative enterprises as % of total number of enterprises), 2016-2018



Science, Research and Innovation Performance of the EU 2022

Source: Eurostat - Community Innovation Survey 2018, (online data code: inn_cis11_bas)

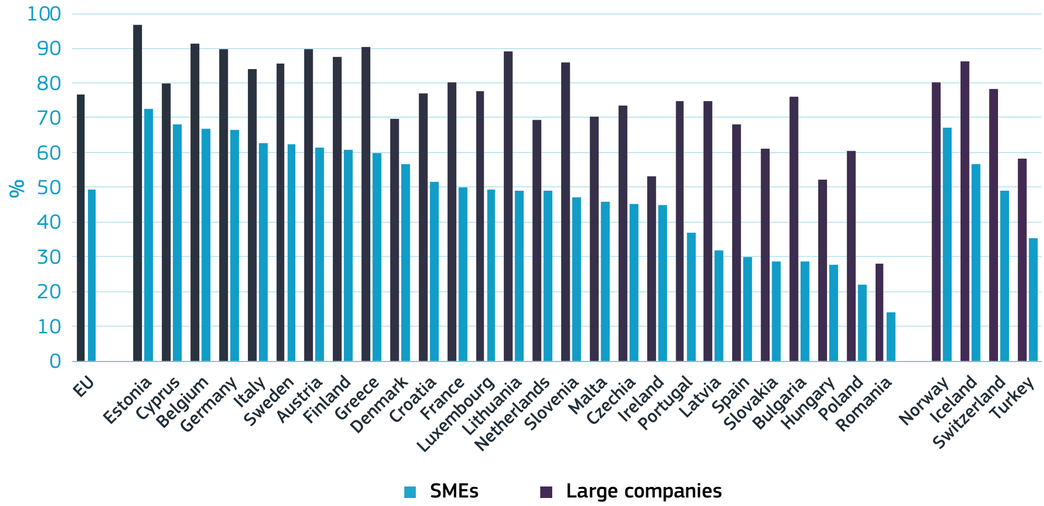
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-3-2.xlsx

In 2018, 50 % of EU firms reported innovation activities, showing an increase of 2 percentage points (p.p.) compared with 2016. Based on the Community Innovation Survey, more than half of Member States showed an increase in their share of innovative enterprises compared with the period 2014-2016. For 14 Member States, this share is higher than the EU average. Estonia and Cyprus are the countries with the highest shares (73.1 % and 68.2 %, respectively), followed by Belgium and Germany (both with 67.8 %).

On the opposite side, Romania and Poland show the lowest performances, reporting only 15 % and about 24 % of innovative companies, respectively. Italy and Sweden experienced an increase of 9 p.p. over the period 2016-2018. Portugal recorded a dramatic decline of 29 p.p., which may not entirely reflect a decrease in the innovativeness of the country, as other methodological factors need to be examined[4].

4 For example, changes in the questionnaire and the order of the questions, changes in way the survey was conducted etc.

Figure 6.3-3: **Share of innovative enterprises by size class[1], 2016-2018**



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation, Chief Economist - Common Strategy & Foresight Unit based on Eurostat - Community Innovation Survey 2018 (online data code: inn_cis11_bas)

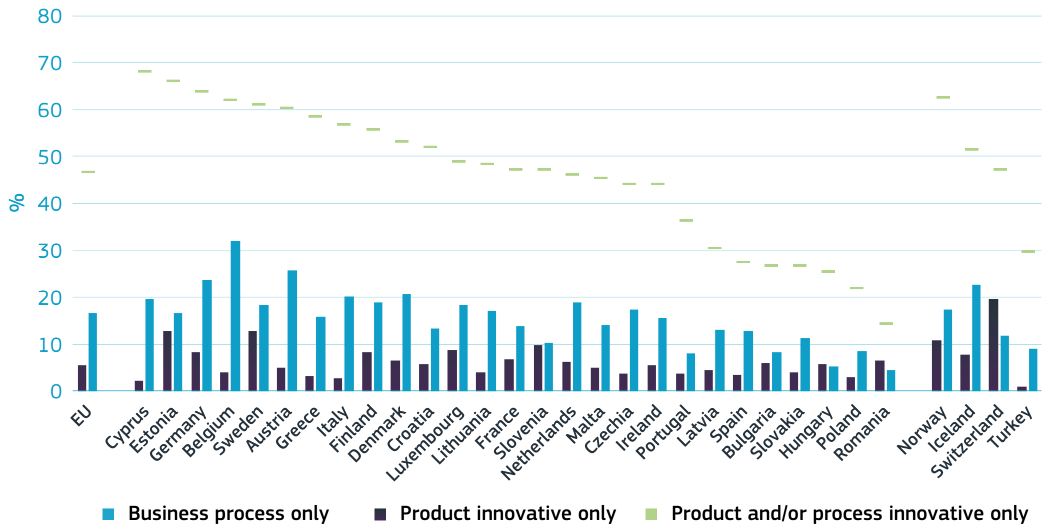
Note: [1]SMEs are firms with 10-249 employees, large companies 250 employees or more.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-3-3.xlsx

Most companies engage in a combination of product and business process innovation activities. The EU share of product and/or business process innovative enterprises only (regardless of any other innovation activities) is about 47% and varies significantly among Member States, from 68% in Cyprus to 14% in Romania. In contrast, the shares of companies engaging in one type of innovation, either product or business, are significantly lower (see Figure 6.3-4). Product innovation is a new or improved good or service that differs significantly from the firm's previous goods or services and that has been introduced to the market. A business process innovation is a new or improved business process for one or more business functions. According to the revised Oslo Manual, business process innovation merges marketing and organisational innovation.

The average share of companies undertaking only product innovations activities in the EU is 5.5%. Estonia and Sweden reported the highest share (about 13%), while Cyprus and Italy showed the lowest performance (less than 3%). The share of companies carrying out activities targeting only business process innovations is significantly higher and averages around 16.7% at EU level. Belgium leads with a share of 32.1%, followed by Austria and Germany.

Figure 6.3-4: Share of innovative enterprises by type of innovation activity, 2016-2018



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Eurostat - Community Innovation Survey 2018 (online data code: inn_cis11_bas)

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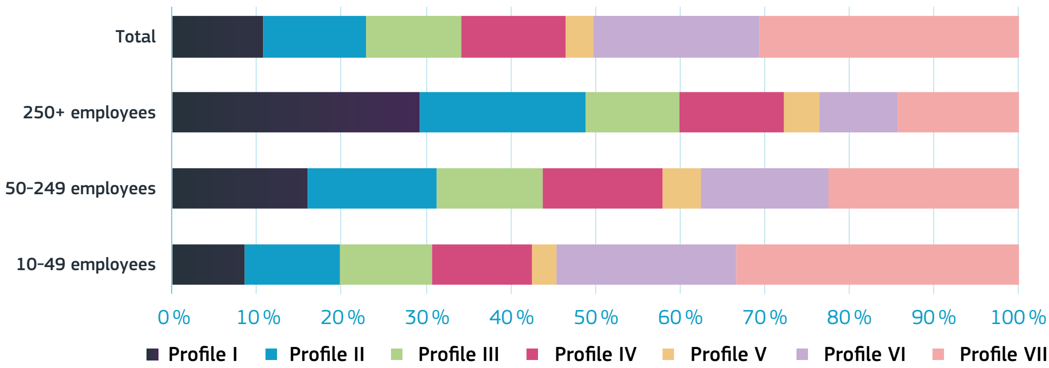
Developing product innovation with market novelties (profile I) is limited to a few large firms with internal competences. Data from the innovation profiling (Box 6.3-1) shows that about 11 % of all enterprises in the EU are in-house innovators with market novelties (Profile I). These enterprises are most frequent (one in three) among larger enterprises (250 or more employees), which represent about 4 % of the reference total.

Within European businesses, the capa-bi-lity to innovate is mostly related to firm size characteristics. Figure 6.3-5 shows that enterprises of Profile I and II, i.e. product innovators, are more common among large enterprises. Similarly, non-innovators of Profiles VI and VII are significantly more frequent among small enterprises, which represent the vast majority of European businesses (almost 80 % of the reference total). Profiles III and IV are not sensitive to the size of the enterprises.

Figure 6.3-5: Distribution of enterprises by size class and innovation profile[1]



	10-49 employees	50-249 employees	250+ employees	Total
Profile I	9 %	16 %	29 %	11 %
Profile II	11 %	15 %	20 %	12 %
Profile III	11 %	12 %	11 %	11 %
Profile IV	12 %	14 %	12 %	12 %
Profile V	3 %	4 %	4 %	3 %
Profile VI	21 %	15 %	9 %	20 %
Profile VII	33 %	23 %	14 %	31 %

Science, Research and Innovation Performance of the EU 2022

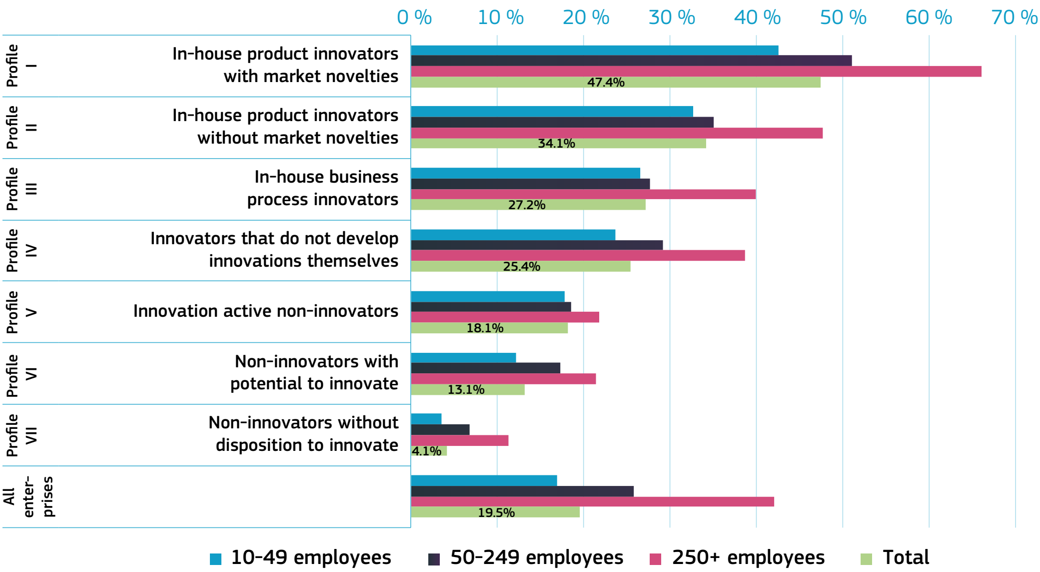
Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Eurostat - Community Innovation Survey 2018

Note: [1]Based on 18 EU Member States. Data are not available for Austria, Czechia, and Sweden.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-3-5.xlsx

The propensity of an enterprise to invest in new technologies is related to the size and the type of innovative activity. The acquisition of new technology represents an important source of embodied knowledge for innovation in enterprises. On average, only one-fifth of enterprises invested in new embodied technologies, with the propensity to invest increasing significantly with firm size. Figure 6.3-6 shows, for each of the innovation profiles, the shares of enterprises that purchase new technology, which was not used in enterprise before. About half of the product innovators with market novelties purchased new technologies. Medium-sized firms that internally develop new products with market novelties tend to purchase new technologies more than the big firms with product innovators without market novelties (Figure 6.3-6).

Figure 6.3-6: Share of firms which purchased new technology that was not used in enterprise before by size class and innovation profile[1]



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Eurostat - Community Innovation Survey 2018

Note: [1]Based on 18 EU Member States. Data are not available for Austria, Czechia, and Sweden.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-3-6.xlsx

Box 6.3-1: Innovation profiling

DG Eurostat

Innovation in businesses involves a range of activities requiring multiple capabilities. With different characteristics and innovation abilities, enterprises can contribute to economic growth and social development in various ways. In this perspective, the profiling of enterprises according to their innovation behavior may improve our knowledge of the diversity of the innovation patterns.

Using Community Innovation Survey (CIS) microdata, analysed in collaboration with most National Statistical Offices, it is possible to identify seven mutually exclusive innovation profiles.

The logic followed in developing the profiles is in line with policy purposes, focusing on the conditions that allow innovation to occur in businesses, rather than on the characteristics of successful innovators. The process identifies enterprises with and without innovation activities at the first level. The second level distinguishes enterprises that have implemented an innovation during the CIS reference period, or not. Finally, at the third level, it focuses on the innovation capabilities of enterprises, including the presence and level of R&D activities, innovation cooperation, the presence of ongoing or abandoned innovation efforts, and the innovation potential of companies that have not introduced innovations.

Figure 6.3-7: Combining the Community Innovation Survey core variables: innovation profiling

<table>
<tr><td colspan="14">Combining the CIS core variables: innovation profiling</td></tr>
<tr><td rowspan="7"></td><td colspan="13">Enterprises</td></tr>
<tr><td rowspan="5">Total</td><td colspan="9">with innovation activities</td><td colspan="3">without innovation activities</td></tr>
<tr><td rowspan="4">Total</td><td colspan="6">with innovations</td><td colspan="5">without innovations</td></tr>
<tr><td rowspan="3">Total</td><td colspan="4">with substantial own innovation capabilities</td><td>without substantial own innovation capabilities</td><td rowspan="3">Total</td><td>that worked on innovations but did not implement them</td><td rowspan="3">Total</td><td rowspan="3">that tried or considered to innovate but were impeded</td><td rowspan="3">that did not try or consider to innovate</td></tr>
<tr><td rowspan="2">Total</td><td colspan="3">View: Market relevance of innovation</td><td rowspan="2">Total</td><td rowspan="2">Total</td></tr>
<tr><td>with product innovations not offered before by competitors</td><td>with an enlarged assortment [1)]</td><td>with only business process innovation</td></tr>
<tr><td>I + II + III + IV + V + VI + VII</td><td>I + II + III + IV + V</td><td>I + II + III + IV</td><td>I + II + III</td><td>I</td><td>II</td><td>III</td><td>IV</td><td>V + VI + VII</td><td>V</td><td></td><td>VI</td><td>VII</td></tr>
<tr><td>with R&D activities</td><td></td><td></td><td></td><td></td><td>I.A</td><td>II.A</td><td>III.A</td><td>IV.A</td><td></td><td>V.A</td><td></td><td></td><td></td></tr>
<tr><td>without R&D activities</td><td></td><td></td><td></td><td></td><td>I.B</td><td>II.B</td><td>III.B</td><td>IV.B</td><td></td><td>V.B</td><td></td><td></td><td></td></tr>
</table>

Seven innovation profiles:

I - In-house product innovators with market novelties, including all enterprises that introduced a product innovation that was developed by the enterprise and that was not previously offered by competitors.

II - In-house product innovators without market novelties, including all enterprises that introduced a product innovation that was developed by the enterprise but that is only new to the enterprise itself.

III - In-house business process innovators, including all enterprises that did not introduce a product innovation, but that did introduce a business process innovation that was developed by the enterprise.

IV - Innovators that do not develop innovations themselves, including all enterprises that introduced an innovation of any kind but did not develop it themselves (enterprises without significant own innovation capabilities).

V - Innovation active non-innovators, including all enterprises that did not introduce any innovation but that either had ongoing or abandoned innovation activities.

VI - Non-innovators with potential to innovate, including all enterprises that did not introduce any innovation, and which had no ongoing or abandoned innovation activities but that did consider to innovate.

VII - Non-innovators without disposition to innovate, including all other enterprises, those that neither introduced an innovation nor had any ongoing or abandoned innovation activities nor considered to innovate.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-3-7.xlsx

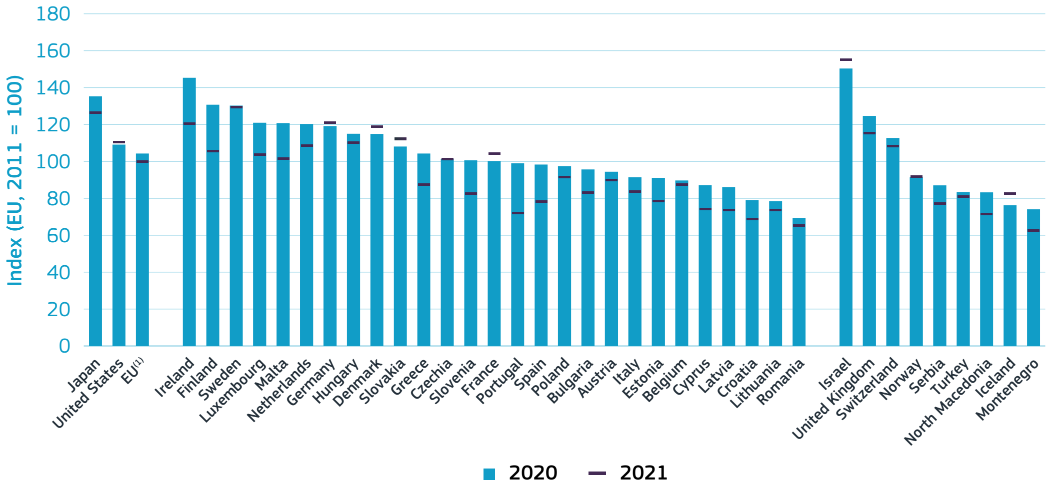
2. Innovation output

Innovation output is the result of innovation activities within an economy. Several indicators, from composites to single indicators, can be used to measure innovation output. In its latest edition, the Global Innovation Index (GII) used several metrics, from indicators on knowledge creation and diffusion to intangible assets, to produce its innovation output sub-index. For several years now, the European Commission has published a composite indicator that aims to measure the extent to which ideas from innovative sectors can reach the market, providing better jobs and making Europe more competitive. The innovation output indicator aggregates four components to measure innovation output: patents, employment in knowledge-intensive activities, trade in knowledge-based goods and services, and innovativeness of high-growth enterprises.

In 2020, the EU lagged behind the US and Japan in terms of innovation output. These results are mainly due to weak EU performance in the components related to patent applications, employment in knowledge-intensive activities, and trade in knowledge-intensive services. Between 2011 and 2020, the EU's performance improved, helping to close the gap with US (Figure 6.3-8). However, the gap with Japan grew. Despite a small improvement in some of the indicator's components (namely, the innovativeness of high-growth enterprises, employment in knowledge-intensive activities and trade in knowledge-based goods), the overall EU performance did not suffice to catch up with Japan. These results are in line with the European Innovation Scoreboard, according to which the EU lags behind Japan and the US; and with the GII, in which Japan and the US perform particularly well in the output sub-index.

Ireland, Finland and Sweden are the top three EU countries in terms of innovation output. While Ireland underperforms in the component of patent applications, it is the top performer in the components of trade in knowledge-intensive services and innovativeness of high-growth enterprises. Finland and Sweden, on the other hand, are very strong in terms of patent applications. Conversely, Romania, Lithuania and Croatia reported the lowest performance in 2020. A more detailed analysis of the performance per component is presented in section 3 – Economic Impact of Innovation. Between 2011 and 2020, the innovation performance improved in 22 out of the 27 EU Member States, especially in Portugal, Ireland and Finland. Performance declined slightly in Germany, Denmark, Slovakia and France, and stagnated in Czechia. The strong progress of Portugal was mainly due to a significant increase in employment of fast-growing enterprises.

Figure 6.3-8: **Innovation output indicator, 2011 and 2020**



Science, Research and Innovation Performance of the EU 2022

Source: European Commission, DG Joint Research Centre (Bello, M. et al., 2022)

Note: (1)EU: Two sets of values are available: for worldwide and for European comparison. The values for worldwide comparison, which exclude trade within EU countries, are shown on the graph. The value for European comparison for 2020 is 105.2.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-3-8.xlsx

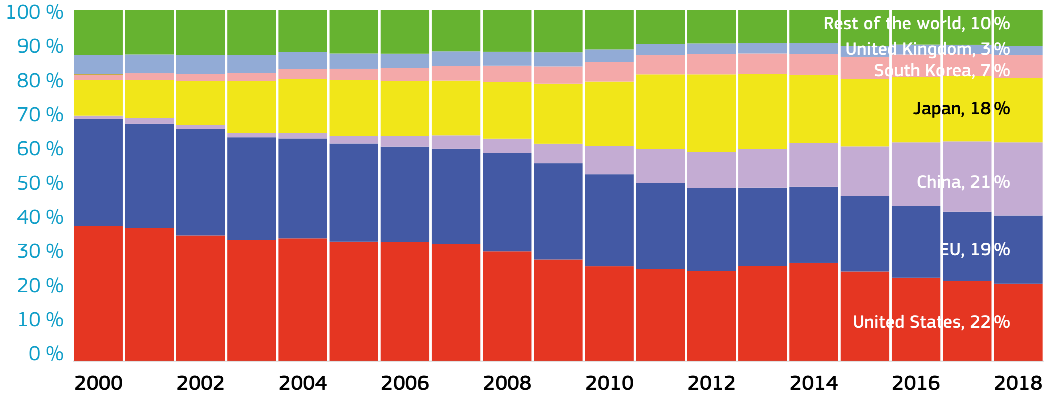
Patent data provides a useful way to measure innovation performance. Around 80% of the patent applications filed under the PCT[5] worldwide came from Japan, China, the EU and the US (Figure 6.3-9). However, the distribution of the share of applications among them changed over time. While the EU and the US accounted for 31% and 38% of worlds' patent applications in 2000 respectively, their share declined to 19% and 22% in 2018. In contrast, China is the country with the largest increase over time, especially after 2008, overtaking both the EU and Japan in 2017. If the trend shown in Figure 6.3-9 continues, China will overtake the US in coming years. Unlike scientific publications, for which the rise of China was mostly at the expense of the US (see Chapter 6.1), in the case of patent applications, the rise of China and Japan came at the expense of both the US and the EU.

The sectoral distribution of patent applications varies between the four global players. On the one hand, the EU applies for proportionally more patents in the medium and low-tech sectors, such as the automotive and machinery sectors. On the other hand, China and the US apply for proportionally more patents in high-tech fields such as the pharmaceutical and other chemistry sectors (polymers, materials or nano-technology) and in knowledge-intensive services like IT (despite the fact that knowledge-intensive services represent a very low share worldwide). Finally, Japan appears to be stronger mainly in the medium-tech sector. [6]

5 The Patent Cooperation Treaty (PCT) is an international patent law treaty which assists applicants in seeking patent protection internationally for their inventions. By filing one international patent application under the PCT, applicants can simultaneously seek protection for an invention in a large number of countries.

6 See Chapter 2.2- Zoom Out: Technology and Global Leadership for more details.

Figure 6.3-9: World shares (%) of patent applications filed under PCT[(1)], 2000-2018



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Science-Metrix using EPO PATSTAT database

Notes: [(1)]Patent Cooperation Treaty (PCT) patents, at the international phase designating the European Patent Office. Fractional counting method, inventor's country of residence and priority date used.

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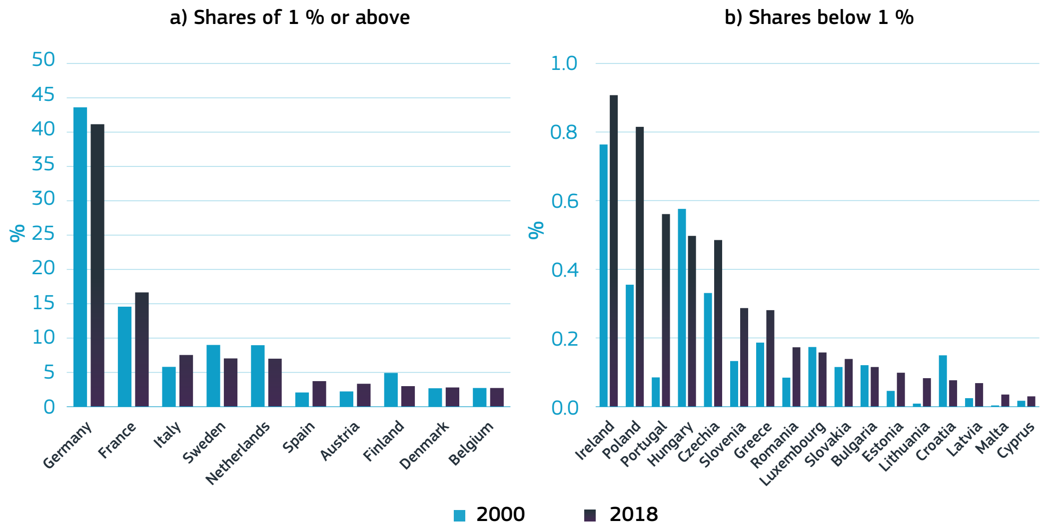
There exists a clear regional divide in patent applications in the EU (Figure 6.3-10). In the EU, Germany accounted for over 40 % of patent applications filed under the PCT in 2018. France came a distant second with a share of 17 %, followed by Italy (8 %) and Sweden (7 %). Unlike scientific publications, patent applications in the EU are considerably more concentrated, with 95 % coming from only 10 Member States. However, there is a similar trend to that of scientific production, with eastern and southern EU Member States like Portugal, Italy, Spain and Poland increasing their share between 2000 and 2018, while countries like Germany, Netherlands, Sweden and Finland lost ground.

Although looking at the world share is important, using relative terms provides a better comparison across countries. In this case, Japan and South Korea topped the ranking with more than 10 patent applications per billion GDP in 2018. Trailing in third place, the US had four patent applications, followed closely by China, the EU and Canada (Figure 6.3-11). Over time, despite their already high share, both Japan and South Korea managed to improve enormously, with 5 and 4.6 more patent applications per billion GDP, respectively. However, the impressive growth (315 %) came from China. It overtook both EU and Canada, having increased considerably from a very low level in 2008. The EU and the US on the other hand showed a small decline.

Figure 6.3-10: EU share of patent applications filed under PCT by Member State, 2000 and 2018



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Science-Metrix using EPO PATSTAT database

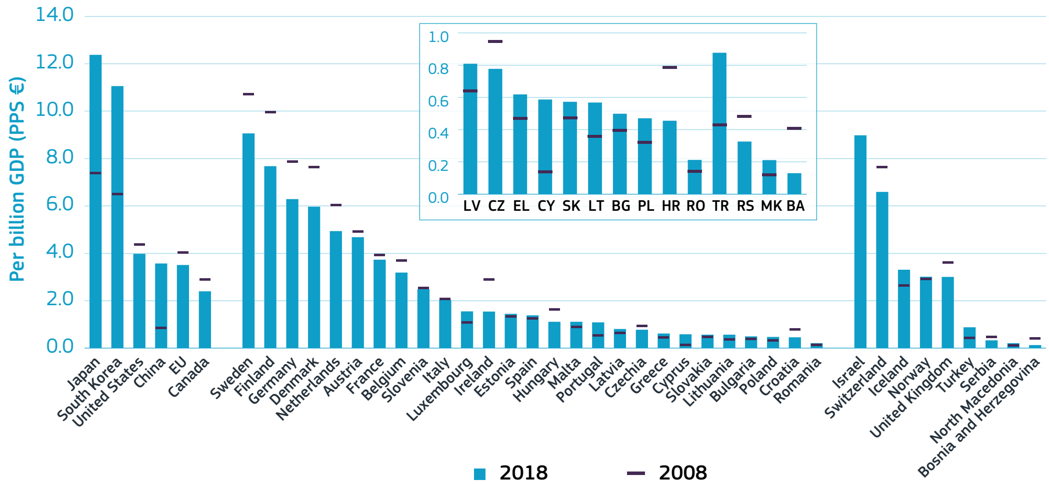
Notes: [1]Patent Cooperation Treaty (PCT) patents, at the international phase designating the European Patent Office. Fractional counting method, inventor's country of residence and priority date used.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-3-10.xlsx

Within the EU, performance varies considerably across Member States, with a persistent regional divide. While northern and western EU countries like Sweden, Finland and Germany perform well, southern and eastern countries like Romania, Croatia and Poland perform poorly. Between 2008 and 2018, about half of the Member States reported a stagnation or decline in the share of patent applications per billion GDP (Figure 6.3-11). Among those, Finland displayed the biggest drop, with -2.3 patent applications per billion GDP, followed by Sweden and Denmark, both with -1.7. In percentage terms, however, Ireland declined by 47 % and Croatia 42 %. Conversely, Portugal and Cyprus increased the most during the same period.

It is important to highlight that patenting is affected by several structural factors. These include: the share of the manufacturing sector in the economy as manufacturing companies tend to patent more than service-sector companies (EPO and EIPO, 2019); the technological intensity of both the manufacturing and the service sectors; the size distribution of the enterprises (larger enterprises tend to have higher patent propensity); and the location of the company's headquarters (patenting tends to be carried out in countries with favourable legislation).

Figure 6.3-11: Patent applications filed under the PCT[1] per billion GDP (PPS €), 2008 and 2018



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Science-Metrix using EPO PATSTAT database, Eurostat and OECD

Notes: [1]PCT patents at the international phase designating the European Patent Office. Fractional counting, inventor's country of residence and priority date used.

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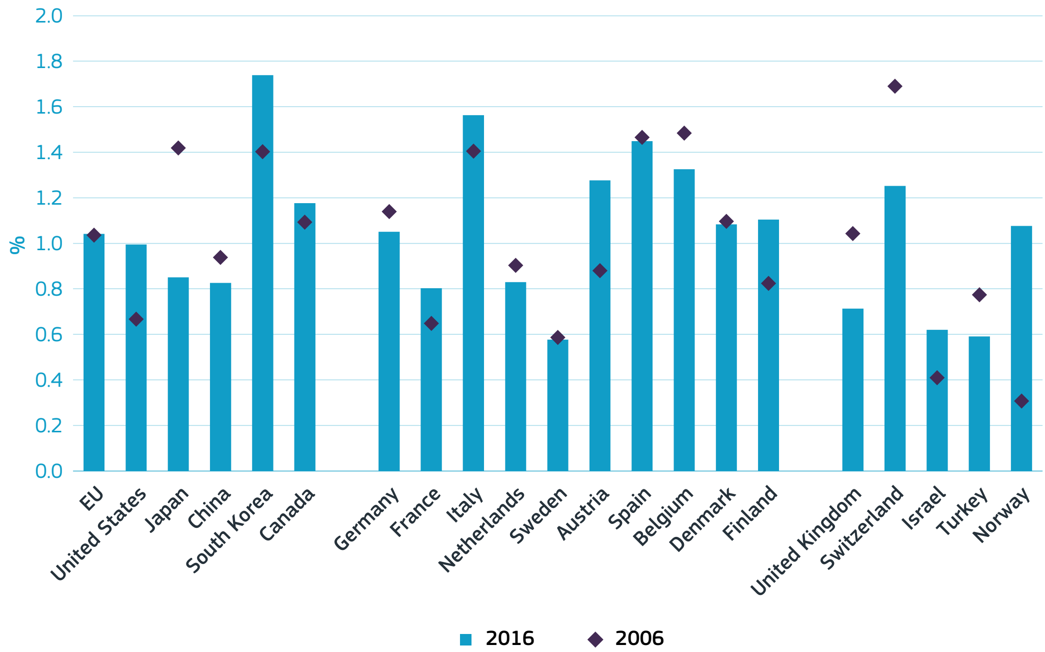
Particularly novel patented innovations will be the subject of greater citation. For this reason, the number of citations received by a patent (forward citations) has been used in the literature as a measure of the innovative output embodied in the technology (Alan C. Marco, 2007). In addition, an analysis of patent citations is a core methodology in the study of knowledge diffusion (Alcácer, 2006). Outside the EU, South Korea is the top performer, with 1.7 % of its patent applications to the EPO among the top 1 % most cited patent applications worldwide (Figure 6.3-12). Canada (1.2 %) is in second place, followed by the EU (1 %). The US is next with a share of less than 1%, followed by Japan and China. However, in absolute terms, the EU has the highest number of patent applications overall due to a European bias in using the EPO. Among the top 10 EU countries with the highest number of patent applications to the EPO, Italy has the highest share. On the opposite side, Sweden is the EU country with the lowest share.

Between 2006 and 2016, patent quality in the EU has remained stable. On the other hand, Japan showed a significant decline and South Korea and the US a considerable increase. Out of the 10 EU countries analysed, both Finland and Austria displayed a substantial increase. The figures suggest that, despite the lower number of patent applications overall, countries like South Korea, Spain, Belgium or Norway, are able to have, proportionally, more patent citations, than countries with a bigger number of patent applications. The only exceptions are Italy and Switzerland with high numbers of patent applications of higher quality.

Figure 6.3-12: Top 1% most cited patent applications to the EPO[(1)], 2016 and 2006



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Science-Metrix using EPO PATSTAT database

Note: [(1)]Patent counts are based on the priority date, the inventor's country of residence and fractional counts. This indicator represents the WIPO technology field and year normalised counts of the number of patents cited by other patents. This indicator is normalised by year and WIPO technology field to account for variations in patterns of citations between fields and years. Only the top 10 EU countries in terms of patent applications to the EPO were considered. Countries ranked by the number of patent applications to the EPO in 2016.

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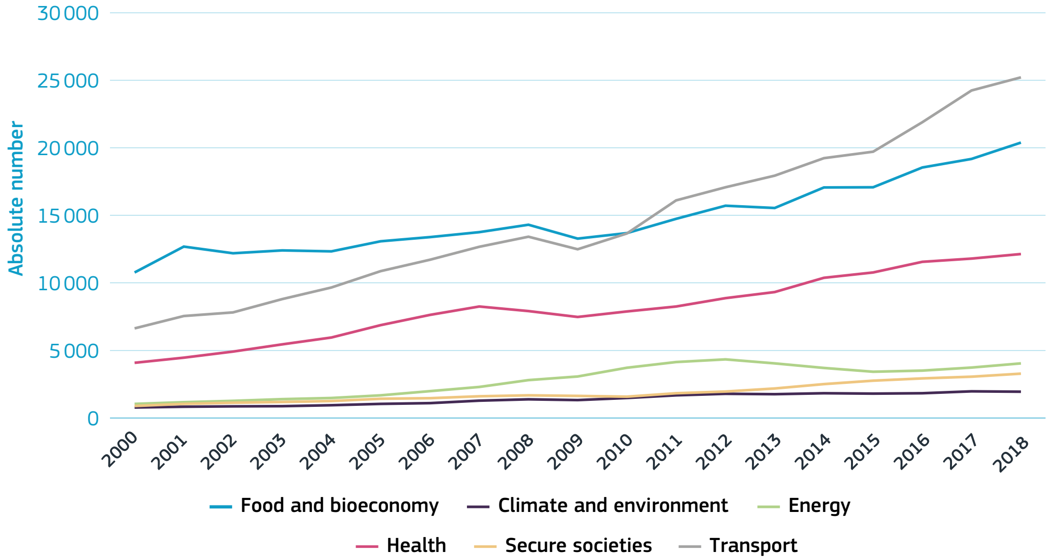
The world's number of patent applications filed under the PCT increased in all Societal Grand Challenges over time. The Societal Grand Challenges, defined under Horizon 2020, are one way of assessing how innovation contributes to addressing sustainability and the challenges our society is facing. Between 2000 and 2018, the fields with the highest number of patent applications filed under the PCT were transport and food and bioeconomy. In 2018, they recorded more than 25 000 and more than 20 000 patent applications, respectively. Health came third with around 12 000 patent applications in 2018.

All three fields have a high propensity for patenting[7]. Despite a decline between 2012 and 2015, due to a change in the methodology, energy was the field that increased the most in relative terms (+288 %). Transport showed the second-largest percentage increase (280 %), and the largest growth in absolute terms, with about 18 500 more patents in 2018 than in 2000, overtaking food & bioeconomy in 2010.

7 EPO and EIPO (2019), IPR-intensive industries and economic performance in the European Union.

Figure 6.3-13: Total number of patent applications filed under the PCT in the world by Horizon 2020 Societal Grand Challenge[(1)], 2000-2018



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Science-Metrix using EPO PATSTAT database

Notes: [(1)]PCT patents at the international phase designating the European Patent Office. Fractional counting, inventor's country of residence and priority date used.

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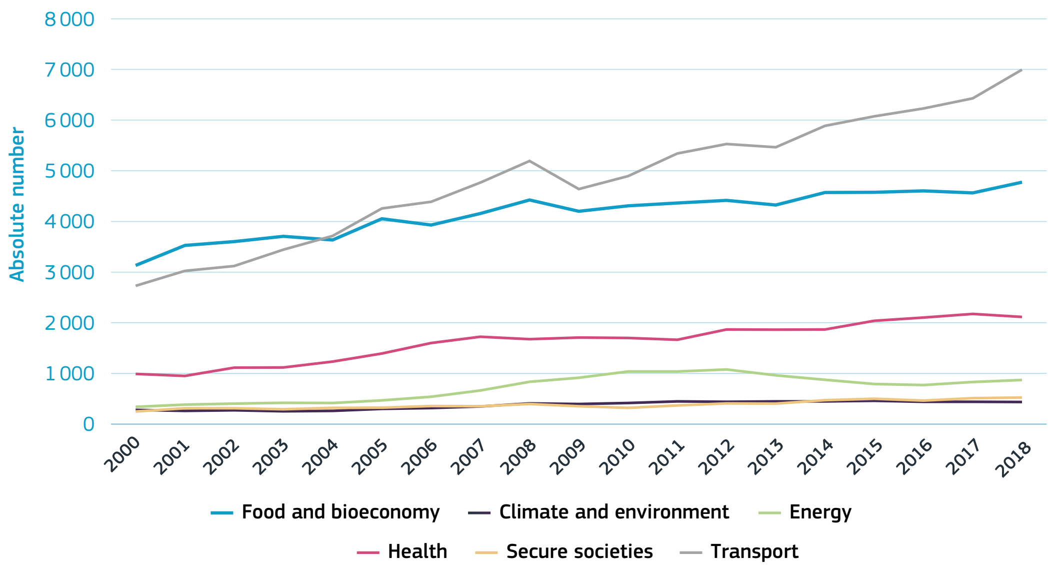
The EU was unable to match the level of growth seen worldwide. Figure 6.3-14 shows that the number of patent applications in the EU has remained stable over time, especially in the fields of food and bioeconomy, climate and environment, and energy. The only exception is transport, which continued to increase significantly, overtaking food and bioeconomy in 2004. In relative terms, however, four fields (energy, health, security and transport) more than doubled their number of patent applications. Food and bioeconomy and climate and environment increased by 53% and 55%, respectively, between 2000 and 2018.

Figure 6.3-14: Total number of patent applications filed under the PCT[(1)] in the EU by Horizon 2020 Societal Grand Challenge, 2000-2018



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Science-Metrix using EPO PATSTAT database

Notes: [(1)]PCT patents at the international phase designating the European Patent Office. Fractional counting, inventor's country of residence and priority date used.

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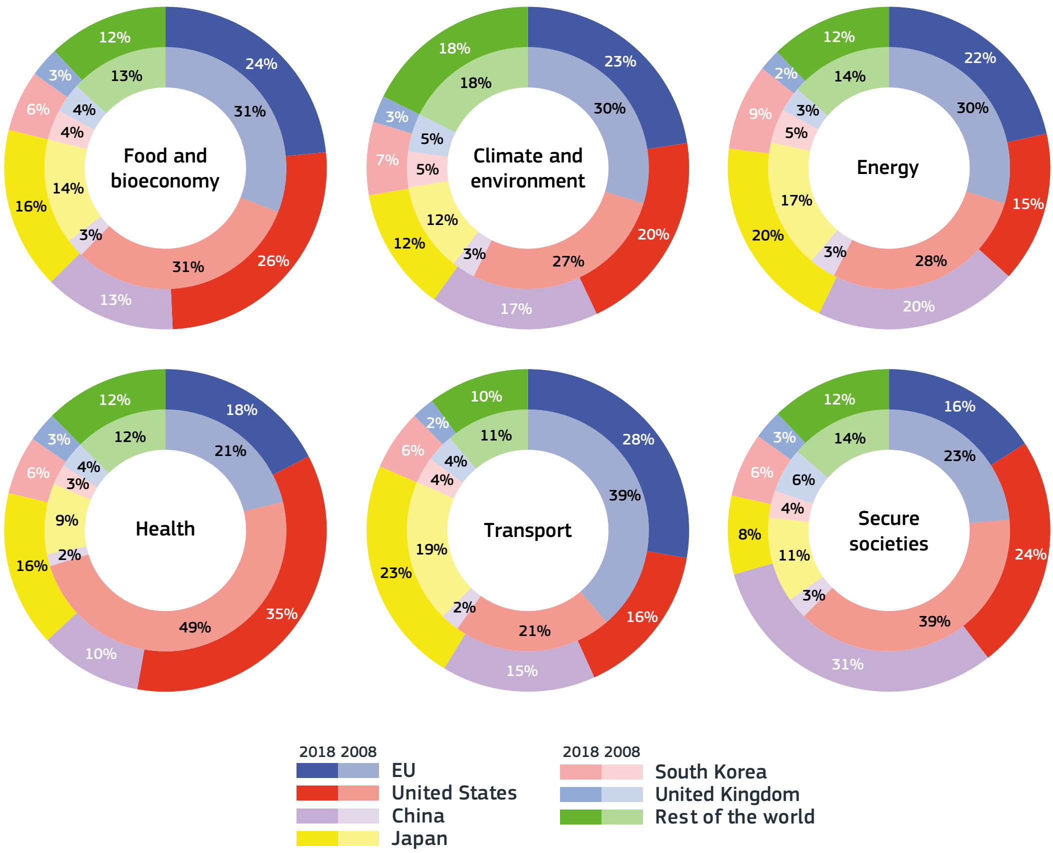
The EU remained the top worldwide patent applicant in the fields of climate & environment (23%), energy (22%) and transport (28%). However, the analysis per SGC, displayed in Figure 6.3-15, shows that the EU experienced significant losses in the world shares in all fields between 2008 and 2018. The biggest decline was in transport, with minus 11 percentage points (p.p.), despite an increase in the absolute number of patent applications over the same period. The US, while maintaining leadership in the fields of health and food & bioeconomy, followed the same pattern, with an even stronger decline, especially in security (-15 p.p.), health (-14 p.p.) and energy (-13 p.p.).

China increased its world share in all fields. However, unlike scientific production, where it leads in almost all fields, China only topped the rank in security, with an impressive increase of more than 28 p.p., from 3% in 2008 to 31% in 2018. China's performance also improved significantly in the energy sector, with an increase of more than 17 p.p. Japan, despite being weak in scientific production, stands out strongly in technology output, with important shares in the societal challenges of health, energy, and transport.

Figure 6.3-15: Share in the world (%) of patent applications filed under the PCT[1] by country/region and Horizon 2020 Societal Grand Challenge, 2018 (exterior) and 2008 (interior)



Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Science-Metrix using EPO PATSTAT database

Notes: [1]PCT patents at the international phase designating the European Patent Office. Fractional counting, inventor's country of residence and priority date used.

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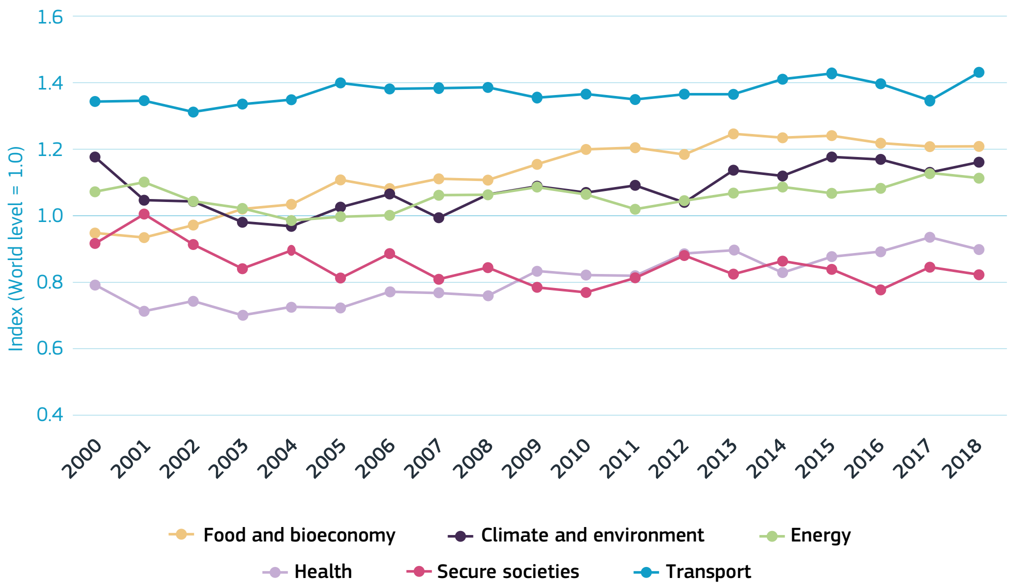
Figure 6.3-16: EU specialisation index[1] compared to the world by Horizon 2020 Societal Grand Challenge, 2000-2018



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Science-Metrix using EPO PATSTAT database

Notes: [1]Specialisation refers to the intensity in the EU for a given societal challenge relative to the intensity in the world for the same societal challenge. Fractional counts and date of application used.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-3-16.xlsx

Compared with the world, the EU is more specialised[8] in the fields of energy, climate and environment, food and bioeconomy and transport. These results might be explained by the very strong patent-intensity automotive sector in some Member States (such as Germany), as well as by some strong performance in renewables and energy-efficiency sectors (Hoogland et al., 2021). On the other hand, the EU is less specialised than the world in the fields of health and security.

Between 2000 and 2013, the EU improved substantially in food and bioeconomy, with a stagnation after that year. To a lesser extent, the EU became progressively more specialised in energy and climate and environment, especially since 2007, when the European Commission launched its Communication to limit climate change[9]. Compared with scientific publications, the EU appears to be stronger in the societal challenge of climate and environment, with both specialisation indexes above world level.

8 The Specialisation Index (SI) is an indicator of intensity in a given entity (e.g. Belgium) for a given area (e.g. health patents), relative to the intensity in a reference entity (e.g. the world or the entire output as measured by the database) for the same area. In other words, when a country is specialised in a given area, it places more emphasis, compared with the reference entity, on that area at the expense of others. An index value above 1 means that a given entity is specialised relative to the reference entity, whereas an index below 1 means the entity is not specialised. Specialisation is therefore said to be a zero-sum game: the more an entity specialises somewhere, the less it does elsewhere. To ensure that it is a real zero-sum game, the application or registration numbers used to compute the SI are based on fractional counting.

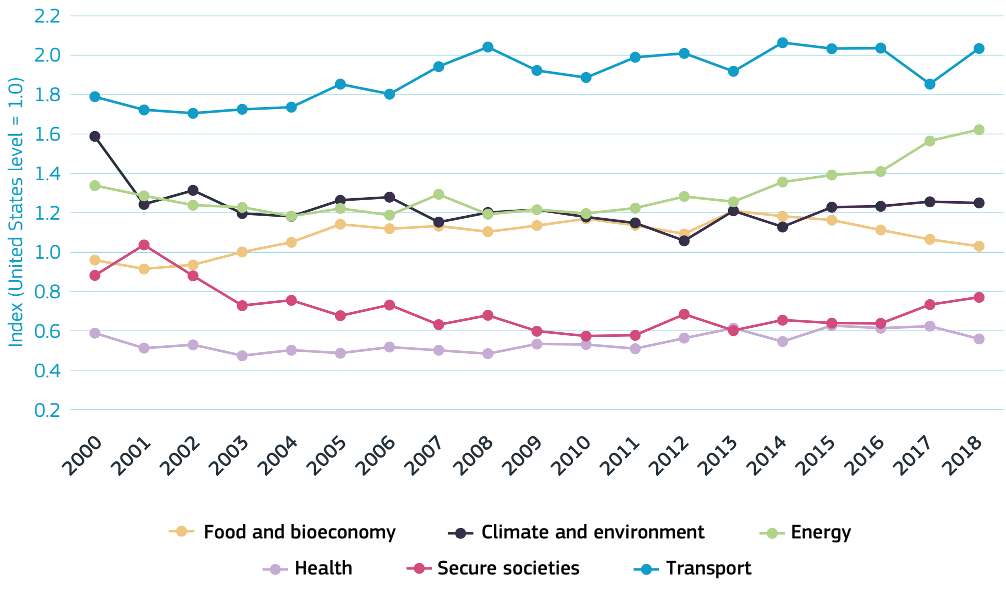
9 Communication from the Commission to the Council, the European Parliament, the European Economic and Social Committee and the Committee of the Regions - Limiting global climate change to 2 degrees Celsius - The way ahead for 2020 and beyond. EUR-Lex - 52007DC0002 - EN - EUR-Lex (europa.eu)

The EU is also more specialised in several challenges when compared with both the US and China. In particular, the EU is more specialised than the US in the challenges of energy, climate & environment, food & bioeconomy and transport (Figure 6.3-17). In addition to those, the EU is also more specialised than China in health (Figure 6.3-18). However, the EU is less specialised than both countries in the challenge of security. Over time, when compared with the US, and especially in the last years, the EU progressed in the field of energy, but lost ground in food & bioeconomy. Compared with China, energy and food & bioeconomy have been relatively stable, while secure societies and health have declined.

The EU holds a competitive advantage in health over China and in energy and climate & environment over the US. When combining the specialisation indexes of scientific publications (analysed in Chapter 6.1) with patent applications in health, the EU is more specialised than China in both cases. This gives the EU a competitive edge over China in that field. The same applies to the US for the fields of energy and climate & environment, in which the EU shows a competitive edge, as both specialisation indexes, in scientific production and patent applications, are significantly above 1.

Non-technological innovation is a major factor of competitiveness and productivity growth in the economy, notably in the service industries. However, the measurement of non-technological innovation and of innovation

Figure 6.3-17: EU specialisation index[1] compared with the United States by Horizon 2020 Societal Grand Challenge, 2000-2018

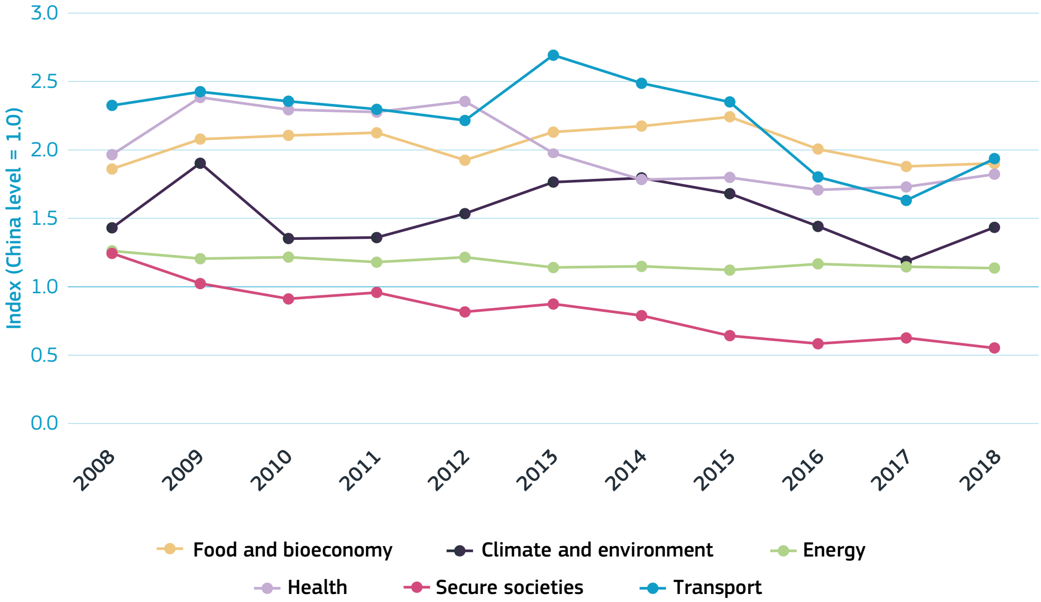


Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Science-Metrix using EPO PATSTAT database

Notes: [1]Specialisation refers to the intensity in the EU for a given societal challenge relative to the intensity in the United States for the same societal challenge. Fractional counts and date of application used.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-3-17.xlsx

Figure 6.3-18: EU specialisation index[(1)] compared with China by Horizon 2020 Societal Grand Challenge, 2008-2018



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Science-Metrix using EPO PATSTAT database

Notes: [(1)]Specialisation refers to the intensity in the EU for a given societal challenge relative to the intensity in China for the same societal challenge. Fractional counts and date of application used.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-3-18.xlsx

Read more in Chapter 13 – Part 2 on The green and digital twin transitions across EU regions *(Julie Delanote, Ludovica Massacesi, Désirée Rückert, Christoph Weiss, EIB)*

It is shown that the EU is a global leader for patenting activities at the crossroads of digital and green technologies. It also found that less developed and transition EU regions have a relatively high share of patents in green-digital technology domains: they hold fewer patents than more developed EU regions, but have a strong focus on green and digital innovation.

in the service industries is currently very poor, as traditional data sources like R&D or patents do not apply to these types of innovations (Millot, 2009). For this reason, data on other types of intellectual property rights such as trademark[10] and community design[11] applications can help assess non-technological innovation. In particular, trademarks constitute a rich and easily accessible data source; they are highly correlated with various innovation variables (patents, share of innovative sales); and they are present in almost every sector of the economy. Trademark data are then likely to convey information on two key (overlapping) aspects of innovation that are not well covered by traditional indicators: innovation in the service sectors and marketing innovation (Millot, 2009). In addition, trademark analysis can contribute in capturing relevant aspects of innovation phenomena and the process of industrial change (Mendonça et al., 2004); and trademarks for brand creation relate more often to product innovation (Flikkema et al., 2019). On the other hand, design innovation is a pillar of product differentiation, especially in crowded marketplaces (Sarlangue, 2021).

The innovation divide among EU Member States is less pronounced in trademarks and community design applications than in patent applications. Although the most innovative countries, like Denmark and Finland, are top performers in patent applications and also in trademarks and community designs, small countries like Malta, Cyprus, Estonia or Luxembourg tend to perform particularly well in one or both types (trademarks and community designs) of IPRs (Figures 6.3-19a and 6.3-20a). This might be due to the innovation capacity of firms in less technology-oriented sectors, favourable legislation, easy procedures and attractive taxation systems for IPR applications.

The relative importance of some sectors in the economy also plays a significant role. For example, high propensity sectors for trademarks like business services and advertisement have a substantial share in Luxembourg, while the gaming and software sectors are relevant in Malta. Comparing countries of similar size, Italy stands out with a good performance in both types of IP, primarily due to its strong fashion and alcoholic beverages sectors, for which both community designs and trademarks are important.

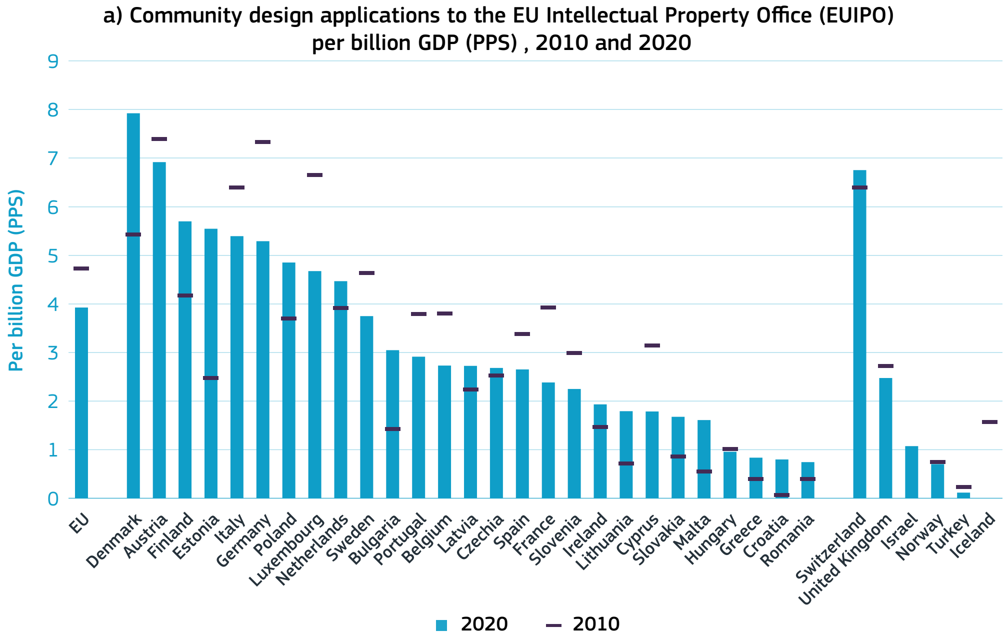
China is the top performer in both types of IP applications. Using data from the World Intellectual Property Office (WIPO), the EU comes third in terms of community designs, well behind China and South Korea. In terms of trademarks, the EU lags behind Japan and Canada. In contrast with patent applications, the EU performs better than the US in the two types of IP analysed (Figures 6.3-19b and 6.3-20b).

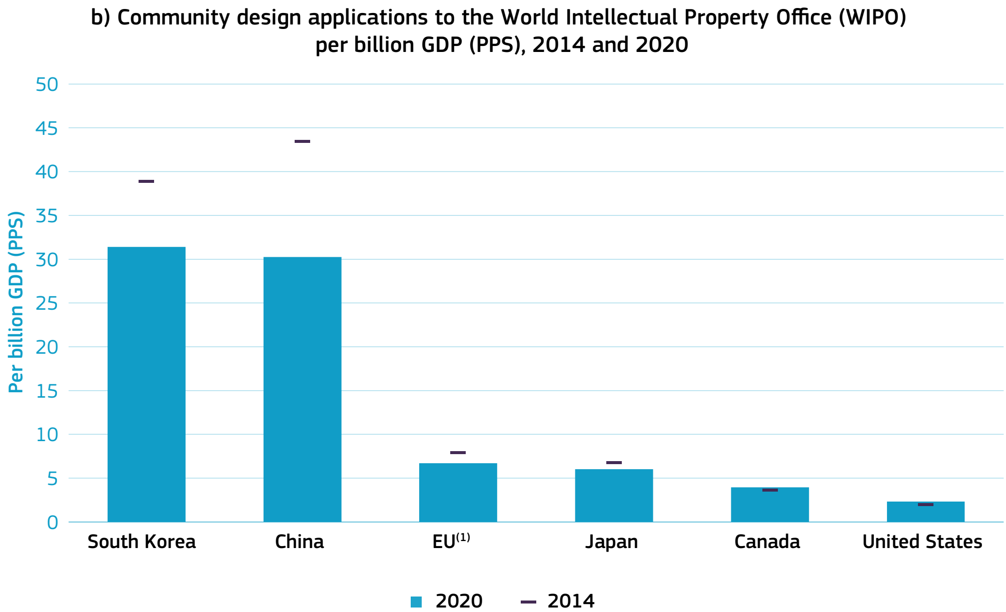
Over time, the EU improved in trademark applications, but declined in community designs. Most Member States reported an increase in their application intensities, especially for trademarks. Significant improvements were seen in Malta, Estonia and Cyprus for trademarks, and in Denmark and Estonia for community designs. China, despite showing a similar trend, reported a much larger degree of variation, with a big drop in community designs, but an impressive rise in trademarks – i.e. from an intensity similar to that of Canada and South Korea in 2014, to more than double this in 2020.

10 A trademark is a sign capable of distinguishing the goods or services of one enterprise from those of other enterprises. Trademarks can be words, pictures, stylised words, logos, a colour or colour combination, a shape, a sound or a combination of those signs. (source: WIPO)

11 A registered Community design (RCD) is an exclusive right that covers the outward appearance of a product or part of it. It covers the visual appearance of a product, part of a product and/or its ornamentation, i.e. a design covers the appearance of a product but cannot protect its functions, which fall under the regime of patent protection. (Source: EUIPO)

Figure 6.3-19a and 6.3-19b: Community design applications





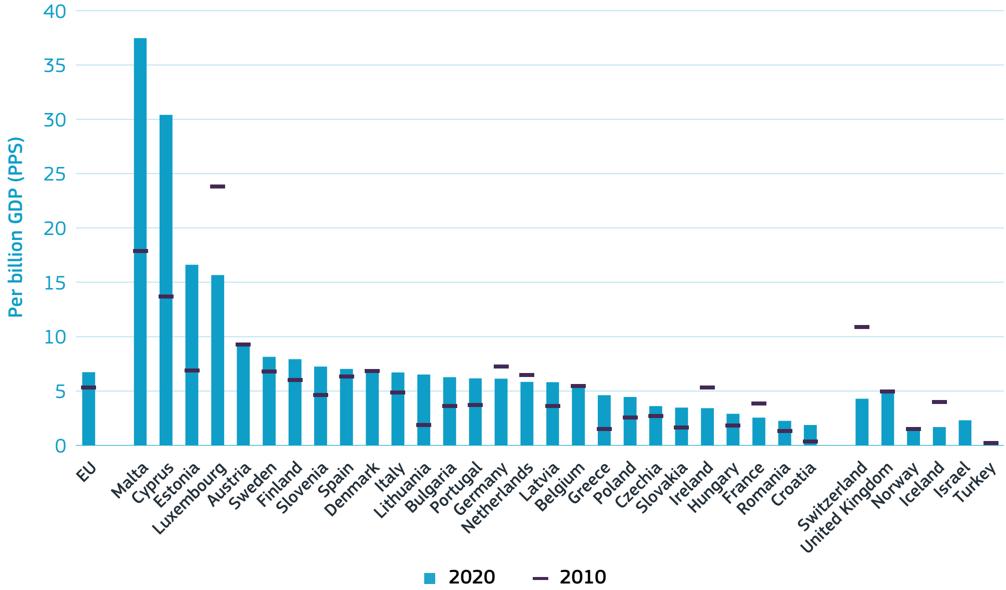
Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Science-Metrix using data from EUIPO database, Eurostat, OECD and EIS 2021

Note: [(1)]Figures for international comparison come from the European Innovation Scoreboard 2021, which uses data from WIPO to avoid European bias.

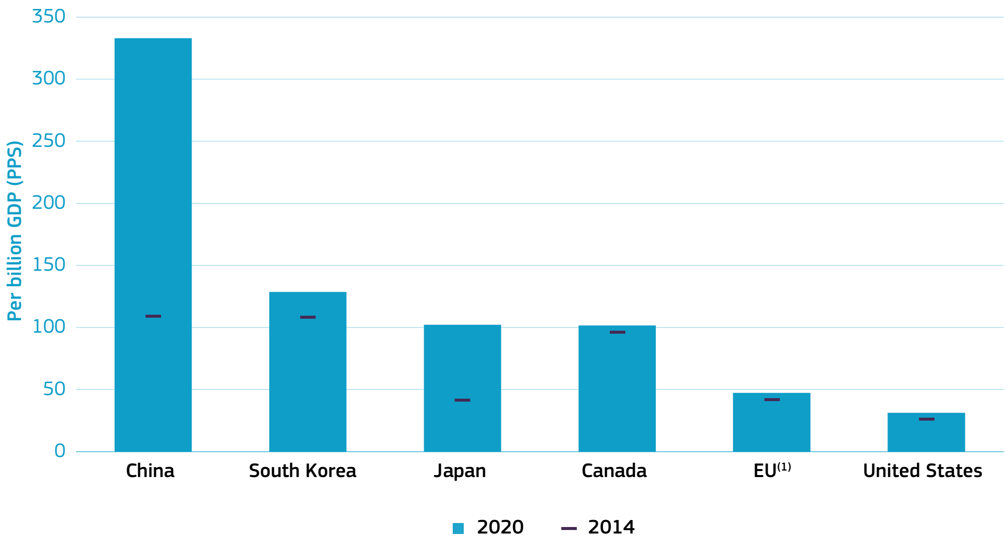
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-3-19.xlsx

Figure 6.3-20a and 6.3-20b: Trademark applications

a) Trademark applications to the EU Intellectual Property Office (EUIPO) per billion GDP (PPS), 2010 and 2020



b) Trademark applications to the World Intellectual Property Office (WIPO) per billion GDP (PPS), 2014 and 2020

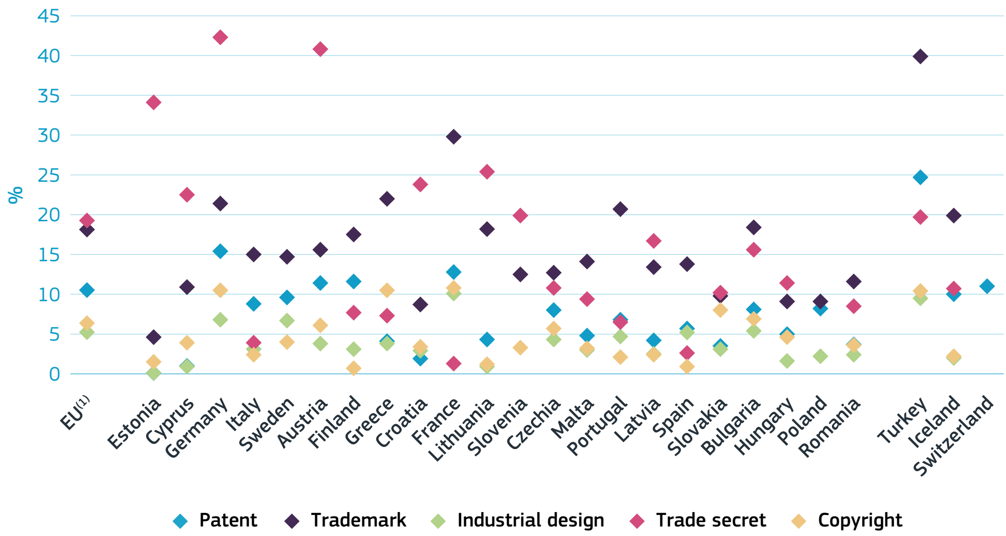


Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Science-Metrix using data from EUIPO database, Eurostat, OECD and EIS 2021

Note: (1)Figures for international comparison come from the European Innovation Scoreboard 2021, which uses data from WIPO to avoid European bias.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-3-20.xlsx

Figure 6.3-21: **Share of innovative enterprises that applied for IPR, 2016-2018**



Science, Research and Innovation Performance of the EU 2022

Source: Eurostat, Community Innovation Survey 2018 (online data code: inn_cis11_ipr)

Note: (1)EU value is calculated by DG Research and Innovation based on the availability of data per Member State. Countries are ranked by their share of innovative enterprises.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-3-21.xlsx

Overall, trade secrets[12] and trademarks were the most commonly used IPR by innovative enterprises in the EU for the period 2016-2018. Based on the Community Innovation survey data, countries with the highest share of innovative firms (such as Estonia, Cyprus and Germany) are characterised by the largest use of trade secrets and trademarks (Figure 6.3-21). These findings might be explained by the fact that trade secrets and trademarks can be applied to both products/ services and processes that are new to the market and new to the firm (Wajsman et al., 2017), thereby increasing the scope of these types of IP for innovation protection.

Regarding patent applications by innovative enterprises, Germany, France, Austria, and Finland have the highest values, with shares between 10% and 15%, in line with previous findings. Despite having the highest share of innovative enterprises, Estonia shows very low shares of these enterprises applying for IP other than trademarks. As mentioned before, differences in the dominant economic sector to which innovative companies belong and variations in IPR legislation can explain the variation across countries.

12 Trade secrets are intellectual property (IP) rights on confidential information which may be sold or licensed. In general, to qualify as a trade secret, the information must be: commercially valuable because it is secret; be known only to a limited group of persons; and be subject to reasonable steps taken by the rightful holder of the information to keep it secret, including the use of confidentiality agreements for business partners and employees. (Source: WIPO)

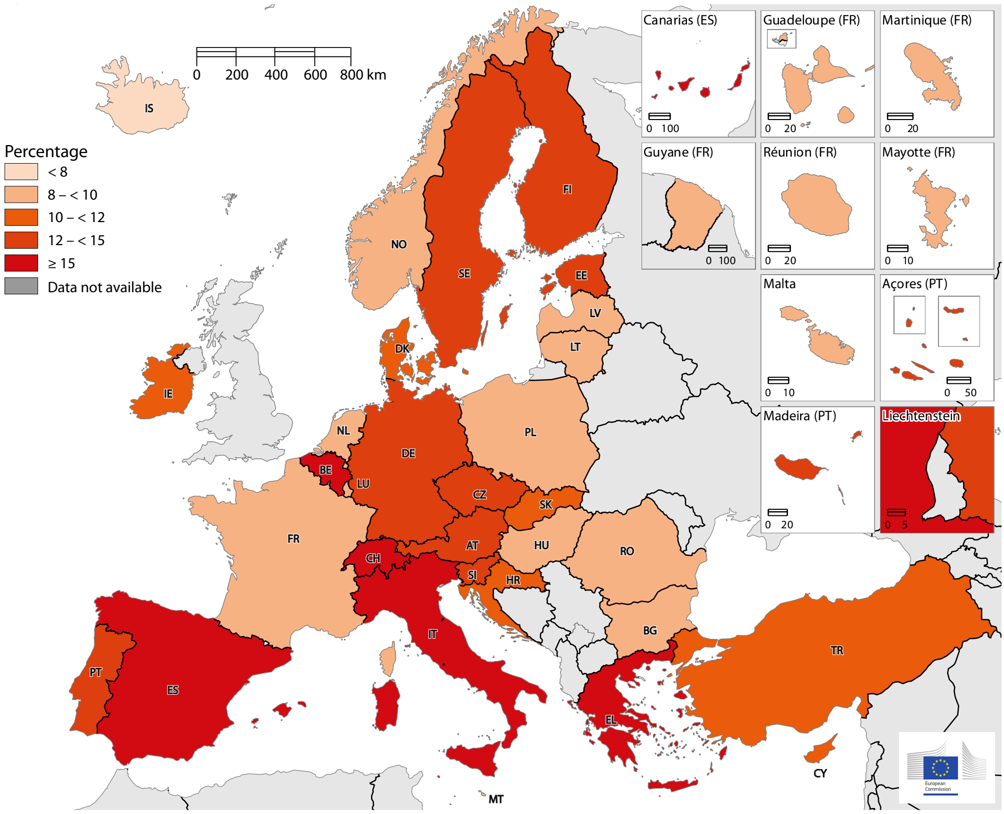
3. Economic impact of innovation

Innovation is a key driver of economic growth. The link between innovation and economic growth and the impact of innovation on productivity have been investigated by many economists and are analysed in chapter 4.1. Innovative products and processes tend to generate more output with the same input (i.e. increase productivity). As productivity rises, businesses profits rise, more goods and services are produced, wages increase, and consumers can buy more – in other words, the economy grows. However, in some cases, it has been noticed that large investments in innovation-related activities have generated little economic return in terms of new products, competitiveness, growth and employment (Edquist and McKelvey, 1998). Research on this phenomenon, known as the 'innovation paradox', suggests that the increasing dependence on a small number of large firms can negatively affect the long-term productivity potential of national economies (Fragkandreas, 2021). This section provides evidence on the economic impact of innovation in EU Member States and selected global competitors.

In 2018, the share of turnover from new or significantly improved products in the EU was 12.9%, slightly higher compared with 2016 (+ 0.4 p.p.). The highest shares are recorded in southern European countries such as Greece (23%), Italy (16.9%) and Spain (16.1%). Compared with the previous reporting period 2014-2016, 19 out of 27 Member States showed an increase in their shares. Greece achieved the largest improvement (7 p.p.), followed by Sweden (+ 5 p.p.) and Denmark (+ 5 p.p.). On the opposite side, Slovakia dropped by 9 p.p., and Ireland by 6.5. Luxembourg, a strong innovator according to the latest edition of the EIS, is ranked last in this indicator. Similarly, the Netherlands, despite its strong innovation system, ranks fourth.

The more innovative enterprises, the more the turnover from innovation. Figure 6.3-23 shows that the level of innovation of an economy, measured by the share of innovative enterprises, is positively correlated with the economic output of the innovation activities, measured by the share of turnover from innovation. Exceptions such as Spain, Romania and others (where the share of turnover from innovation corresponds to a low share of innovative enterprises) may indicate that innovation is performed mainly by a few large companies, while most SMEs do not innovate. The opposite trend (i.e., share of innovative enterprises corresponding to a relatively low share of turnover from innovation) observed, for example, in Estonia or Luxembourg, may be linked to the type of innovation and the economic sectors of the innovative enterprises.

Figure 6.3-22: Map of share (%) of turnover of innovative enterprises from new or significantly improved products(1), 2016-2018



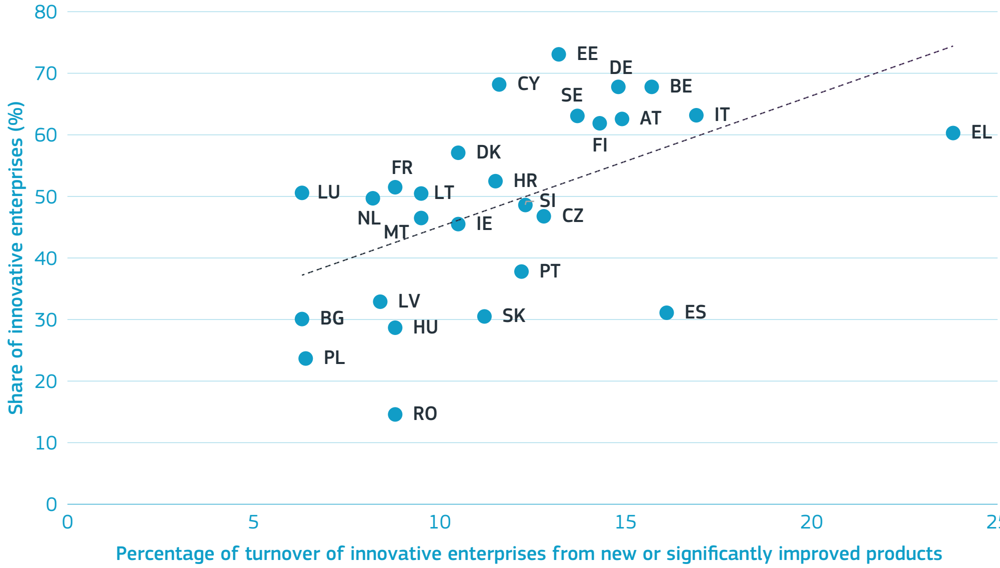
Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Eurostat - Community Innovation Survey 2018 (online data code: inn_cis11_prodt)

Note: (1)Total turnover of new or significantly improved products as a percentage of total turnover.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-3-22.xlsx

Figure 6.3-23: Share of innovative enterprises compared with percentage of turnover from innovation



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Eurostat - Community Innovation Survey 2018 (online data code: inn_cis11_prodt and inn_cis11_bas)
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-3-23.xlsx

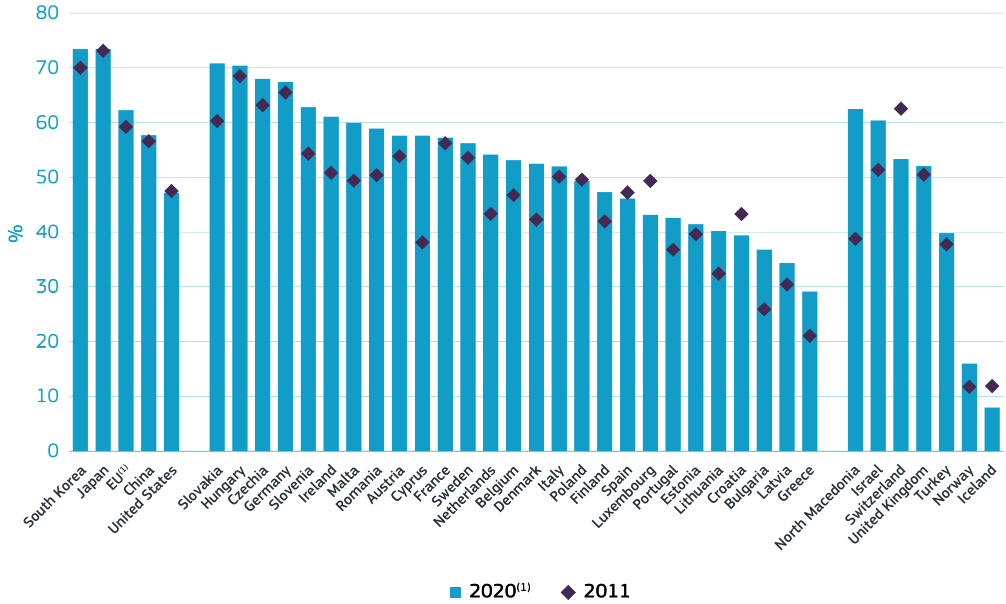
Scientific evidence shows that medium-and-high-technology products are positively associated with economic growth, productivity and welfare (Bello et al., 2022). The indicator on the exports of medium-and-high-technology products as a percentage of total product exports measures the technological competitiveness of a country, but also reflects the ability to commercialise the results of research and innovation products. On the other hand, the indicator on exports of knowledge-intensive services aims to capture the competitiveness of the services sector, by reflecting the ability of an economy to export services with high levels of value added and successfully take part in knowledge-intensive global value chains. Both indicators are part of the innovation output indicator.

In 2020, about 62 % of total EU exports concerned medium-and-high-technology products. The EU is third among its global competitors in the exports of medium-and-high-technology products as a percentage of total product exports (excluding intra-EU trade). Although the EU share has improved since 2011 by 3 p.p.[13], it has not reached the levels of Japan and South Korea, both leading with 73.4 % thanks to their strong ICT and automotive sectors. However, the EU remains ahead of the US and China.

13 The increase in MHT export share between 2011 and 2020 is mainly driven by an increase in the total value of MHT exports. No COVID-19 effect was detected.

Within the EU, Slovakia and Hungary report the highest share (both above 70%), followed by Czechia and Germany. The high performance of these countries, except for Germany, results mainly from the presence of foreign-affiliated companies in the automotive, machinery, and electrical and electronic equipment sectors, which jointly dominate their exports. Noteworthy are the increases in Cyprus, Bulgaria, the Netherlands, Slovakia, Malta, Ireland, and Denmark (with more than 10 p.p. since 2011). Another important finding is the stagnation in exports of medium-and-high-technology products as a percentage of total product exports for the major EU economies: Germany, France, Italy, and Spain.

Figure 6.3-24: Exports of medium-and-high-technology products as a % of total product exports, 2011 and 2020



Science, Research and Innovation Performance of the EU 2022

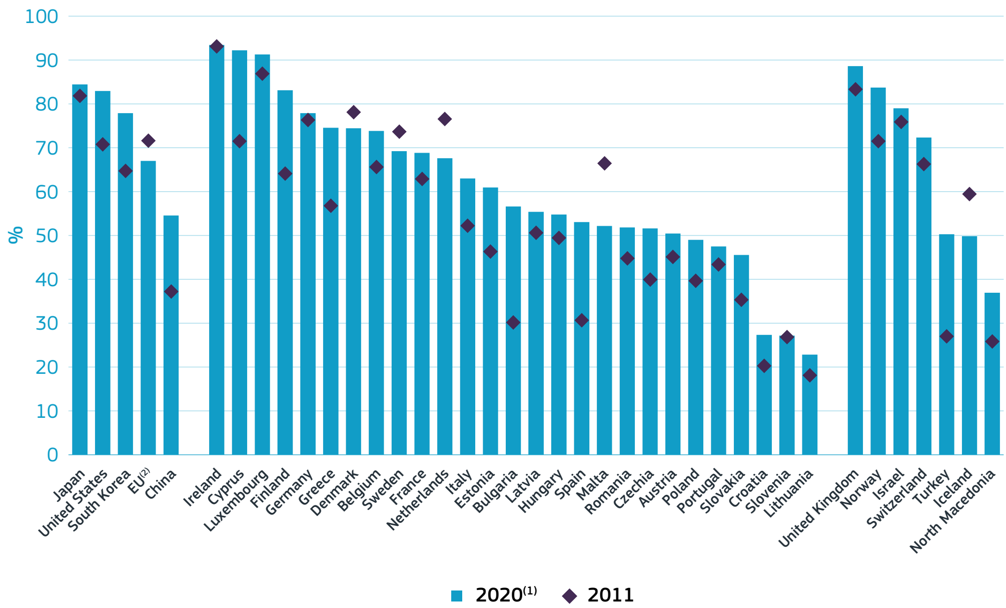
Source: European Commission, DG Joint Research Centre based on Eurostat, Comext 'DS-018995' and UN Comtrade (Bello, M. et al, 2022)

Note: (1)Two sets of values are available: for worldwide and for European comparison. The values for worldwide comparison are shown in the graph. The value for EU comparison for 2020 is 57.7%.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-3-24.xlsx

In 2020, 67% of EU services exports were knowledge-intensive. Due to a decrease of 4.5 p.p. since 2011, the EU lost second position and fell behind Japan, the US and South Korea, but remained ahead of China. Interestingly, the better performance of the EU, when excluding intra-EU trade, indicates that the share of knowledge-intensive services exported outside the EU is proportionally larger than the share of knowledge-intensive services exported to EU Member States (Bello et al., 2022). The top-performing countries globally with shares between 89% and 94% are Ireland, Cyprus and Luxembourg, followed by the UK. Within the EU, all but four Member States (Malta, the Netherlands, Sweden, and Denmark) have increased their performance since 2011. The EU countries experiencing the largest increase are Bulgaria, Spain, and Cyprus. By contrast, the largest drop was observed in Malta.

Figure 6.3-25: Exports of knowledge-intensive services as a % of total service exports, 2011 and 2020



Science, Research and Innovation Performance of the EU 2022

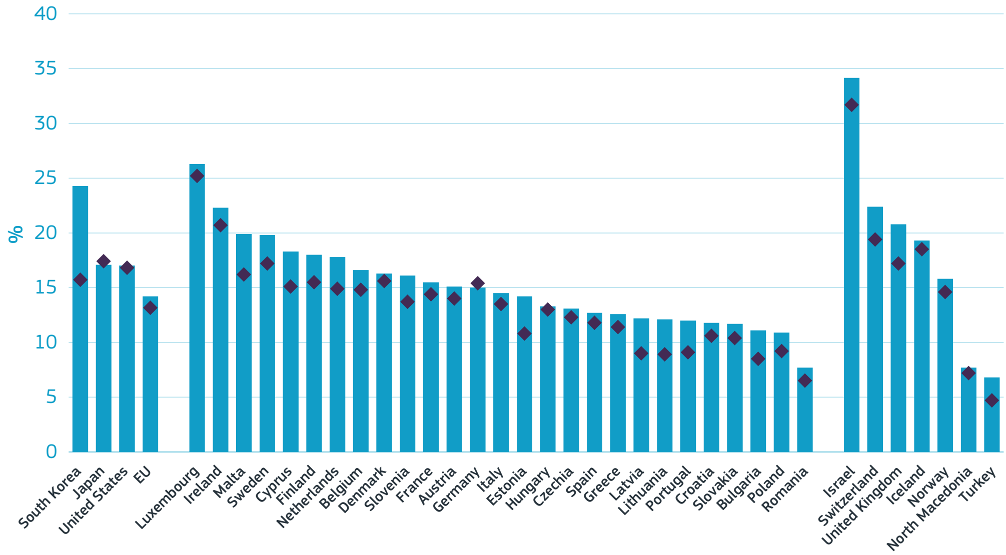
Source: European Commission, DG Joint Research Centre based on Eurostat (bop_its6_det), OECD (TISP_EBOPS2010) and ITC (Bello, M. et al, 2022)

Note: (1)IE, LU, IL, DK, IS, SI: year 2019. (2)Two sets of values are available: values for worldwide and for European comparison. The values for worldwide comparison are shown in the graph. The value for EU comparison for 2020 is 63.2%.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-3-25.xlsx

The creation of jobs in knowledge-intensive activities remains a challenge for the EU. In 2020, employment in knowledge-intensive activities in business industries as a percentage of total employment was less than 15 %, well below South Korea, Japan and the US (Figure 2.3-26). Israel is the global leader, with 34 % of its employment in knowledge-intensive activities. Among EU Member States the top performers are Luxembourg (26.3 %) and Ireland (22.3 %). The EU average showed a small increase since 2011, reflecting the improvement in all Member States, except Germany (which recorded a slight decreasing trend). Malta and Estonia experienced the largest increases, with 3.7 p.p. and 3.4 p.p., respectively, followed by Cyprus, Latvia and Lithuania. The structure of the economy has a significant impact on this indicator. Countries with strong financial and/or ICT service sectors tend to perform better than the rest.

Figure 6.3-26: Employment in knowledge-intensive activities in business industries as a % of total employment, 2011 and 2020



Science, Research and Innovation Performance of the EU 2022

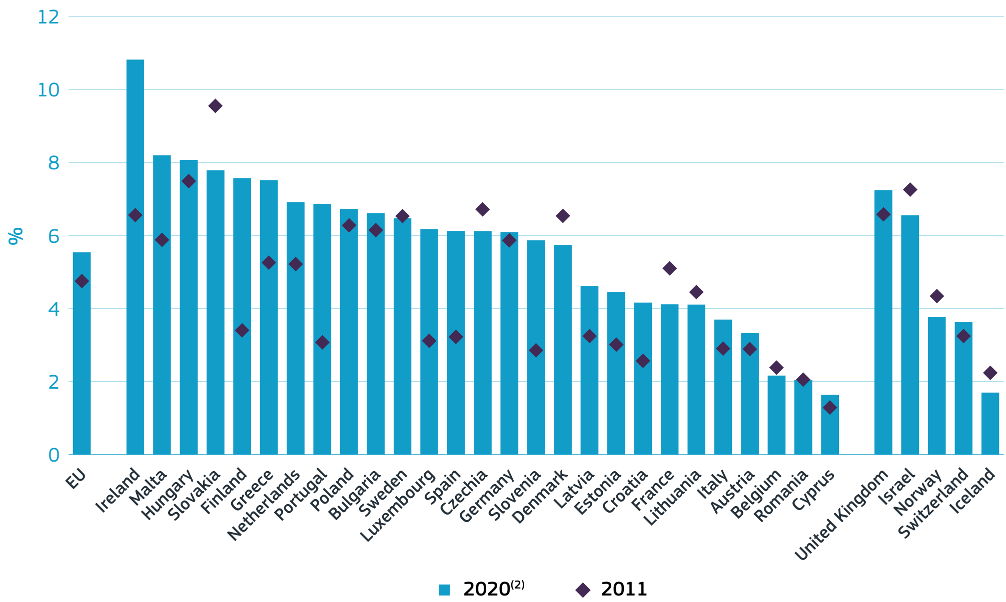
Source: European Commission, DG Joint Research Centre based on Eurostat (online data source: htec_kia_emp2) Japan Statistical Office, US BLS CBP and OECD (Bello, M. et al, 2022)

Note: (1)KR: year 2015. IL: year 2018.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-3-26.xlsx

Member States' capacity to rapidly transform their economies in response to new socio-economic needs varies significantly. The employment share in the fast-growing enterprises in innovative sectors is used as a proxy to measure this capacity. In 2019, Ireland was the top EU performer (10.8%), followed by Malta (8.2%) and Hungary (8.1%) (Figure 6.3-27). Looking at the evolution over the period 2011-2019, most EU countries improved their performances, leading to a 1 p.p. increase in the EU average. Ireland is again at the top of the ranking, reporting the highest growth over the period considered. Finland and Portugal follow. Conversely, the most significant drops are observed in Slovakia, France, Denmark, and Czechia. Interestingly, countries with strong innovation systems (according to the European Innovation Scoreboard) such as Belgium, Austria, and France score very low in this indicator, while countries experiencing strong economic changes (e.g., Eastern Member States, Ireland or Greece) have better scores and growth performance. This pattern may suggest that the indicator captures both the dynamism of the economy and the overall performance of innovative sectors (IOI).

Figure 6.3-27: Employment in fast-growing enterprises[1] in the top 50% most innovative sectors as a% of total employment, 2011 and 2020



Science, Research and Innovation Performance of the EU 2022

Source: European Commission, DG Joint Research Centre based on Eurostat (online data code: bd_9pm_r2)(Bello, M. et al, 2022)

Note: [1]Number of employees in high growth enterprises measured in employment (growth by 10% or more). [2]Data for 2020 were in some cases partly available. Thus, for calculating the composite indicator, missing data have been estimated by replicating the data of the closest available year, (Bello, M. et al, 2022).

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-3-27.xlsx

4. Knowledge valorisation

Knowledge valorisation is becoming increasingly important. In its latest Communication *A new ERA for Research and Innovation*[14], the European Commission calls for 'strengthening innovation ecosystems for knowledge circulation and valorisation' by developing and testing a 'networking framework in support of Europe's R&I ecosystems', as well as by updating and developing 'guiding principles for knowledge valorisation and a code of practice for the smart use of intellectual property'. Collaboration, mobility and further investment are identified as key aspects to achieve a strong system for knowledge creation and valorisation.

Knowledge valorisation encompasses several dimensions. In the literature, knowledge valorisation is a broader concept than innovation because the latter only refers to a successful introduction into the market. In contrast, knowledge valorisation also includes the often long lasting chain of processes that starts with first thoughts about market introduction and the research/development steps needed to reach this goal. There is also a broader conceptualisation of knowledge valorisation, namely as a complex and interactive process in which knowledge is made ready and available, and in which interaction between knowledge institutes and firms is crucial in all stages (Geenhuizen, 2010). Knowledge valorisation, the transfer of knowledge from R&D organisations to other parties envisaging the creation of social and economic value from it, is fundamentally driven by the fact that industrial economies need to change their development paradigm from one based on resources exploitation to a new one based on knowledge and innovation (Ala et al., 2014).

In addition, a single focus on the economic dimension neglects other important impacts of research, such as the impact of knowledge on the general public and societal welfare (van de Burgwal, 2019).

Knowledge valorisation is sometimes confused with knowledge transfer. However, whereas knowledge transfer highlights the formal transfer of academic knowledge to parties in the commercial sector for economic benefit, knowledge valorisation takes a broader scope and looks at the creation of societal value from knowledge by translating research findings into innovative products, services, processes and/or business activities (van de Burgwal, 2019). As the European Commission's Expert Group defined it: 'Knowledge Transfer (KT) aims to maximise the two–way flow of technology, IP and ideas. In turn this enables companies (existing and new) or other non–academic organisations and the public sector, to drive innovation leading to economic and social benefit and enables publicly funded research organisations (PROs) to advance research and teaching.' (Campbell et al., 2020).

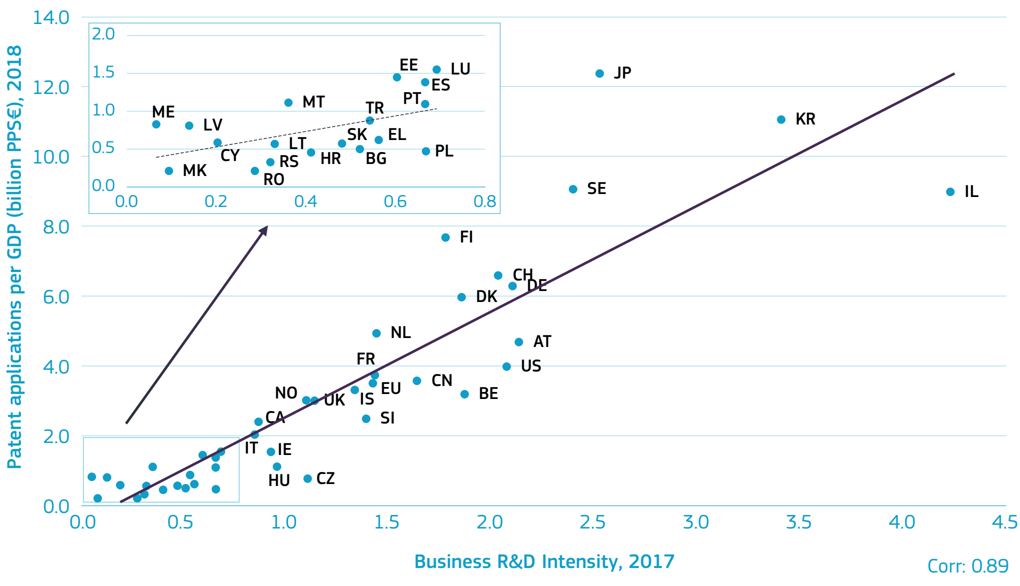
Countries with higher business expenditure in R&D tend to have higher patent applications. In 1942, Schumpeter indicated that R&D is an activity rewarded by the possession of a patent that generates profits for its owner. And in 1990, economist Paul Romer admitted that a patent is an instrument for encouraging R&D and the transfer of scientific knowledge.

14 COM(2020), Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions: A new ERA for Research and Innovation. EUR-Lex - 52020DC0628 - EN - EUR-Lex (europa.eu)

In other words, by assuming business investment in R&D as knowledge input and patents as knowledge output, patents can be considered a return on investing in R&D (Mohnen, 2019). This suggestion is confirmed by the strong correlation between business R&D intensity and patent intensity (Figure 6.3-28). South Korea, and to a lower extent Switzerland, Germany and Denmark follow exactly the trend line, with both high levels of business expenditure in R&D and high levels of patent applications. On the lower side, a group of countries like Cyprus, Lithuania, and Turkey show both low levels of business expenditure in R&D and low levels of patent applications.

Japan, with relatively high patent intensity, seems to make the most out of its business investment in R&D. The same can be said for some EU countries like Finland, Sweden, and to some extent, Estonia. On the other hand, Israel seems unable to translate its relatively high business expenditure in R&D into more patent applications. The same situation is seen in EU countries like Czechia, Belgium, or Poland. Economic structure might be an important factor in explaining those results, with sectors with low patent propensity investing more in R&D, and vice-versa. The EU, with a similar level of patent intensity to that of China and the US, but lower business R&D intensity, seems to make more out of its business expenditure in R&D than those two

Figure 6.3-28: Patent applications filed under the PCT per billion GDP (in PPS€), 2018 and business R&D intensity, 2017



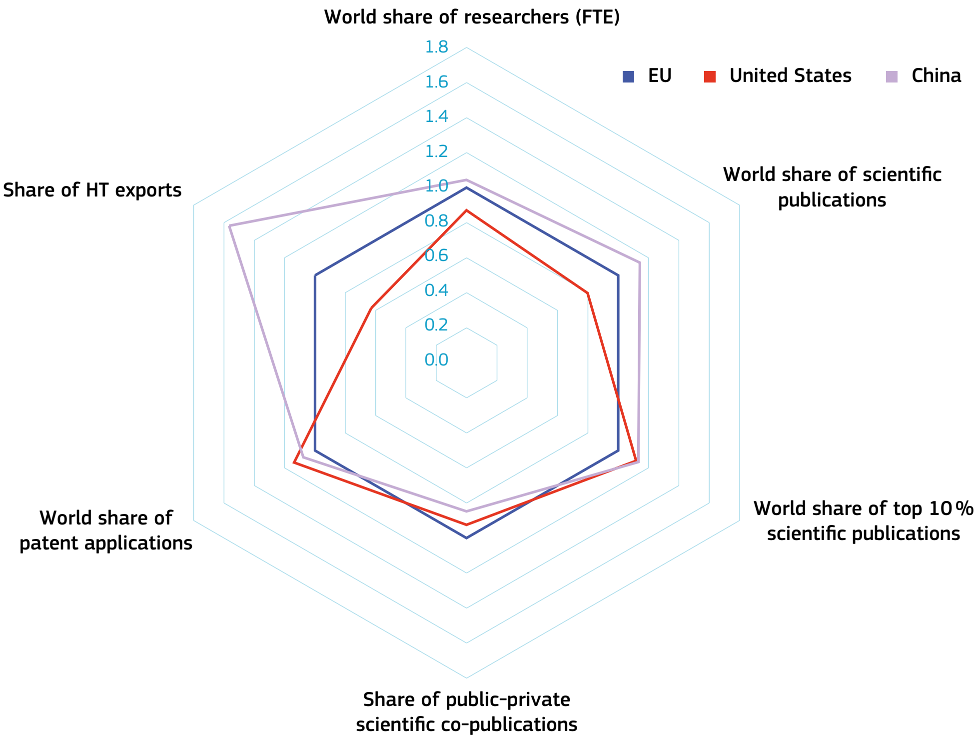
Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Science-Metrix using data from EPO PATSTAT database, Eurostat and UNESCO
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-3-28.xlsx

countries. Similarly, the relative importance of some sectors in the economy play a role. According to the latest Industrial R&D Investment Scoreboard[15], the top US R&D performers are companies in the ICT sector, while in the EU the top R&D performers are companies in the automotive and pharmaceutical sectors, which are patent intensive, but less R&D intensive.

More efforts are needed to bridge the gap between basic research, innovation and marketable solutions. When looking at Figure 6.3-29, even though the EU has a large qualified workforce and strong collaboration between academia and the business sector, the US and China outperform it in terms of patent applications. Equally worryingly, despite the enormous scientific production of the EU, especially in comparison with the US, its quality is proportionally lower than that of China and the US. In addition, the EU fails to excel in the share of high-tech exports, especially in comparison with China. If the EU wants to catch up and become more competitive internationally, it needs to promote a culture of knowledge valorisation in its R&I system, ensuring that knowledge-based institutions manage their intellectual capital effectively, and by improving the links between academia, industry, citizens, and policymakers.

Figure 6.3-29: Knowledge valorisation approach, latest available year



Science, Research and Innovation Performance of the EU 2022
Source: DG Research and Innovation - Common R&I Strategy and Foresight Service - Chief Economist Unit based on Science-Metrix using data from EPO PATSTAT and Scopus database, Eurostat, JRC, OECD and UNESCO
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-6-3-29.xlsx

15 European Commission (2021), The 2021 EU Industrial R&D Investment Scoreboard.

Read more in Chapter 15 – From Lab to Market: Evidence from Product Data
(Gaétan de Rassenfosse, EPFL)

'One key piece of information that scholars and analysts have been missing so far concerns how science translates into actual products'. Understanding how scientific results reach the market is essential to better understand the dynamics underpinning innovation ecosystems, and to provide more targeted policy instruments and incentive schemes.

The chapter investigates this issue, providing a method to trace ideas as they progress from the lab to consumers. The analysis provides interesting insights on the factors that facilitate technological transfers from academic level to full market deployment, with a focus on the European science landscape.

A strong valorisation policy relies on a toolbox of instruments that acknowledges different knowledge valorisation channels (European Commission, 2020). Many strategies, instruments and measures have been developed at European, national, and regional level by private and public players, to enhance knowledge transfer and valorisation. In the context of the 2021 consultation on the guiding principles for knowledge valorisation, stakeholders pointed out the need for an extended policy incorporating a new direction:

- Academia-industry connections and the interaction of innovative companies in different sectors provide key channels for knowledge diffusion and valorisation. The EU Framework Programmes and Member States support these collaborations through, for example, collaborative research or public-private partnerships. Digital solutions such as platforms provide new opportunities for industry cross-fertilization and for better linking the various actors in the innovation system. However, to maximise this collaboration, entrepreneurial practices, processes and skills need to be developed.
- Ensuring the valorisation of R&I-based knowledge assets is today a much broader activity based on co-creation between many actors, including local communities and citizens, in the socio-economic ecosystem. Without citizen engagement even the best-designed valorisation strategies and activities would not achieve the highest impact or support the economic, social and ecological transition in a way that includes all EU communities or regions.
- Intellectual property fosters innovation, creativity and knowledge sharing as the basis for progress, growth and employment. IP protection is a tool to balance the interests of both society and innovators. Nevertheless, the report contains recommendations for broadening the scope from management of intellectual property to intellectual asset management to cover results and products generated by R&I activities more broadly (e.g. publications, data, know-how, processes, practices, technologies, inventions, software etc.).

- A modern valorisation policy requires a change of focus from management of intellectual property in knowledge transfer activities, to knowledge valorisation and value-creation. It is vital to consider the broadest possible societal utilisation of intellectual assets generated by R&I activities and to include elements such as policy uptake, standardisation (see Box 2), tacit knowledge, social sciences, humanities and arts.

In addition, examining and sharing experiences and best practices of knowledge valorisation is a powerful way to improve national and European strategies. **The EU Knowledge Valorisation Platform[16] connects players across the EU, enabling them to share their knowledge and experiences** in putting excellent research results and data to practical use. The platform promotes cross-border peer learning and sharing of best practices. It provides a forum to stimulate cooperation across borders and sectors by involving all knowledge valorisation actors, from academia and industry to policy-makers and civil society. It enables the exchange of knowledge and expertise to support the design, implementation and evaluation of policies, investments and measures.

16 Stakeholder consultation on the guiding principles for knowledge valorisation – Report of the results https://ec.europa.eu/info/research-and-innovation/research-area/industrial-research-and-innovation/eu-valorisation-policy/knowledge-valorisation-platform_en

Box 6.3-2: The important role of standardisation

Standards help to bridge the gap between research and market and increase the probabilities of market uptake of technological innovations. Standardisation has an important role in R&I investment agendas as it helps pave the way for large-scale deployment of new and strategic technologies. Horizon Europe, the new Framework Programme for R&I for 2021-2027, will support valorising R&I results through standardisation to the highest possible extent.

As emphasised in the European Green Deal and in the New Industrial Strategy for Europe, developing new standards, coupled with increased EU participation in international standardisation bodies, is essential to boosting the competitiveness and resilience of European industry and to building a sustainable future. Standards will help to valorise and channel scientific discoveries and inventions to the green and digital transition and the EU's open strategic autonomy.

The EU Standardisation Strategy stresses the untapped potential of EU-funded pre-normative research in supporting future trends in standardisation, by allowing new technologies to create opportunities for our industries. The role of Horizon Europe is underlined as it entails a strong anticipation of standardisation needs and strong linkages between strategic priorities and pre-normative research.

The Commission is assessing how to better support researchers and innovators participating in EU-funded R&D&I projects take part in standardisation activities. It launched the Standardisation Booster, a platform to help beneficiaries – whose Horizon 2020 and Horizon Europe research results are likely to lead to the revision or creation of a standard – test the relevance of their results for standardisation. Engaging the research and innovation community early on in standards development also provides an opportunity to build expertise and skills in standardisation.

Today, researchers, spin-offs and start-ups often do not consider standardisation a priority: they are not always aware of the benefits of standardisation, they do not have the necessary resources or they consider that time spent on standardisation activities is not sufficiently rewarded. A consistent approach to facilitate standardisation activities and raise strategic awareness among researchers and innovators will be promoted by a dedicated European code of practice for researchers on standardisation.

5. Conclusions: innovation capacity in the EU is strong, but improvements are needed

Between 2020 and 2021, innovation performance, as measured by the European Innovation Scoreboard, improved for most Member States and the EU in general. Nevertheless, the performance gap between north-western and eastern and southern EU countries persists. Globally, despite improvements since 2014, the EU is still underperforming compared with South Korea, Canada, Australia, the US, and Japan, mainly due to low intellectual property applications and R&D expenditure by the business sector. Europe's insufficient patent intensity has been flagged by the innovation output indicator as the main reason for the EU falling behind Japan and the US.

Patent data are a useful tool to measure innovation performance. In 2018, around 80% of patent applications filed under the PCT worldwide came from Japan, China, the EU and the US. Over time, China showed the largest increase, overtaking both the EU and Japan in 2017. If the trend continues, China will overtake the US in the coming years. In terms of patent applications per billion GDP, in 2018, Japan and South Korea toped the ranking, followed by the US, China and the EU. However, it is important to highlight that patenting is affected by structural factors such as the share of the manufacturing sector in the economy, or the technological intensity of the manufacturing and service sectors.

The innovation divide persists across Member States, with Germany accounting for more than 40% of patent applications filed in the EU under the PCT in 2018. France came a distant second, with a share of 17%, followed by Italy (8%) and Sweden (7%). In relative terms, northern and western EU countries like Sweden, Finland, and Germany perform very well, while southern and eastern EU countries like Romania, Croatia, and Poland perform poorly. In addition, in the 2008-2018 period, about half of the Member States reported a stagnation or decline in the share of patent applications per billion GDP. However, in terms of contributions to the EU total, eastern and southern EU Member States like Portugal, Italy, Spain, and Poland increased their share between 2000 and 2018, while countries like Germany, the Netherlands, Sweden, and Finland lost some ground.

The EU remained the top patent applicant in 2018 in the fields of climate & environment (23%), energy (22%) and transport (28%) worldwide. However, the EU experienced significant losses in the world shares in all fields between 2008 and 2018. The US, while maintaining leadership in the fields of health and food & bioeconomy, followed the same pattern, with an even stronger decline. **China, on the other hand, increased its world share in all fields**, but unlike scientific production, where it leads in almost all fields, China only topped the ranking in security. Japan, despite being weak in scientific production, stood out strongly in technology output, with important shares in the societal challenges of health, energy, and transport.

The EU holds a competitive advantage in health over China, and in energy and climate & environment over the US. When combining the specialisation indexes of scientific publications with those of patent applications in health, the EU is more specialised than China in both cases. The same applies to the US for the fields of energy, and climate & environment, as both specialisation indexes, in scientific production and patent applications, are significantly above 1.

Non-technological innovation is a major factor of competitiveness and productivity growth in the economy, notably in the service industries. Data on other types of intellectual property rights, such as trademark and community design applications, can help assess non-technological innovation. The innovation divide among Member States is less pronounced in trademarks and community design applications than in patent applications. Small countries like Malta, Cyprus, Estonia, and Luxembourg perform particularly well in both trademark and community designs applications. Over time, most Member States reported an increase in their applications intensities, especially for trademarks.

The share of EU companies engaging in innovation activities increased to 50% in 2018, but the discrepancies between Member States are significant. Innovation is particularly important for large companies, as almost 80% of them reported innovation activities. In the EU, large companies are driving product innovations, as one in three in-house product innovators with market novelties belong to this category (250 or more employees). This represents about 4% of the total number of enterprises. For SMEs, important hampering factors to innovation are high costs, lack of internal finance and lack of qualified employees. However, the impact of these factors varies significantly across Member States (Community Innovation Survey, 2018).

The EU remains one of the key global manufacturers of medium-and-high-technology products, behind South Korea and Japan. In 2020, these represented about 62% of total EU exports (excluding intra-EU trade). The EU performs less well in exports of knowledge-intensive services. With 67% in 2020 and a gap of about 15 p.p. with the top scorer, the EU ranks behind Japan, the US, and South Korea. However, regarding patent applications, the EU applies for proportionally more patents in the medium and low-tech sectors; while China and the US apply for proportionally more patents in the high-tech sectors in knowledge-intensive services.

More efforts are needed to bridge the gap between research, innovation and marketable solutions. Although the EU has a large, qualified workforce and strong collaboration between academia and business, the US and China outperform it in patent applications. If the EU wants to become more competitive internationally, it needs to promote a culture of knowledge valorisation in its R&I system, ensure that knowledge-based institutions manage their intellectual capital effectively, and improve the links between academia, industry, citizens and policy-makers.

A modern policy requires a change of focus from managing intellectual property in knowledge transfer activities, to knowledge valorisation and value creation. It entails broadening the scope from intellectual property management to intellectual asset management, to cover more results or products generated by R&I. Furthermore, it needs to address all ecosystem actors involved in R&I activities, including local communities and citizens. Finally, it must develop an entrepreneurial mindset with its practices, processes and skills.

References

Ala, Soraia, Pedro Vilarinho, and COTEC PORTUGAL (2014), 'Knowledge valorization and the European Paradox: a case study', *Recent Advances in Applied Economics: 6th International Conference on Applied Economics, Business and Development (AEBD'14). Eds. Mastorakis, Nikos E., Panos M. Pardalos and Michael N. Katehakis. Lisbon: WSEAS Press.*

Alan C. Marco (2007), 'The dynamics of patent citations', *Economics Letters*, Volume 94, Issue 2, pp. 290-296, ISSN 0165-1765. https://doi.org/10.1016/j.econlet.2006.08.014

Bello, M., Caperna, G., Damioli, G. and Mathevet, I. (2022), *Innovation Output Indicator 2021*, Publications Office of the European Union, Luxembourg, JRC129410, Forthcoming.

Campbell, A., Cavalade, C., Haunold, C., Karanikic, P. and Piccaluga, A. (2020), *Knowledge Transfer Metrics - Towards a European-wide set of harmonised indicators*, Karlsson Dinnetz, M. editor(s), EUR 30218 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-76-18885-8 (online), doi:10.2760/907762 (online), JRC120716.

Campbell, D. (2021), *Policy brief D, Framework Programme contribution to knowledge transfer between the public and private sectors (in the form of co-publications and citation of publications in patents)*, European Commission, Directorate-General for Research and Innovation. https://data.europa.eu/doi/10.2777/193111

Edquist, C. and Mckelvey, M.D. (1998), *High R&D intensity without high tech products: a Swedish paradox? In: Institutions and economic change*. Cheltenham: Edward Elgar.

Emmanuelle Sarlangue (2021), 'Registered Community designs in the video game industry: a neglected yet potent tool', *Interactive Entertainment Law Review*, pp. 87-101, doi: 10.4337/ielr.2021.0002.

EPO and EIPO (2019), *IPR-intensive industries and economic performance in the European Union*, ISBN: 978-3-89605-235-3.

European Commission (2021), *European Innovation Scoreboard 2021*, Publication Office of the European Union, ISSN 2467-4427. https://data.europa.eu/doi/10.2873/340166

European Commission, Directorate-General for Research and Innovation (2020), *Research & innovation valorisation channels and tools: boosting the transformation of knowledge into new sustainable solutions*, Publications Office of the European Union, Luxembourg. https://data.europa.eu/doi/10.2777/480584

Fragkandreas, Th. (2021), *Innovation-Productivity Paradox: Implications for Regional Policy*, Background paper for the OECD-EC High-Level Expert Workshop series "Productivity Policy for Places", March 3 and 5.

Geenhuizen, Marina (2010), *Valorisation of knowledge: preliminary results on valorisation paths and obstacles in bringing university knowledge to market,* The Eighteenth Annual High Technology Small Firms Conference, University of Twente, Enschede, the Netherlands, May 27-28 2010.

Hoogland, O., Torres, P., Janzow, N., et al., (2021), *Patents as a measure of innovation performance : selection and assessment of patent indicators : provision of technical assistance and study to support the development of a composite indicator to track clean-energy innovation performance of EU members*, European Commission, Directorate-General for Research and Innovation, Publications Office of the European Union, Luxembourg. https://data.europa.eu/doi/10.2777/77424

Juan Alcácer, Michelle (2006), 'Gittelman; Patent Citations as a Measure of Knowledge Flows: The Influence of Examiner Citations', *The Review of Economics and Statistics*, 88 (4), pp. 774–779. doi: https://doi.org/10.1162/rest.88.4.774

Meindert Flikkema, Carolina Castaldi, Ard-Pieter de Man, Marcel Seip (2019), 'Trademarks' relatedness to product and service innovation: A branding strategy approach', *Research Policy*, Volume 48, Issue 6, pp. 1340-1353, ISSN 0048-7333. https://doi.org/10.1016/j.respol.2019.01.018

Millot, V. (2009), *Trademarks as an Indicator of Product and Marketing Innovations*, OECD Science, Technology and Industry Working Papers, No. 2009/06, OECD Publishing, Paris. https://doi.org/10.1787/224428874418

Mohnen, Pierre (2019), 'R&D, innovation and productivity', *The Palgrave handbook of economic performance analysis*, pp. 97-122.

OECD/Eurostat (2018), *Oslo Manual 2018: Guidelines for Collecting, Reporting and Using Data on Innovation, 4th Edition, The Measurement of Scientific, Technological and Innovation Activities*, OECD Publishing, Paris/ Eurostat, Luxembourg. https://doi.org/10.1787/9789264304604-en

Ramzi, Trabelsi, Kallal Rahim, and Maher Skhiri (2022), 'Scientific Knowledge Valorization in the Public R&D Sector: a Survey and a PLS-SEM Approach', *Journal of the Knowledge Economy*, pp. 1-29.

Romer, Paul M. (1990), 'Endogenous technological change', *Journal of political Economy* 98.5, Part 2, pp. S71-S102.

Sandro Mendonça, Tiago Santos Pereira, Manuel Mira Godinho (2004), 'Trademarks as an indicator of innovation and industrial change', *Research Policy*, Volume 33, Issue 9, pp. 1385-1404, ISSN 0048-7333. https://doi.org/10.1016/j.respol.2004.09.005.

Schumpeter, Joseph (1942), 'Capitalisme, socialisme et démocratie', *Première traduction française publiée en*, Paris.

Van de Burgwal, Linda HM, Ana Dias, and Eric Claassen (2019), 'Incentives for knowledge valorisation: a European benchmark', *The Journal of Technology Transfer* 44.1, pp. 1-20.

Wajsman, Nathan, and Francisco García-Valero (2017), *Protecting innovation through trade secrets and patents: Determinants for European Union firms*, European Union Intellectual Property Office.

WIPO (2021), *Global Innovation Index 2021: Tracking Innovation through the COVID-19 Crisis*. Geneva: World Intellectual Property Organization.

CHAPTER 7

A FERTILE ENVIRONMENT FOR R&I

CHAPTER 7.1

ACCESS TO FINANCE: THE IMPORTANCE OF EQUITY AND VENTURE CAPITAL

KEY FIGURES

€62.4 billion
of private-equity investments in the EU in 2020

€8.5 billion
of venture-capital investments in the EU in 2020

7 times
more venture-capital capital funding in the US than the EU

1.1 %
of capital raised in the EU venture-capital market captured by EU women-led tech-companies

KEY QUESTIONS WE ARE ADDRESSING

- What are the main challenges faced by EU enterprises in financing their innovation activities?
- How did the EU private-equity (PE) and venture-capital (VC) markets respond to the COVID-19 crisis?
- How big is the gender financing gap in the EU?
- What are the latest trends in the diffusion of alternative financing instruments, FinTech and green technologies in the EU?

KEY MESSAGES

What did we learn?

- The EU financing system continues to be strongly bank-dependent and equity investments still play a relatively minor role.
- Intangible assets are more effectively financed by non-bank financing, given the difficulties in using them as collateral for bank lending
- EU VC investments were only marginally hit by the COVID-19 crisis.
- Nevertheless, the EU still struggles to attract more risk-taking and more patient investments, especially at the scale-up stage.
- Digital finance activities are becoming increasingly popular in the EU, and investments in FinTech and green technologies have expanded over time.
- The EU VC market is characterised by a significant gender gap.

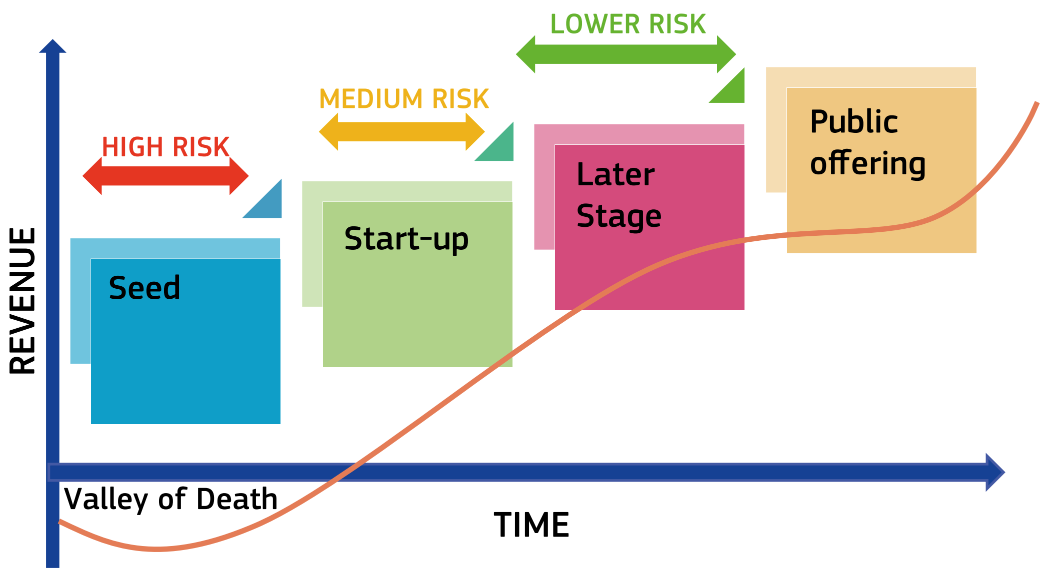
What does it mean for policy?

- Switching to a green and digital economy requires a significant amount of financing. Further progress in the EU capital markets union would particularly benefit innovative firms operating in intangible-intensive sectors. New financing tools also need to be targeted towards more innovative EU businesses, while ensuring coherence with the existing financial instruments available to EU firms.
- Integrating sustainability criteria into business financing is essential to the decarbonisation of the economy.
- The increasing financing opportunities from online finance must be balanced by policies to reduce the fragmentation of the Digital Single Market and to facilitate digital innovation, while ensuring consumer protection.
- Providing financial support to women in innovation and entrepreneurship is essential to create fair, inclusive and prosperous European R&I ecosystems.

Financing innovation is particularly challenging. First, the output from innovation activities has public-good properties and is partly non-rival and non-excludable, i.e. other economic actors can benefit without paying for it (Hahn et al., 2019). As a result, the risk of not being able to reap the full return of innovation investments may discourage firms from allocating resources to R&D spending. Second, innovation activities typically result in the production of technological knowledge, which is a non-tangible asset. As such, it cannot be easily deployed or sold (Hall and Lerner, 2010). In addition, innovation projects are typically riskier as they can lead to both positive and negative outcomes (Hahn et al., 2019). The uncertainty naturally embedded in innovation activities typically leads to financial frictions that limit the ability of firms to secure financial resources from external investors (Hall et al., 2016).

It is possible to distinguish four financing stages along a firm's development path: seed financing, start-up, later-stage development and public offering. Seed financing is required at the preliminary stage of a company's development process, before the firm becomes commercially viable. Funding at this stage is typically used to finalise product definition or product design. Investments at seed stage are thus highly risky and accompanied by negative cash flows (Invest Europe, 2021). This phase represents the most delicate moment in a company's path to growth and is typically referred to as the 'valley of death'. The start-up stage (or early stage) refers to businesses that are about to start the commercialisation of their products. In this case, financial resources are typically used to cover capital expenditure. Later-stage investments usually target fully operating companies, which can also decide to go public to raise additional funding on the stock market (Figure 7.1-1).

Figure 7.1-1: Venture Capital Investment Cycle



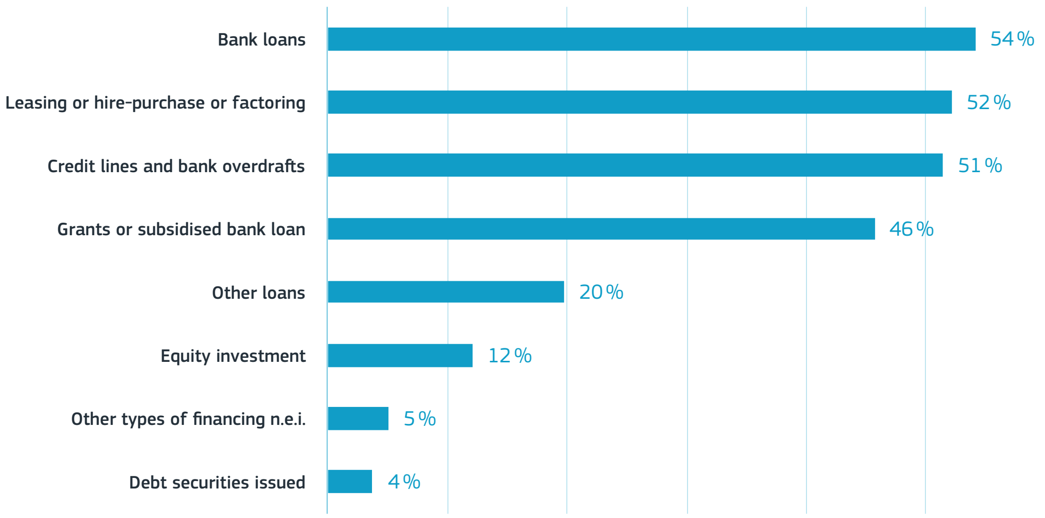
Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-7-1-1.xlsx

The short-term character of traditional financing systems is an important constraint on innovation investment. As noted by Mazzuccato (2016), the declining trend in innovation investment observed in Western countries in recent decades can be partially attributed to the increase in short-term investment in the private sector. Patience is a key ingredient in innovation investments as innovative activities typically take time to deploy their results, in terms of both market products and financial returns. The lack of 'patient capital' (long-term investment) represents an important constraint on financing innovation (Mazzuccato, 2016).

1. The EU private-equity and venture-capital market

The financing of EU companies remains strongly bank-driven. As reported in Figure 7.1-2, traditional bank products, such as loans, credit lines and bank overdrafts, continue to represent the most relevant sources of external finance for European enterprises. Alternative external resources such as equity investment play a moderate role (12 %), but remain critical to helping firms facing specific financial needs and challenges. The availability of new sources of financing is particularly beneficial for innovative start-ups with significant intangible assets as it supports them to boost their performance. This is highly relevant in the context of the twin transition, for which new financing instruments are becoming increasingly popular.

Figure 7.1-2: Share of relevant external sources of finance for enterprises in the euro area, 2020



Source: ECB, SAFE survey (2021)
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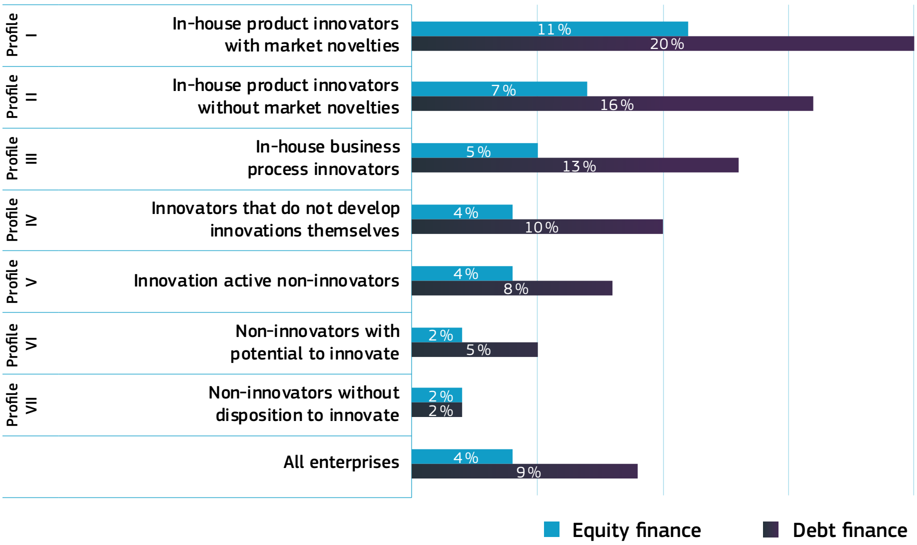
Furthermore, EU firms prefer to rely on internal resources (e.g. retained earnings) to finance their innovation activities. When looking at the financial behaviour of innovative firms, it is possible to distinguish seven different innovation profiles[1], based on the conditions that allow innovation to occur within the different businesses (see Chapter 6.3 – Innovation output, and societal and market uptake). For each identified profile, the use of external financing sources (either debt or equity finance) appears to be very limited (Figure 7.1-3). **On average, EU firms make more use of debt finance to finance their innovation activities** (9% against the 4% using equity finance). Equity finance is mostly used by enterprises identified as product innovators, namely enterprises identified as in-house product innovators with market novelties (profile I) (Figure 7.1-3). This is partially due to the fact that innovative firms are typically active in intangible-intensive sectors, and non-tangible assets are difficult to pledge as collateral for bank lending (Demmou and Franco, 2021).

Figure 7.1-3: Use of equity and debt finance by innovation profile(1), 2016-2018



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Community Innovation Survey (CIS).

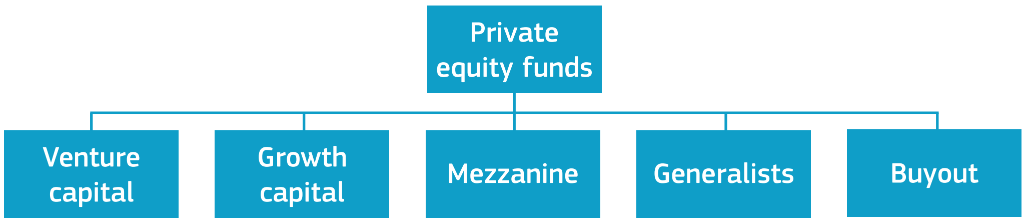
Note: (1)Based on 20 EU Member States for Equity finance and 19 EU Member States for Debt finance.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-7-1-3.xlsx

1 I: In-house product innovators with market novelties, including all enterprises that introduced a product innovation that was developed by the enterprise and that was not previously offered by competitors; II: in-house product innovators without market novelties, including all enterprises that introduced a product innovation that was developed by the enterprise but that is only new to the enterprise itself; III: in-house business-process innovators, including all enterprises that did not introduce a product innovation, but that did introduce a business-process innovation that was developed by the enterprise; IV: innovators that do not develop innovations themselves, including all enterprises that introduced an innovation of any kind but did not develop it themselves (enterprises without significant own-innovation capabilities); V: innovation-active non-innovators, including all enterprises that did not introduce any innovation but that either had ongoing or abandoned innovation activities; VI: non-innovators with potential to innovate, including all enterprises that did not introduce any innovation, and which had no ongoing or abandoned innovation activities but that did consider to innovate; VII: non-innovators without disposition to innovate, including all other enterprises, that neither introduced an innovation nor had any ongoing or abandoned innovation activities nor considered innovating.

Equity investments are critical for innovative start-ups to grow, and act at different stages of a firm's development path (Figure 7.1-4). VC funds focus on firms in their earlier stages of development, while generalist funds use selection criteria other than the firm's stage of development. Growth funds make PE investments in relatively mature companies looking for primary capital to expand or to enter new markets, while buyout funds are typically related to acquisitions of firms through the purchase of majority or controlling stakes. Mezzanine funds are hybrid funds that rely on both debt and equity financing (Invest Europe, 2021).

Figure 7.1-4: The components of private-equity capital



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Invest Europe definitions

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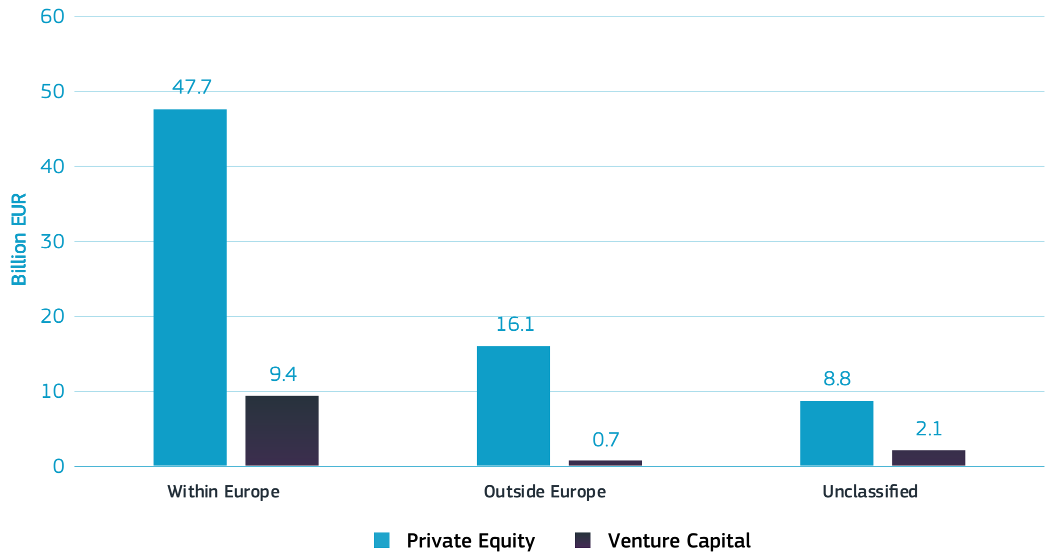
The largest share of PE funds raised by EU companies comes from investors within Europe. In 2021, EUR 72.6 billion[2] of PE funds were raised in the EU (Invest Europe, 2021). Over 68 % of the resources came from funds within Europe (EUR 47.7 billion), whereas EUR 16.1 billion were raised from outside Europe (Figure 7.1-5). The same trend is observed for VC funds, suggesting that non-European VC funds typically decide to invest elsewhere.

In 2020, PE investments in EU portfolio companies experienced a mild contraction before increasing again in 2021. In 2021, PE investments in EU portfolio companies experienced a significant increase, after the mild contraction reported in 2020. Investments from PE funds located all over the world (including Europe) into portfolio companies based in the EU increased by about 41 % between 2020 and 2021, from EUR 64.3 billion to EUR 90.8 billion (Figure 7.1-6).

The number of EU firms receiving PE investments is not homogeneous across sectors. The ICT sectors accounted for the largest share of firms, with over 2 500 companies receiving PE financing in 2021, and total investment of almost EUR 28.8 billion. Firms operating in the consumer goods and services segment follow, with over 1 200 financed companies and total investment standing at EUR 18.4 billion (Invest Europe, 2022). Biotech and healthcare firms rank third in terms of number of firms receiving PE financing, and total amount of investment received (999 firms and EUR 13.7 billion, respectively).

2 The data refers to the incremental amount raised over the year.

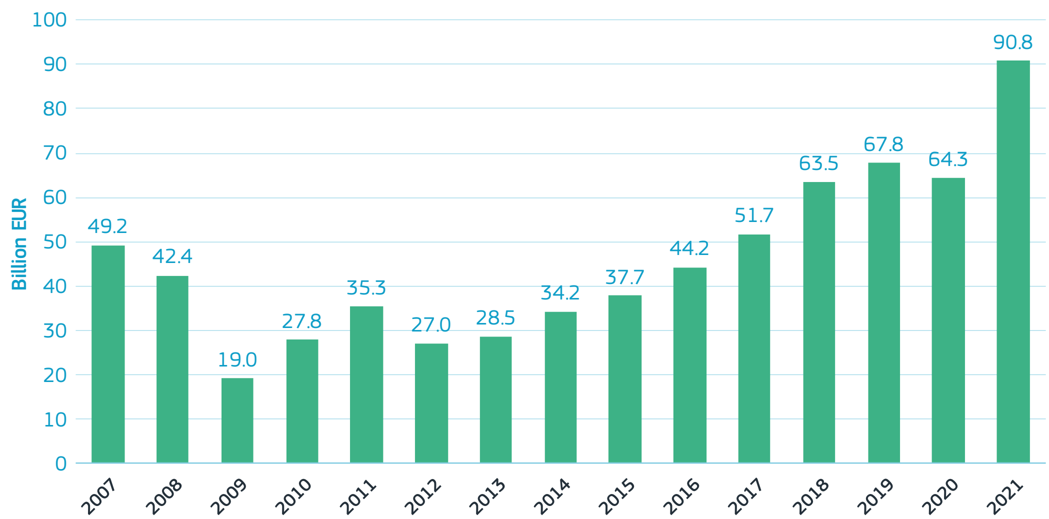
Figure 7.1-5: Private Equity funds raised in the EU in 2021, by geographical origin



Science, Research and Innovation Performance of the EU 2022

Source: Invest Europe, 2022
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-7-1-5.xlsx

Figure 7.1-6: Private-equity investments[(1)] in EU portfolio companies, 2007-2021



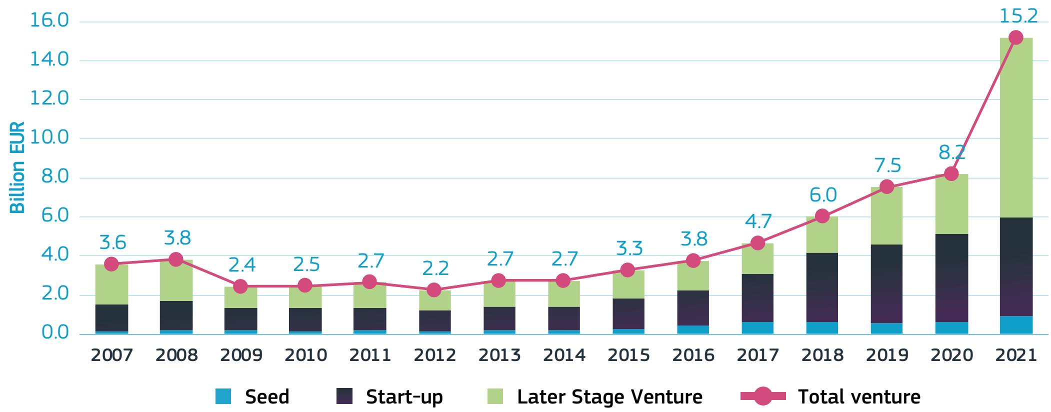
Science, Research and Innovation Performance of the EU 2022

Source: Invest Europe, 2022
Note: [(1)]Data are measured following the market statistics approach, an aggregation of the figures according to the country in which the investee company is based, regardless of the location of the PE fund. At the European level, this relates to investments in European companies regardless of the location of the PE firm.
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-7-1-6.xlsx

VC is a type of PE investment focusing on start-up companies with high growth potential (Flachenecker, 2020). VC support is not limited to the provision of financial resources but may include non-financial support such as management advice, technical assistance, networking and expertise (Testa et al., 2022). The latter aspect is particularly relevant for technological start-ups, such as those operating in the AI and blockchain sectors, which are typically considered to be very complex by potential investors (Testa et al., 2022).

VC investments in the EU increased from 2013 onwards, with investments in later-stage ventures accounting for the largest increase between 2019 and 2021. In 2021, VC investments almost doubled as compared to 2020 and reached about EUR 15.2 billion. Differences are observed across different development stages. VC capital financing targeting firms at the seed stage[3] slightly increased after having remained more or less stable between 2017 and 2020. Financing allocated to later-stage[4] ventures increased considerably, rising from EUR 2.9 billion to EUR 9.2 billion between 2019 and 2021. Investments in start-up stage ventures also recorded a positive performance, increasing from EUR 4 billion to EUR 5 billion over the same period (Figure 7.1-7).

Figure 7.1-7: Venture capital investments(1) in the EU by development stage, 2007-2021



Science, Research and Innovation Performance of the EU 2022

Source: Invest Europe, 2022

Note: (1)Data are measured following the market statistics approach, an aggregation of the figures according to the country in which the investee company is based, regardless of the location of the PE fund. At the European level, this relates to investments in European companies regardless of the location of the PE firm.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-7-1-7.xlsx

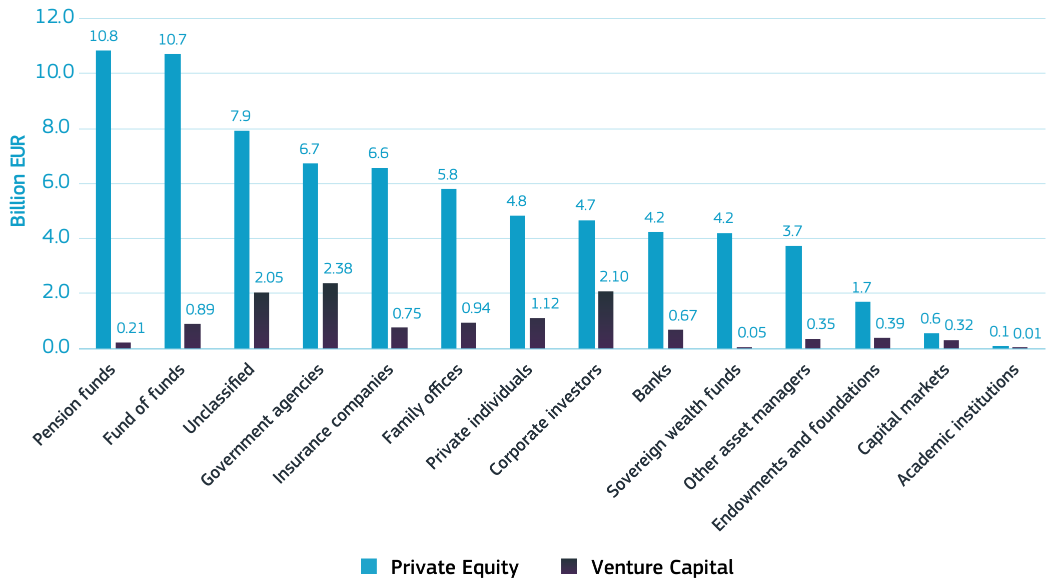
3 Funding provided before the investee company has started mass production/distribution with the aim to complete research, product definition or product design, also including market tests and creating prototypes. This funding will not be used to start mass production/distribution.

4 Financing provided for an operating company, which may or may not be profitable. Late-stage venture financing tends to be financing into companies already backed by VCs, typically in C or D rounds.

Nevertheless, large institutional investors continue to avoid riskier investments in the EU. Pension funds and insurance companies represent an important player in the EU VC landscape, although their involvement in European VC remains highly underdeveloped (Kraemer-Eis, et al., 2021). Pension funds in European ventures account for less than 0.018 % of their total assets (Atomico, 2021), and in 2021 capital raised from pension funds and insurance companies accounted only for about 7.9 % of the total VC funds raised in the EU in 2021. In contrast, VC raised from government agencies in the EU increased significantly between 2019 and 2020. In 2020, capital raised by governments accounted for about 31 % of total VC funding in the EU (Invest Europe, 2021). In 2021, VC capital raised from government agencies still accounted for the largest share of total VC funds raised in the EU (about 19.4 %, approximately EUR 2.4 billion), although reporting a decrease compared to the 2020 levels.

VC in the EU is mainly concentrated in a few EU Member States that are either 'innovation leaders' or 'strong innovators' as classified in the European Innovation Scoreboard. VC investors are often regional actors (Kraemer-Eis et al., 2016) or appear to focus only on some European regions and countries, thereby limiting the capacity of raising capital from across the entire EU. As shown in Figure 7.1-9(a), most VC investments are concentrated in a few EU countries, such as Germany and France (approximately EUR 3.8 billion and EUR 3 billion, respectively), which altogether received about 46 % of VC financing in 2021. The Netherlands and Spain rank third and fourth in terms of absolute amount of VC investments received, with about EUR 1.8 billion and EUR 1.3 billion, respectively. The rest of the EU countries received a significantly lower proportion of VC financing, pooling together about EUR 4.1 billion, (approximately 27 % of the overall VC resources directed to EU companies). When considering countries' economic size, VC investments represent only a tiny percentage (< 0.5 %) of EU Member States' GDP (Figure 7.1-9(b)).

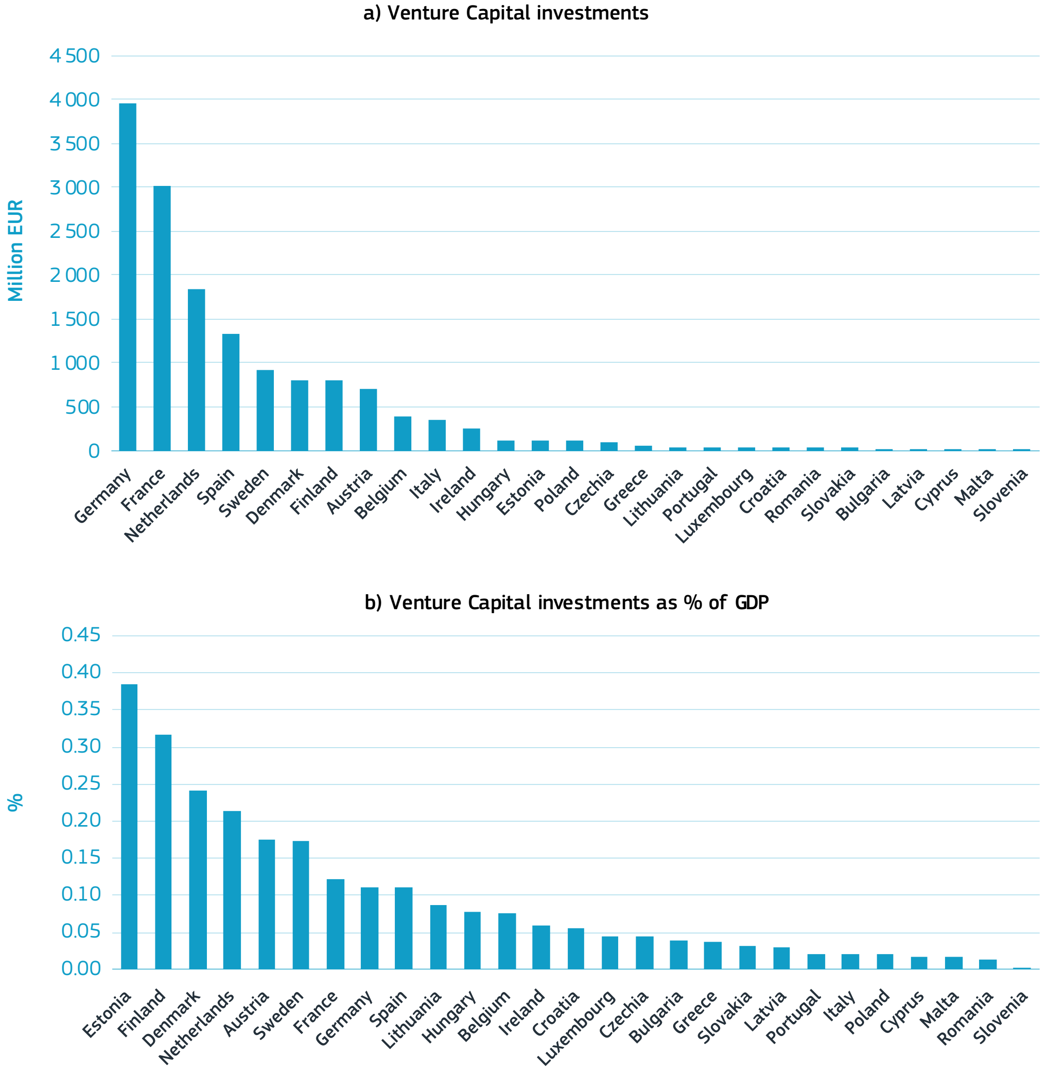
Figure 7.1-8: Private Equity and Venture Capital Funds raised in Europe in 2021, by investor type



Source: Invest Europe, 2022

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-7-1-8.xlsx

Figure 7.1-9: Venture Capital investments[1] in EU Member States in million EUR and as % of GDP, 2021



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on Invest Europe, 2021, and Eurostat (online data code: nama_10_gdp)

Note: [1]Data are measured following the market statistics approach, an aggregation of the figures according to the country in which the investee company is based, regardless of the location of the private equity fund. At the EU level, this relates to investments in EU companies regardless of the location of the private equity firm; Data for MT not available.

[2]Other includes SK, SI, HR, LT, LV, EE, EL, CZ, RO, BG.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-7-1-9.xlsx

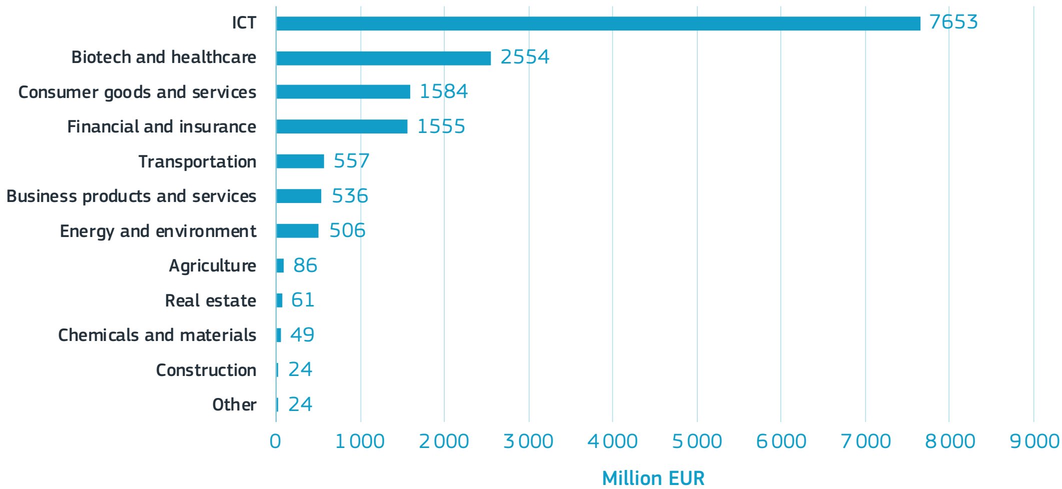
The overall positive trend registered between 2019 and 2020 suggests that VC investments were not significantly disrupted by the COVID-19 crisis. In 2020, VC investments stood at EUR 8.2 billion, recording a 9% increase compared to 2019 values (EUR 7.5 billion) (Invest Europe, 2022). The EU VC market has survived the COVID-19 pandemic without major disruptions, showing a significant degree of resilience. As noted by Kraemer-Eis et al. (2021), the set of public support measures issued in reaction to the pandemic played a key role in maintaining such a good performance, preventing the EU VC industry from experiencing serious damage.

Furthermore, EU VC investments appear to be concentrated in specific sectors. VC investments are strongly concentrated in the ICT sector, which accounted for about 50% (EUR 7.6 billion) of the total VC financing received by EU companies in 2021. The biotech and healthcare sector followed with EUR 2.5 billion, while firms in the consumer goods and services segment received EUR 1.5 billion (Figure 7.1-10). Finance and insurance ranked fourth with EUR 1.5 billion. More traditional sectors are less targeted by VC investors.

The sectorial concentration of VC investments helps to explain why the VC market was not significantly disrupted by the pandemic. The sectors most targeted by VC investors (such as the ICT sector) were also not significantly hit by the pandemic. Homogeneous effects were observed across different stages of VC investment, as well as across different ages of companies receiving the funding. Notably, the only exception was the healthcare industry, which recorded a 77% increase in total volumes invested after the onset of the pandemic (Crisanti et al., 2021).

VC investments mostly focus on SMEs. As noted by Bellucci et al. (2021), the median profile of firms receiving VC investments are typically SMEs with between 8 and 15 employees. It follows that this type of firm is most likely to be affected by policies to incentivise VC financing in the market (Bellucci et al., 2021). Furthermore, Bellucci et al. (2021) provide evi-

Figure 7.1-10: Venture capital investments[(1)] in the EU per sector, 2021



Science, Research and Innovation Performance of the EU 2022

Source: Invest Europe, 2021

Note: [(1)]Data are measured following the market statistics approach, an aggregation of the figures according to the country in which the investee company is based, regardless of the location of the private equity fund. At the EU level, this relates to investments in EU companies regardless of the location of the private equity firm.

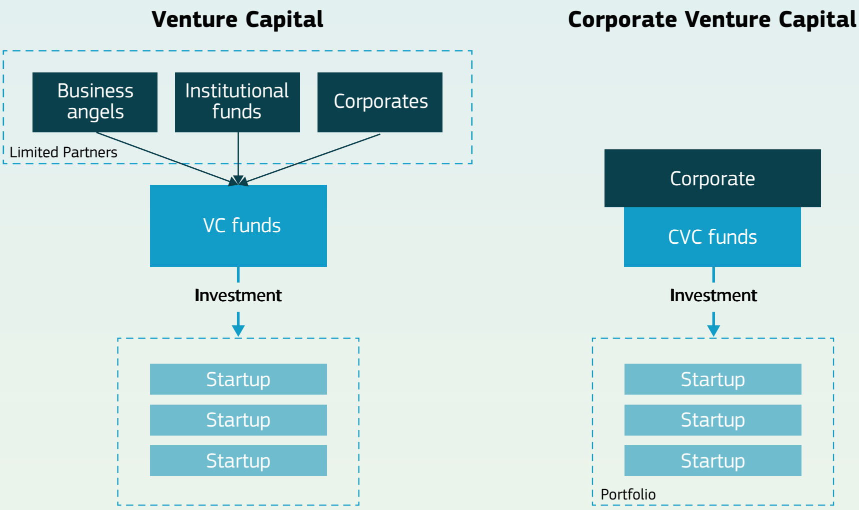
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-7-1-10.xlsx

dence of a correlation between the size and financial maturity of firms. They find that VC instruments such as accelerators, business angels and VC seed investments are typically directed towards micro-enterprises, which have less than 10 employees and less than EUR 2 million in total assets. Later-stage VC investments typically target small enterprises, as defined by the European Commission. In terms of age, 3-year-old firms turn out to be the main target of all VC-backed instruments (Bellucci et al., 2021).

Box 7.1-1: Corporate venture capital

Corporate venture capital (CVC) is becoming increasingly important in the global entrepreneurial financing landscape. Corporate venture funds are VC funds with only one limited partner, typically a company that fully owns the fund and wishes to invest in start-up companies (Figure 7.1-11)[5]. The ability of CVCs to foster innovation is an established fact in the economic literature. Chemmanur et al. (2014) focus on the patenting outcomes of firms receiving VC financing, finding that CVC-backed firms are typically more innovative than independent venture capital (IVC)-backed companies. Napp and Minshall (2011) show that CVC activities produce beneficial effects on both start-ups and large companies targeted by the investment. Such beneficial effects are not only limited to the availability of financial resources, but are also linked to technical expertise that corporate investors can provide as well as the

Figure 7.1-11: Venture capital vs corporate venture capital



Source: https://techmind.vc/en/corporate-venture-capital-vs-venture-capital-whats-the-difference/

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-7-1-11.xlsx

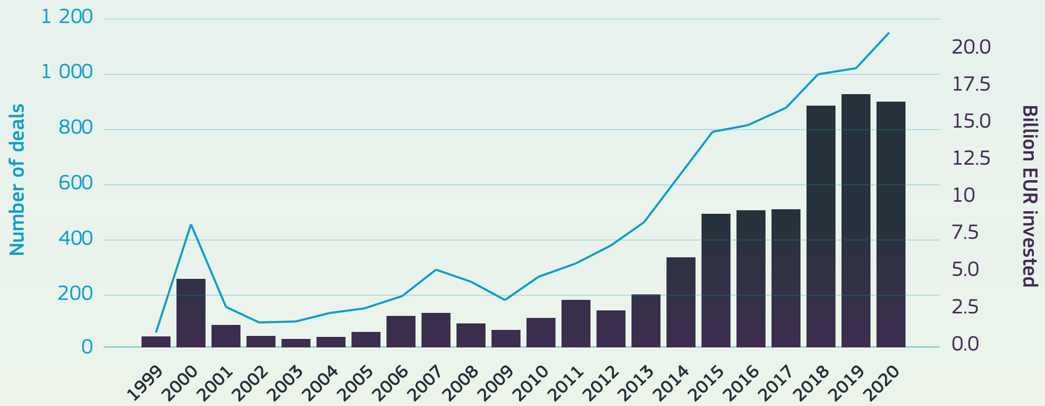
5 Corporate venture capital vs venture capital, what's the difference? (techmind.vc)

possibility of gaining access to complementary technologies that can boost firms' productivity and growth (Flachenecker et al., 2020).

A significant share of CVC targeting start-ups and scale-ups comes from top global R&D investors[6]. In the last two decades, CVC investments by top R&D investors showed an overall upward trend, with few slowdowns (Figure 7.1-12). According to the 2021 EU Industrial R&D Investment Scoreboard, 62 % of the 2 500 companies covered by the analysis invested in start-ups and scale-ups at least once over 2000-2020. In 2019, 22 % of the companies closed at least one start-up deal. Interestingly, most of these companies are placed very high in the scoreboard ranking, with 55 % being in the top 20 % in terms of global R&D. This result suggests that CVC investments play a strategic role in top-innovator companies. As noted by Grassano et al. (2021), investments in start-ups serve different objectives: on the one hand, they complement a company's internal innovation capabilities, helping to address potential internal weaknesses; on the other hand, CVC investments constitute an important part of a company's strategy as they allow the company to rely on and exploit external knowledge, rather than develop it internally.

Significant differences exist in the regional distribution of CVC investments worldwide. US and Japanese top R&D companies account for the highest share of CVC investments (EUR 9.7 billion and EUR 3.0 billion, respectively), and significantly outperform EU companies. In 2019, the latter made investments in start-up companies to a value of around EUR 1 billion. Such a difference reflects the fact that the VC culture is more developed in other parts of the world than in Europe, and is also related to significant sectoral differences. When compared to other economies, such as the US, the EU has a significantly lower number of companies operating in sectors that typically attract the largest share of CVC investments, such as ICT, financial services and the health sector (Grassano et al., 2021).

Figure 7.1-12: Number of deals (left-hand scale) and investment volume (right-hand scale) by R&D-investing companies and their subsidiaries, 1999-2020(1)



Science, Research and Innovation Performance of the EU 2022

Source: The 2021 EU Industrial R&D Investment Scoreboard
Note: (1)Funding data for 2020 not yet consolidated
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-7-1-12.xlsx

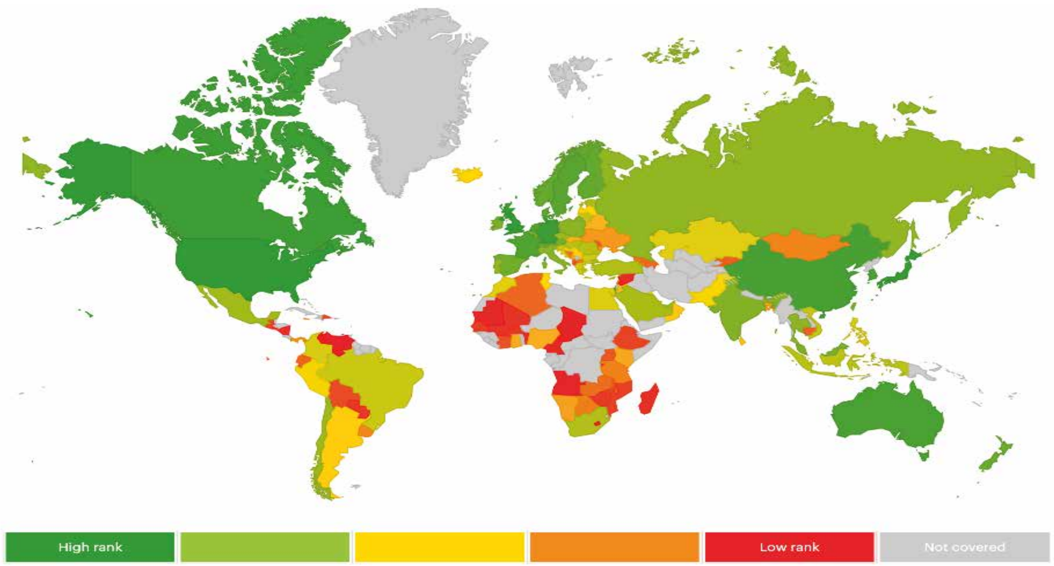
6 Defined following the EU Industrial R&D Investment Scoreboard definition, i.e. the 2 500 companies investing the largest sums in R&D in the world in 2020

2. The EU scale-up financing gap

The US is still the main magnet for investors at the global level, significantly outperforming the EU. According to the 2021 Venture Capital & Private Equity Country Attractiveness Index, the US still ranks first, with a score of 100, followed by the UK (90.3) and Japan (87.4). The EU continues to lag behind with an average score of 77.3.

EU capacity to attract investors is quite heterogeneous across Member States, confirming a significant degree of fragmentation within the EU VC market. Germany and France have the highest capacity to attract investors, with VC attractiveness scores of 87.3 and 83.6, respectively (Figure 7.1-14). The Netherlands, Sweden and Denmark also perform quite well in the EU ranking, with scores well above the EU average of 77.3. Southern countries and Eastern European countries attract investors less well, with scores below the EU average. Croatia, Latvia, Lithuania and Slovakia are among the Member States with the lowest performances, with scores ranging between 53.1 and 47.5.

Figure 7.1-13: **The venture capital and private equity country attractiveness index, 2021**

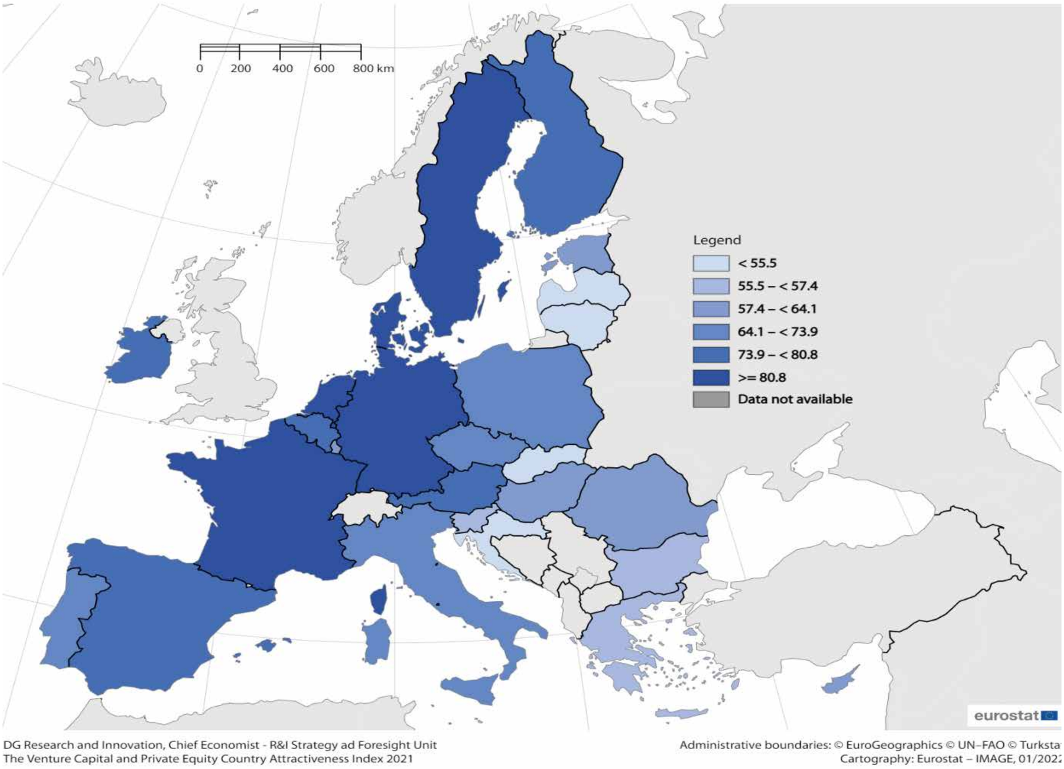


Science, Research and Innovation Performance of the EU 2022

Source: The Venture Capital & Private Equity Country Attractiveness Index, 2021

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-7-1-13.xlsx

Figure 7.1-14: The venture capital and private equity country attractiveness index per EU Member State, 2021



Science, Research and Innovation Performance of the EU 2022

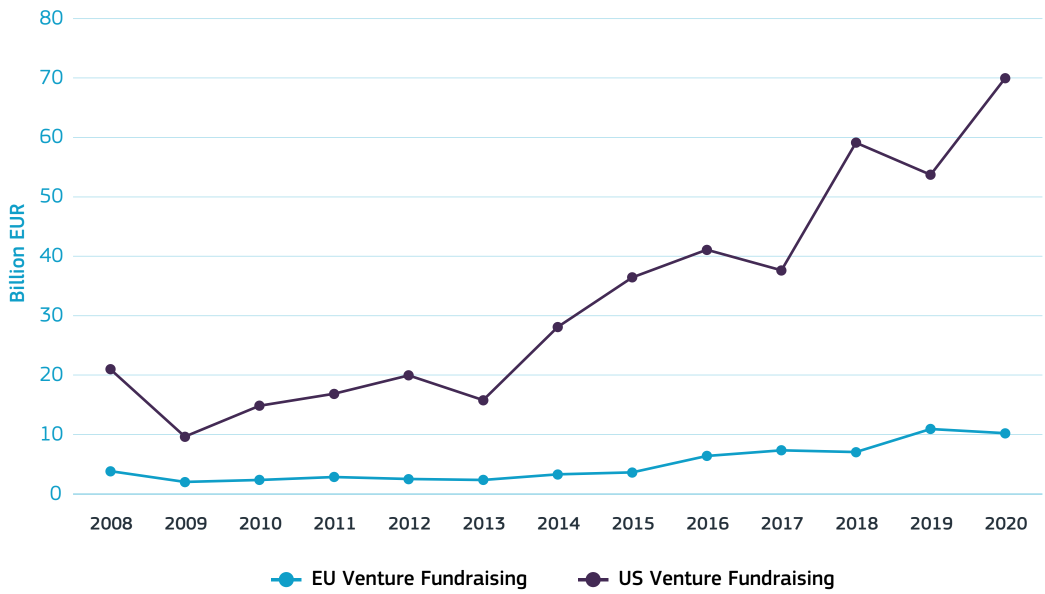
Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit, based on the Venture Capital & Private Equity Country Attractiveness Index, 2021

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-7-1-14.xlsx

The EU suffers from a financing scale-up gap, and the EU VC market still lags behind its main international competitors. As noted by Kraemer-Eis et al. (2021), European firms have more limited access to financing resources compared to other economies. European start-ups encounter difficulties in surviving the initial stage of their development (see Chapter 4.2 – Business dynamism). The EU VC market significantly underperforms compared to both the US and China (Benedetti-Fasil et al., 2021; Quas et al., 2021).

In the US, almost seven times more VC funding is raised than in the EU. There is little to suggest that this gap will reduce in the near future. Even though funds raised in the EU have increased since 2013 and are currently above pre-crisis levels (rising from EUR 2.3 billion in 2013 to EUR 10.2 billion in 2020), venture funds raised in the United States have also risen from EUR 15.8 billion in 2013 to about EUR 70 billion in 2020 (Figure 7.1-15).

Figure 7.1-15: Venture funds raised in EU vs the United States, 2007-2020



Science, Research and Innovation Performance of the EU 2022

Source: Invest Europe, 2021

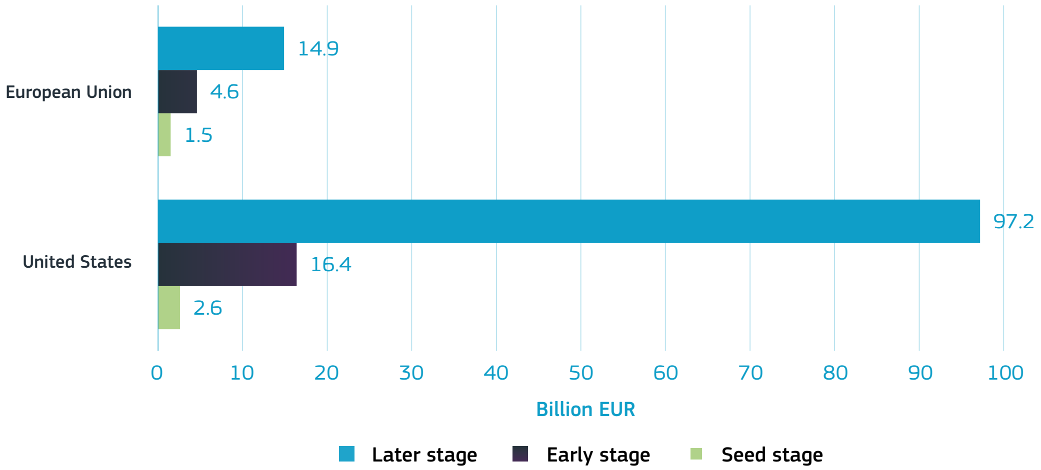
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-7-1-15.xlsx

The financing gap between the US and the EU is particularly striking at the scale-up stage. As reported by Flachenecker et al. (2020), the lack of financial resources to support high-growth firms represents a significant obstacle to the development of a vibrant entrepreneurial system in the EU. Derufle et al. (2017) find that the average investments raised in the EU and the US significantly diverge at the scale-up phase, with US companies receiving on average significantly larger funds. Similarly, Kraemer-Eis and Lang (2017) provide evidence of the existence of an EU-US financing gap at all development stages of firms. As shown in Figure 7.1-16, the EU and the US diverge significantly, especially at the early and later stages of firms' development. The gap at the later stage is the highest, with VC investment levels in the US of EUR 97.2 billion vs EUR 14.9 billion in the EU[7]. At the early stage, US VC investments exceed EU investments by a factor of four, with EUR 16.4 billion and EUR 4.6 billion recorded respectively (Benedetti-Fasil et al., 2021).

Furthermore, a significant gap in late-stage financing exists between the EU and the US. In 2020, the number of funds above USD 100 million in the US was significantly higher than that reported in the EU. The US-EU gap is particularly striking for funds of larger size, namely above USD 250 million, for which the US outperforms the EU by a factor of more than five (Invest Europe, 2021). This signals that despite the increase in late-stage financing experienced by the EU in recent years, a persistent gap still exists as compared to the US.

7 Differences in the investment value reported for the EU across different figures are due to differences in data sources and data-aggregation procedures.

Figure 7.1-16: Venture Capital investments[(1)] in the EU vs the United States by development stage, 2020



Science, Research and Innovation Performance of the EU 2022

Source: Benedetti-Fasil et al. (2021), based on the Dealroom database

Note: [(1)]Investment values for each region and stage are calculated considering the headquarter country of the VC-backed company involved in the deal.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-7-1-16.xlsx

Box 7.1-2: Addressing the lack of appropriate tax incentives

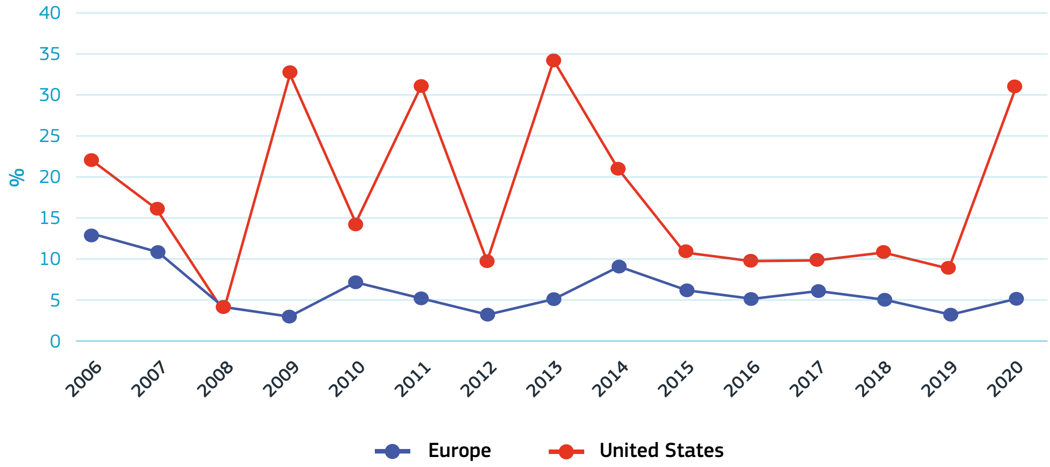
In many EU corporate tax systems, interest payments on debt financing are tax deductible, while the costs related to equity financing are not. Such asymmetric tax treatment induces a bias in investment decisions, making debt financing more appealing despite the potential negative effects of the increase in companies' debt levels. In 2019, total indebtedness of non-financial corporations amounted to almost EUR 14 trillion (99.8 % of GDP in the EU), and the debt-to-equity ratio was 53.3 %[8].

To tackle this tax-induced debt-equity bias, the European Commission launched the debt-equity bias reduction allowance (DEBRA). The overarching objective of the initiative is to encourage companies to rely more on equity contributions and less on debt financing. To do so, the European Commission calls for the introduction of an equity allowance targeting equity-financed new instruments. Legislative initiatives are already in place in six Member States (Belgium, Cyprus, Italy, Malta, Poland and Portugal)[9].

8 DEBRA Inception Impact Assessment - Ares(2021)3879996

9 DEBRA Inception Impact Assessment - Ares(2021)3879996

Figure 7.1-17: Share of IPOs in the total divestment amount (%)



Science, Research and Innovation Performance of the EU 2022

Source: Ambrosio et al. (2021), based on PitchBook data
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-7-1-17.xlsx

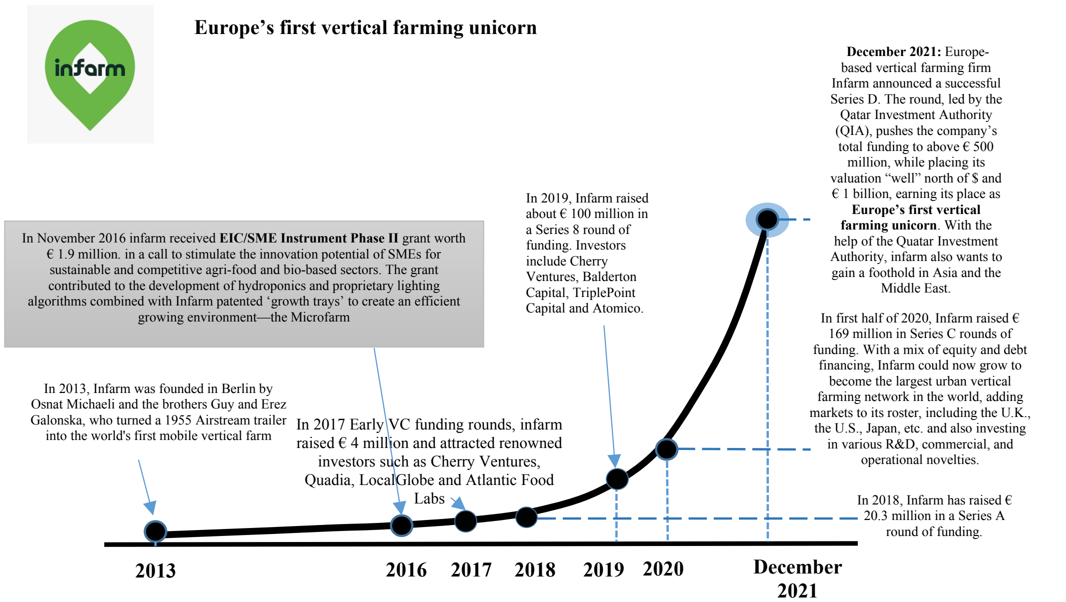
Exit strategies represent another critical step in scale-up investments. Companies have three financing possibilities for scale-up: they can decide to rely on internal funds, to go public or to be fully or partially acquired (Ambrosio et al., 2021). Initial public offerings (IPOs) represent one of the most common exit strategies available to firms. **Nevertheless, EU IPOs play a minor role in scale-up financing compared to in the US.** In the last two decades, the amount of divestment in the US has been significantly higher than in the EU (Figure 7.1-17). In 2020, only 5% of the total divestment took place through IPOs in the EU, as against 30% in the US.

An unicorn investment gap also exists between the EU and its international competitors. The US reported the highest amount of investments in unicorns between 2008 and the first half of 2021, with an average funding per unicorn of EUR 138 million. China and the EU showed the same performance, with average funding of EUR 125 million reported over the same period (Testa et al., 2022). **Furthermore, European unicorns are mostly foreign financed.** Between 2008 and the first half of 2021, three of the top 10 venture capital firms investing in European unicorns were located in the US (Testa et al., 2022).

Tackling the scale-up financing gap remains a top priority in the EU. Ensuring that EU companies get access to the necessary amount of financing resources to scale up is critical to achieving several EU policy objectives. As noted by Quas et al. (2021), tackling the EU scale-up gap would help the EU to secure its technological sovereignty and strategic autonomy. The innovation landscape is constantly changing, and European firms need funds to remain competitive on the global market. Additionally, leading companies in the emerging technological sectors are likely to play a key role in determining future industry standards. Therefore, it is essential to nurture tech leaders within the EU company pool to secure EU strategic autonomy (Quas et al., 2022).

Nevertheless, the EU has several instruments to support companies in their scale-up process, for instance the EIC funds, which have proved to be successful in allowing firms to increase their valuations, including to unicorn status (see Chapter 3.2 – Business dynamism). One example is Infarm, the first European vertical farming unicorn, founded in Germany (Figure 7.1-18).

Figure 7.1-18: An EIC success story: Infarm



Science, Research and Innovation Performance of the EU 2022

Source: European Innovation Council (2022)

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-7-1-18.xlsx

Box 7.1-3: An impact assessment of the EIB venture debt instrument

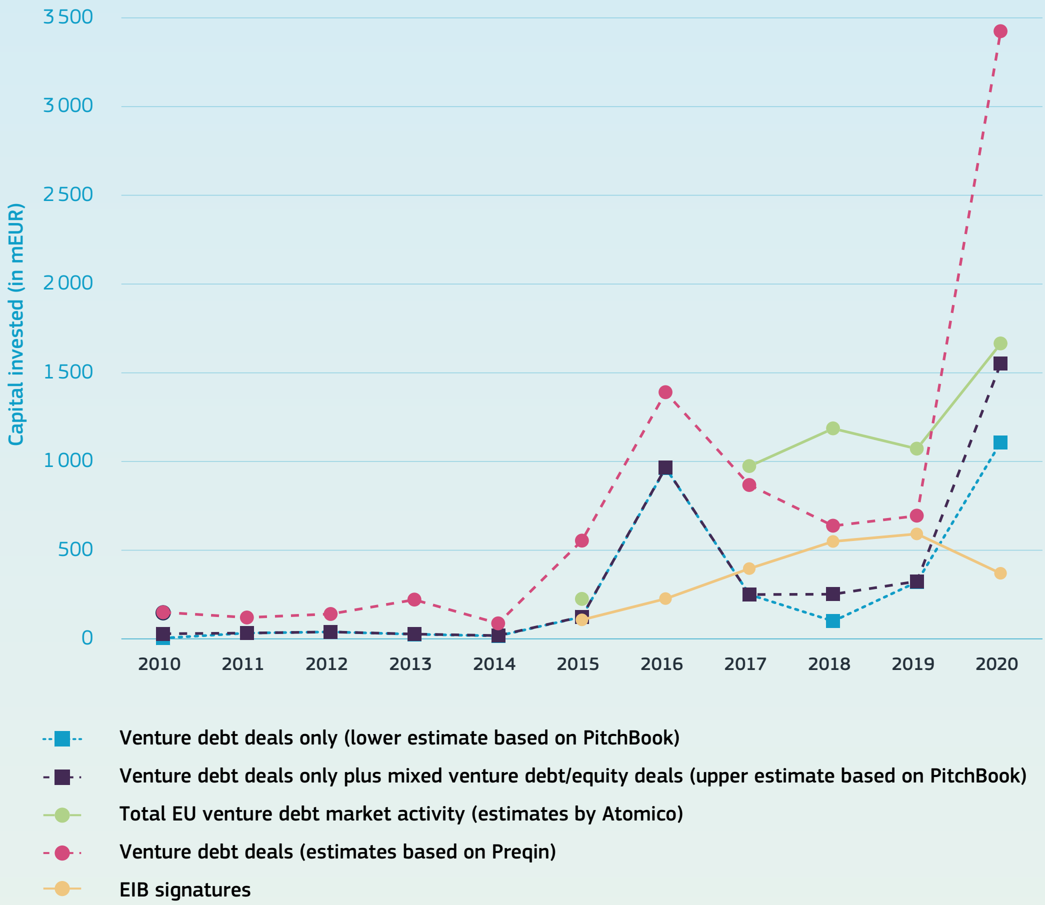
Authors: Matteo Gatti, Wouter Van Der Wielen, Sebastian Schich and Emily Sinnott

Venture debt is a quasi-equity financing instrument that addresses the funding needs of fast-growing, innovative companies by providing them with greater flexibility and a less constraining repayment structure than more traditional senior debt. The instrument targets firms that have already raised venture capital (mainly series B or C) and that want to avoid the dilution costs associated with additional equity injections.

The EU venture debt market has grown considerably over the last few years and the EIB has played a significant role in its expansion. Figure 7.1-19 shows the evolution of the EIB venture-debt portfolio compared to alternative market size estimates (there is no single authoritative source for data). The EIB venture debt impact assessment focuses on the loans signed between January 2015 and June 2021, which total EUR 2.65 billion[10]. This amount corresponds to approximately 0.8 % of the total EIB portfolio and to 3.8 % of the EIB's special activities. The key mandate behind the venture debt instrument is the European Fund

10 This horizon aligns with the period when the EIB signed its first venture debt contracts in 2015 until the cut-off for the analysis in June 2021.

Figure 7.1-19: European venture debt market



Science, Research and Innovation Performance of the EU 2022

Notes: Estimates of capital invested in million euro in EU countries (not including the United Kingdom) from different sources. Estimates by Atomico (2020, 2021) and data from Preqin converted from USD to EUR using exchange rates as reported by the OECD.

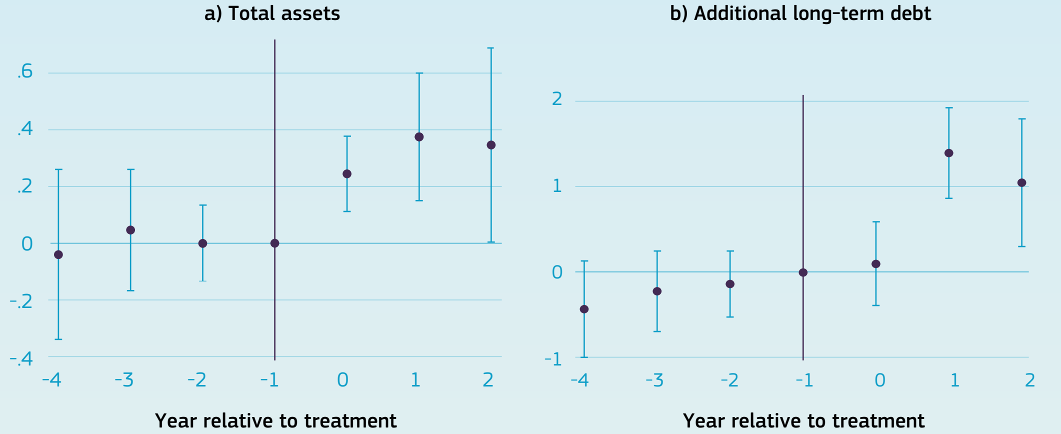
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-7-1-19-.xlsx

for Strategic Investments (EFSI). With the roll-out of the latter, the EIB increased its special activities, and venture debt is a subset of such special activities. The EIB portfolio has a strong focus on social goods, including health – for example COVID-19-vaccine development – e-mobility and sustainability.

A recent assessment of the effectiveness of the EIB's venture debt[11] is one of the first studies to estimate the impact of this instrument on firms' growth and performance. The paper compares 133 EIB beneficiaries to a control group made of firms that are similar to the ones that received venture capital but did not receive any venture debt (although these firms may still receive other forms of finance). Comparability

11 EIB, 'Impact Assessment of EIB Venture Debt' Economics Impact Studies Series (forthcoming in 2022).

Figure 7.1-20: Impact assessment results



Science, Research and Innovation Performance of the EU 2022

Notes: Estimations based on EIB allocation data linked to corporates' financials in ORBIS Bureau van Dijk

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between EIB beneficiaries and the control group is also ensured by the fact that firms in the control group have been selected to match beneficiaries' financials, innovativeness and age. The estimation relies on an econometric model that compares differences between EIB beneficiaries and the control group, before and after receiving venture debt.

The results in Figure 7.1-20 show a strong and positive impact of EIB venture debt on firm growth. Dots in red represent the estimated effect for EIB beneficiaries compared to the ones in the control group, at each point in time. The effects are normalised to zero in the year prior to loan signature (t = -1) and can thus be interpreted as relative to the year immediately before signing the contract. The bands around the dots show the 90 % confidence intervals of the estimates.

Panel (a) shows that EIB venture debt beneficiaries report on average a third higher total assets compared to firms that did not sign any venture debt contract. Panel (b) shows instead that the increase in total assets is partially driven by additional debt funding. Taken together, these results suggest that EIB venture debt beneficiaries experience higher growth due to crowding-in of additional debt.

The analysis also shows positive and significant results on firms' value added, while results on turnover, employment and innovation are positive but not statistically significant. While venture debt may not lead to strong positive results on all these variables, some of these insignificant results may be due to lack of available financial data. Finally, as venture debt is a recent product with data for a limited number of years after venture debt signature, the study only considers a short-term horizon (one-to-three years).

3. Gender gap in VC markets

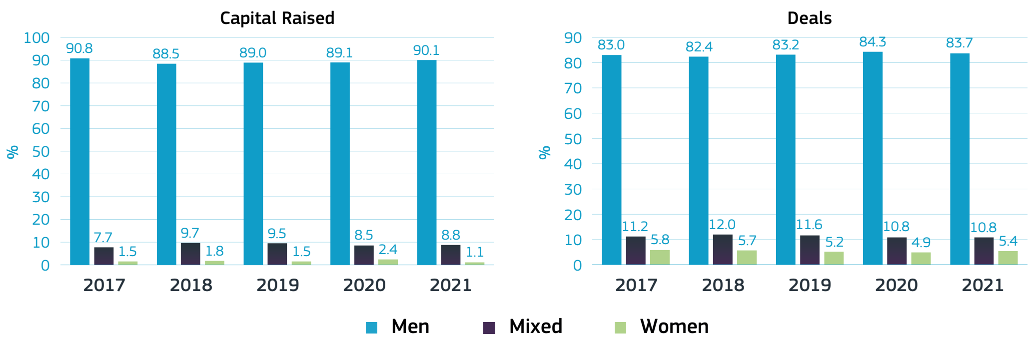
Female-led companies still receive less funding compared to male-led companies and female-male co-funded companies, suggesting that investment policy is biased against female-led businesses. Over 2014-2020, the global VC volume going to enterprises with only female founders was significantly less than that reported by companies with mixed-gender founders (Crunchbase, 2020).

The gender financing gap in Europe remains persistent. In 2020, only 1.7% of the capital raised in European VC markets was captured by tech companies with only female founders. The difference between male-led companies and companies with mixed/female founders remains significant both in terms of capital and number of deals (Atomico, 2021). In 2021, male-only firms accounted for respectively about 90% and 84% of capital and deals concluded, against 1.1% and 5.4% reported for women-led companies, respectively (Figure 7.1-21). The gap also remains huge when considering companies with male-female co-founders, which captured only 8.8% of the capital raised in 2021.

Women-led tech companies struggle to raise capital exceeding USD 50 million. In 2020, no deal over USD 50 million was closed by companies with only female founders. However, women-led companies performed better than in 2019 in rounds of up to USD 20 million. Female-led companies were able to close 6.3% of the deals for rounds of less than USD 10 million, and 3.4% of those between USD 10 million and USD 20 million, confirming difficulties female CEOs encounter in raising high volumes of capital on the market (Figure 7.1-22). A modest improvement was also reported in 2021, when women-led companies managed to close deals in each round size, including those above USD 100 million (1%) (Atomico, 2021).

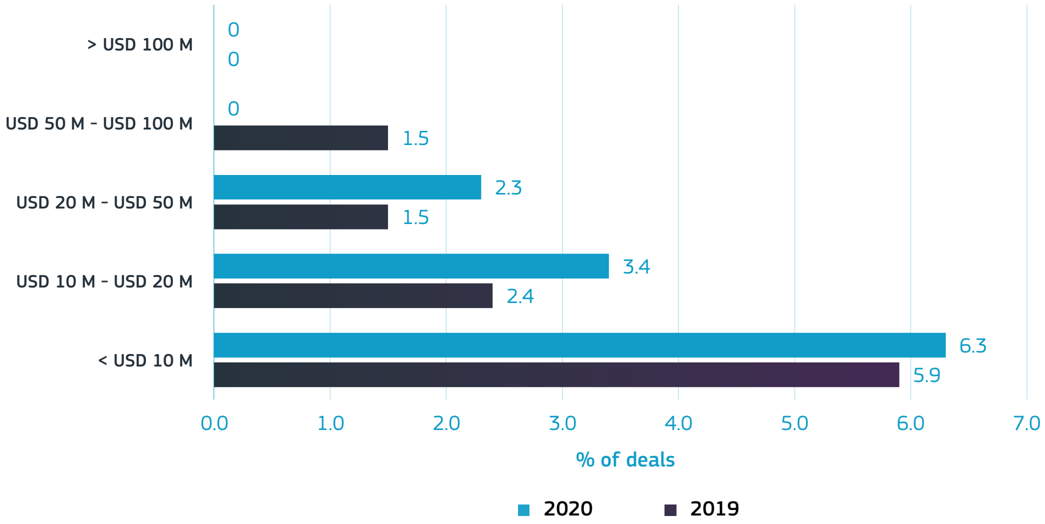
Women investors are keener to back women-led companies. In 2018, 54% of women investors supported at least one business funded by women, while 20% invested in 3-10 women-led companies. In contrast, male investors showed a lower appetite for backing women-led enterprises. In this regard, a potential cause of the lack of finance available to women is the relatively lower number of women investors (Wa4e, 2018).

Figure 7.1-21: Share of capital and deals raised by tech companies in Europe, per founding-team gender composition, 2017-2021



Source: Atomico (2021), based on the Dealroom database
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-7-1-21.xlsx

Figure 7.1-22: Share of deals by round size for women founding teams, 2019 vs 2020



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Source: Atomico (2020), based on Dealroom database
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Women angel groups represent an important source of financing for female-led businesses. Women business angels are more likely to invest in women-owned businesses (Harrison and Mason, 2007). Nevertheless, relevant barriers remain against fully unlocking the potential of angel investing to tackle the gender financing gap in the EU. Results from a survey conducted by Wa4e in 2018 suggest that a lack of understanding of the core process of angel investing and a low awareness of available risk mitigation strategies are some of the main challenges perceived by female entrepreneurs looking for business angels. From a policy perspective, **increasing the visibility and number of women business angels** would help to address these issues, thereby contributing to attracting additional deal flows by female entrepreneurs (Wa4e, 2018).

Another important obstacle to addressing the gender investment gap is the **scarce availability of data**, making it difficult to accurately quantify the magnitude of the financing gap between women-led businesses and those of their male counterparts. Better data are necessary to understand fully the magnitude of the phenomenon and to put in place efficiently a system to monitor the gender dimension of EU investment, thereby improving the design of policy initiatives to tackle this issue.

Box 7.1-4: EU Initiatives for women entrepreneurs

Gender equality is at the heart of the Horizon Europe programme and its Pillar III, 'Innovative Europe', which seeks to create fair, inclusive and prosperous R&I ecosystems in Europe. A full toolbox of measures and programmes to support women in innovation and entrepreneurship is being deployed under this pillar, especially those of the European Innovation Council (EIC).

- The EIC Business Acceleration Services recently launched the **EIC Women Leadership Programme**. This programme is a skills enhancement and networking scheme to help EIC-supported women entrepreneurs and researchers to advance in their careers, create their own spin-offs or spin-outs, and take leading positions in existing companies, through training, coaching and mentoring, and networking.
- The new **Women TechEU initiative** supports women-led deep tech start-ups, tackling the underrepresentation of women entrepreneurs in a key innovation sector that remains dominated by men. The programme offers financial support during the initial steps in the innovation process and during the growth of the company. Moreover, beneficiaries will receive access to mentoring and coaching provided by the Women Leadership Programme, including dedicated networking and pitching events.
- The **EU Prize for Women Innovators** is awarded to women innovators each year for outstanding achievements, and features a 'rising innovator' category for women innovators under 30. The prize is an important recognition of the role that women play in developing game-changing innovations, and provides role models for aspiring women innovators.
- The target for **women-led companies invited to pitch** their projects in the second stage of the EIC Accelerator was raised to 40 %;
- Integration of the **gender dimension** into the relevant **EIC Challenges** to make sure that breakthrough innovations can benefit all people concerned, regardless of their gender.
- The **newly-appointed EIC Board** is gender balanced, with 10 out of 20 board members being women. The EIC Fund Investment Committee and pools of EIC evaluators and business coaches will also remain gender balanced.
- The EIC Work Programme 2022 features a **Pilot European innovation gender and diversity index**, which will aim at improving the availability and benchmarking of gender and other relevant diversity data across the innovation ecosystem (e.g. start-ups, scale-ups, investment funds);
- The European Institute of Innovation and Technology (EIT) launched the new **Women2Invest** initiative, where recent graduates and young professionals coming from STEAM fields will become familiar with the fundamentals of venture capital through paid internships or entry-level positions in a venture capital fund, a corporate venture capital fund, or a corporate venturing unit.

Regarding support for female investors, **InvestEU**, the flagship investment Commission programme under the 2021-2027 Multiannual Financial Framework, will promote the presence of women on several fronts:

- InvestEU will aim at increasing the amount of financing flowing to funds having gender targets. In particular, the joint equity product of the Research, Innovation and Digitisation Window and the SMEs Window will put an emphasis on supporting funds that target gender diversity in their investment strategy. The Guarantee Agreement with the European Investment Bank (EIB) features an **indicative goal of 25% of all Equity Intermediaries** with whom the European Investment Fund (EIF) has entered into Equity Operations **to follow the Gender Criteria** set out in the agreement;

- The InvestEU Advisory Hub will provide targeted capacity building and project advisory support, which will include specific actions to increase women's representation in the investment community and improve access to finance for female-founded and female-led companies.

- The **InvestEU Advisory Board** features a dedicated **sub-group on Gender Equality**.

- The EIF will introduce an **indicator**[12] **to track investments supporting gender equality** (as defined by the EIB policies and procedures) under its key performance and monitoring indicators for impact of financing supported by InvestEU.

12 This includes the number of equity intermediaries complying with gender criteria and the amount invested in equity intermediaries complying with the gender criteria set out in the agreement.

4. FinTechs and alternative financing instruments

Providing enterprises with a more diversified set of financing instruments is crucial to ensuring long-term growth. In order to increase the resilience and efficiency of the EU capital market, it is critical to broaden the range of financing instruments available to EU companies. This is particularly relevant for start-ups and SMEs, which typically struggle to obtain access to the finance needed to increase their ability to innovate and grow (OECD, 2015). Creating an efficient financial system is essential to strengthening the EU's global position. This calls for continuous and increasing efforts to enable the EU financial system to adapt to market changes, thereby allowing EU enterprises to thrive in an increasingly complex and interconnected world. **In this regard, alternative financial instruments (such as digital finance activities[13]) are becoming very popular, as they allow EU firms to overcome the limits typically related to traditional bank products and services.**

FinTech[14] services have grown considerably in recent years and represent an important part of the financing landscape worldwide and in the EU. By providing alternative financing instruments, FinTech markets have the potential to enhance firms' access to finance (Kraemer-Eis et al., 2021). **Debt-based online activities are the most popular FinTech instruments worldwide, followed by equity crowdfunding and non-investment-based crowdfunding, which however still play only a minor role**.

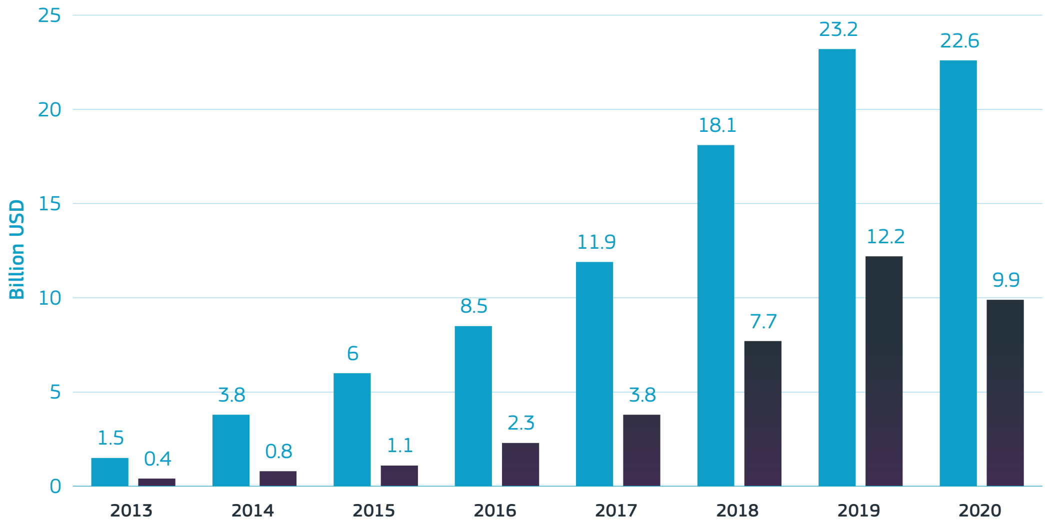
When looking at the global trend in online finance activities, China dominates the international scene in terms of investment volumes raised through online financing instruments (Cambridge Centre for Alternative Finance, 2021). In 2019, the Chinese market volume of online alternative finance stood at USD 83.4 billion, positioning China well above both the US and Europe. Nevertheless, European online alternative finance grew considerably over 2013-2019. Figure 7.1-23 shows the trend in alternative finance volumes with and without the UK. The observed increase is significantly lower in the latter case, suggesting that online finance is more developed in the UK compared to other European countries. The positive trend experienced a halt in 2020, with a drop from USD 23.2 billion in 2019 to USD 22.6 billion in 2020 (-3 %). The drop is even larger when excluding the UK (-19 %). Nevertheless, despite the substantial decrease observed in 2020, online finance volumes remained above the 2018 values, suggesting a good degree of resilience to shocks such as Brexit and the COVID-19 pandemic (Cambridge Centre for Alternative Finance, 2021).

As regards the different types of online instruments, **debt-based online activities account for about 83 % of Europe's online alternative finance** (without the UK), with a total value of USD 8.2 billion. Crowdfunding is another growing online activity, although its performance stagnated between 2020 and 2021 (Kraemer-Eis et al., 2021). The distinctive feature of crowdfunding is to raise external finance from a large

13 Digital finance activities are activities falling outside the spectrum of financial instruments typically supplied by the banking systems. According to the definition provided by the Cambridge Centre for Alternative Finance, online alternative finance models include a wide range of instruments, either debt- or equity-based. These include P2P consumer lending, P2P business lending, equity-based crowdfunding, reward-based crowdfunding, donation-based crowdfunding, and profit sharing, among others.

14 FinTech is a term used to describe technology-enabled innovation in financial services that could result in new business models, applications, processes or products and could have an associated material effect on financial markets and institutions and how financial services are provided.

Figure 7.1-23: European online alternative-finance[(1)] market volumes, 2013-2020



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Source: Cambridge Centre for Alternative Finance (2021)

Note: [(1)]Online alternative finance models include a wide range of instruments, either debt- or equity-based. These include P2P consumer lending, P2P business lending, equity-based crowdfunding, reward-based crowdfunding, donation-based crowdfunding, and profit sharing, among others

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-7-1-23.xlsx

audience of investors, not necessarily limited to specialised investors such as banks, business angels and venture capitalists (OECD, 2015). Besides broadening the base of investors, crowdfunding instruments support information sharing and exchange of best practices (OECD, 2015). **In 2019, investment raised by crowdfunding platforms in Europe (without the UK) amounted to USD 4.3 billion and increased to USD 5.2 billion in 2020** (Cambridge Centre for Alternative Finance, 2021).

Investments in European FinTech companies have increased remarkably in recent years. The term FinTech is also used to refer to companies that have the ability to introduce disruptive innovation in traditional financial service mechanisms (Kraemer-Eis et al., 2021). The number of deals closed by EU FinTech companies has increased over 2010-2019. With the outbreak of the COVID-19 pandemic, financing activities targeting FinTech companies in the EU slightly declined, with the number of deals decreasing to 544 in 2020. Nevertheless, the total deal volume continued to increase, suggesting that the pandemic did not impede further growth opportunities for EU FinTechs (Kraemer-Eis et al., 2021). At the end of Q3 2021, the volume of FinTech financing was already twice that reported at the end of 2019 (Kraemer-Eis et al., 2021).

Investment activities in EU FinTech companies remain geographically concentrated. Germany dominates with 139 deals, followed by France (121), Spain (96), Sweden (76) and the Netherlands (50). These innovative hubs together accounted for about 60% of EU deals and 80% of total deal value. When considering the relative size of countries, Luxembourg outperforms other EU countries with a total of 15 deals (EUR 175 million), confirming the efficiency of its well-developed financial system (Kraemer-Eis et al., 2021).

5. Investments in green technologies

Investing in green technologies will be crucial to implementing the EU's net-zero strategy. With the European Green Deal, the EU has made the path towards sustainable growth an overarching priority of its policy agenda. To reach climate neutrality, the EU is putting in place a series of initiatives aimed at changing the way of doing business at its core. Such a process will affect all sectors of the economy and will significantly impact firms' investment behaviour and financial needs. According to Kraemer-Eis et al. (2021), 56 % of EU SMEs claim that climate change already has impacted their business in recent years, although the impact is not homogeneous across EU countries. The effects of climate change on the EU corporate sector appear to be more disruptive in Spain, Portugal, Romania and France, possibly due to the higher number of droughts and forest fires occurring in these countries (Kraemer-Eis et al., 2021).

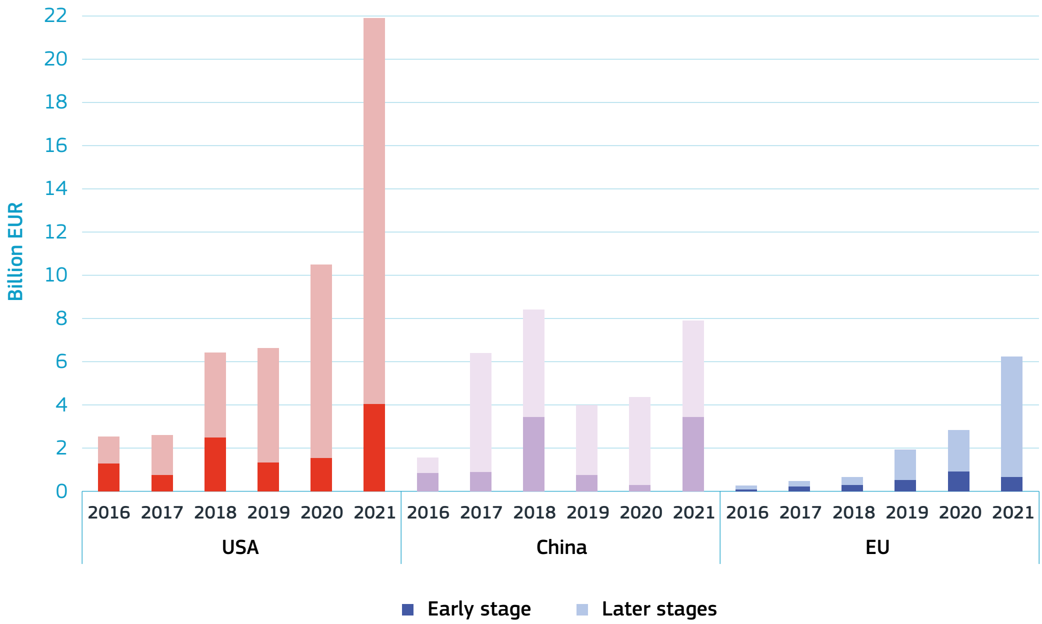
The Fit For 55 package sets the legislative framework within which the European Commission aims to deliver the European Green Deal (European Commission, 2021a). The package embeds an ambition that will determine the nature of the increasing demand for finance, and calls for adequate financing instruments to support businesses in their greening process[15]. In this regard, innovation in green technologies will play a key role by reducing the cost of greenhouse-gas abatement (Kraemer-Eis et al., 2021).

Investments in companies producing green technologies have shown a positive trend from 2016 onwards. After a few years of stagnation between 2013 and 2016, VC and PE investments in European green technology companies have increased significantly since 2017, reflecting growing societal awareness and concerns about environmental and sustainability issues. The number of deals closed increased by 7.2 % between 2017 and 2019 (Kraemer-Eis et al., 2021). As with the FinTech sector, companies innovating in green technologies were only marginally affected by the COVID-19 crisis. After a slight slowdown in 2020, green innovation finance started to accelerate again during the first three quarters of 2021 (Kraemer-Eis et al., 2021).

EU climate tech start-ups and scale-ups have attracted an increasing amount of investment over the last 6 years (Figure 7.1-24. In 2021, the EU accounted for 15 % of global Climate Tech investments, amounting to EUR 6.2 billion. Despite this positive performance, the presence of structural barriers (e.g. market and regulatory fragmentation) holds back EU climate-tech start-ups and scale-ups compared to other major economies, notably China and the US (European Commission, 2021b). EU early stage investments peaked in 2020 while reaching all-time highs in 2021 in China and the US. Although in 2021 the EU reported a higher later stage investment value than China, it continues to fall

15 An important initiative in this regard is the BlueInvest fund, managed the EIF and aiming at providing financing to equity funds that strategically target and support innovative companies active in the Blue Economy. The Blue Economy sector is often perceived as highly risky by investors. As such, the BlueInvest initiative aims to improve access to finance and investment readiness for start-ups, early-stage businesses and SMEs active in the Blue Economy, mobilising EU funds for financial intermediaries investing in this sector. https://ec.europa.eu/oceans-and-fisheries/news/blueinvest-commission-and-eif-agree-mobilise-eu500-million-new-equity-fund-blue-economy-2022-03-28_en

Figure 7.1-24: Venture capital investments in climate-tech start-ups and scale-ups



Science, Research and Innovation Performance of the EU 2022

Source: JRC elaboration based on PitchBook data
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-7-1-24.xlsx

behind both the US and China in terms of total VC investments. Between 2016 and 2021, EU climate tech firms only attracted 12% of all later stage investments, against the 48.5% and 28.5% received by the US and China, respectively.

Along with the expansion of investments in green-tech companies, the success of the European Green Deal will require all economic actors to significantly increase their investments in reducing pollution. Green bonds and green finance are expected to play a more prominent role in supporting EU enterprises, especially SMEs, in their green transition. In this regard, the low propensity of SMEs to invest in climate adaptation measures is a cause for concern. Results from a recent EIB survey suggest that only one in three European SMEs plans to undertake green investments (EIB, 2021). Potential reasons are limited access to finance (indicated as an obstacle by 55% of SMEs surveyed) and the presence of informational barriers, which calls for policy interventions to improve information sharing within the economy and to increase firms' awareness of investment opportunities (Kraemer-Eis et al., 2021).

Box 7.1-5: EU taxonomy for sustainable activities[16]

At the end of 2016, the Commission appointed a High-Level Expert Group on sustainable finance. In its final report, published in January 2018, the expert group delivered a set of key recommendations for building a strong sustainable-finance strategy for the EU. In the race towards the decarbonisation of the EU economy, it is of paramount importance to direct investments towards sustainable activities.

Sustainable finance, referred to as 'the process of taking due account of environmental and social considerations in investment decision-making'[17] calls for increasing investments in longer-term sustainable activities by making environmental, social and governance (ESG) factors an integral part of the investment decision-making process.

The work of the High-Level Expert Group on sustainable finance was followed by the adoption of the EU Action Plan on Financing Sustainable Growth (European Commission, 2018). The action plan sets the key priorities of the EU efforts to re-shape the way investors decide how to allocate their financing resources. In this regard, the action plan pursued three main objectives:

1. reorient capital flows towards sustainable investment;
2. manage financial risks related to climate changes and major environmental disruptions;
3. increase transparency and long-termism in financial and economic activities.

The strategy set out in the action plan is to provide the EU investment landscape with a clear system to identify green economic activities and, thus, reduce the uncertainty related to this type of investment. This effort resulted in the EU Taxonomy Regulation[18], which entered into force in July 2020. The regulation pursues six overarching environmental objectives (Figure 7.1-25).

Under the umbrella of these objectives, the Taxonomy establishes four conditions that economic activities have to meet in order to qualify as environmentally sustainable (Article 3 of Regulation 2020/852).

1. The activity has to 'contribute substantially' to at least one of the aforementioned environmental objectives.
2. The activity 'does not significantly harm' any of the environmental objectives.
3. Carrying out the activity does not result in the violation of minimum 'social safeguards'[19].
4. The activities comply with technical screening criteria (TSC), which clarify how an economic activity contributes to environmental objectives.

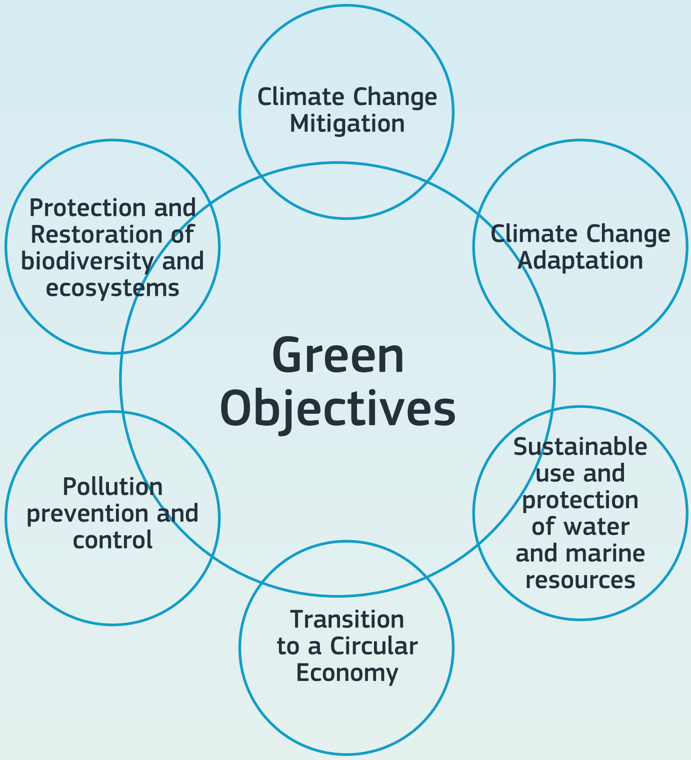
16 https://ec.europa.eu/info/business-economy-euro/banking-and-finance/sustainable-finance/eu-taxonomy-sustainable-activities_en

17 Commission Communication 'Action Plan: Financing Sustainable Growth' (COM(2018) 097 final)

18 Regulation (EU) 2020/852 of the European Parliament and of the Council of 18 June 2020 on the establishment of a framework to facilitate sustainable investment, and amending Regulation (EU) 2019/2088

19 I.e. the activity should respect principles written in the Declaration of the International Labour Organization on Fundamental Principles and Rights at Work, and in the International Bill of Human Rights (Article 18 of Regulation 2020/852).

Figure 7.1-25: **Objectives of sustainable economic activities**



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-7-1-25.xlsx

In line with the objectives of the Green Deal and the EU Taxonomy Regulation, Horizon Europe supports R&I activities that respect EU climate and environmental priorities. As such, the new framework programme for R&I incorporates the 'do no significant harm' (DNSH) principle, according to which R&I activities should not result in a significant harm to any of the aforementioned six environmental objectives. Within the framework programme, the DNSH principle is used to assess the activities carried out during the project, as well as the expected life-cycle impact of the innovation at a commercialisation stage (when relevant).

6. Conclusions: financing innovation – towards a green and digital Europe

To switch successfully to a green and digital economy, the EU needs a considerable amount of investment in innovation activities. EU capital markets remain considerably fragmented, pushing EU companies to rely mainly on domestic markets to meet their financial needs. This results into a heterogeneous degree of access to finance within EU territory, as well as different financing costs between EU countries. Furthermore, bank loans remain the predominant financing instruments in the EU, while equity capital still plays a minor role compared to other international economies. Given the specific characteristics of non-tangible assets, **improving access to finance is essential to untap the growth potential of knowledge-based economies**. Intangible-intensive sectors have strong productivity potential, but typically face more financial constraints than the rest of the economy. As such, these are the segments that would benefit the most from further financial development (Demmou and Franco, 2021). Less financial friction would improve firms' ability to finance their innovation activities, thereby improving their productivity performance. Additionally, progress on the EU capital markets union would positively impact market reallocation processes, increasing productive firms' financial opportunities and easing their access to equity financing (Demmou and Franco, 2021). External financing plays a critical role in enhancing investment opportunities, but its use remains limited to the biggest product innovators with in-house competencies. In contrast, internal funding continues to be the primary source of innovation for all European businesses. **Enhancing access to equity, especially for small innovative firms, is thus key to creating growth opportunities**.

Furthermore, the need to increase access to equity markets has become more pressing with the outbreak of the COVID-19 to balance the considerable increase in company debt levels. The achievement of EU policy objectives strongly depends on the EU's ability to enable a large amount of investment to reach strategic economic segments, thereby supporting the development and adoption of innovative technologies critical to the green and digital transitions. At the same time, **ensuring coherence between already existing instruments in essential to innovation funding**.

The integration of sustainability criteria into the financing of firms is at the heart of the EU strategy to achieve a climate-neutral Europe. With the European Green Deal, the EU puts sustainable finance at the centre of its policy action. The fragilities that emerged with the COVID-19 pandemic, combined with the increasing risks related to climate change, will lead to a massive increase in investment demand. Green technologies critical to achieving the EU net-zero emission targets for 2050 are still at a prototype level, and considerable amount of capital will need to be channelled through the economy, not only to support the greening of EU businesses but also to guarantee that the EU does not lose its technological sovereignty in this field (see Chapter 2.1 – Zoom out: technology and global leadership).

The digitalisation of finance can help to increase access to finance. Digital financing activities are becoming increasingly important in the EU and worldwide. Online financing instruments have the potential to enhance access to finance, especially for EU start-ups and SMEs, which typically encounter significant constraints in meeting their financial needs. **Embracing digital finance will support innovation, creating new opportunities to develop better financial products for both businesses and consumers** (European Commission, 2020). Nevertheless, the increasing digitalisation of finance also poses important challenges. In its Communication of September 2020, the European Commission set the key priorities of its digital finance strategy, including tackling fragmentation in the Digital Single Market, adapting the EU regulatory framework to facilitate digital innovation and promoting data-driven finance while ensuring the protection of consumers.

The gender investment gap remains a concern in the EU. Women-led companies remain significantly underrepresented on the VC market. One of the main barriers to investment in female-led businesses is the lack of women investors, who are typically keener to provide financing support to women entrepreneurs. Promoting gender equality is a key objective of the Horizon Europe programme. With Pillar II, 'Innovative Europe', the new framework programme for R&I aim to create a fair and inclusive R&I ecosystems in Europe. As such, the pillar embeds a series of initiatives deployed mainly under the EIC portfolio.

References

Ambrosio, F., Brasili, A., Niakaros, K. (2021), *European scale-up gap: too few good companies or too few good investors*?, European Commission, Directorate-General for Research and Innovation, https://data.europa.eu/doi/10.2777/886042.

Atomico (2020), *State of European Tech 2020*.

Atomico (2021), *State of European Tech 2021*.

Bellucci, A., Gucciardi, G. and Nepelski, D. (2021), *Venture Capital in Europe. Evidence-based insights about Venture Capitalists and venture capital-backed firms*, EUR 30480 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-26939-7, doi:10.2760/076298, JRC122885.

Benedetti Fasil, C., Domnick, C., del Rio, J-C., Fákó, P, Flachenecker, F., Gavigan, J. P., Janiri, M. L., Stamenov, B. and Testa, G. (2021), *High Growth Enterprises in the COVID-19 Crisis Context demographics, environmental innovations, digitalization, finance and policy measures*, EUR 30686 EN, Publications Office of the European Union, Luxembourg, 2021, ISBN 978-92-76-37269-1, doi:10.2760/63402, JRC124469.

Cambridge Center of Alternative Finance (2021), *The 2nd Global Alternative Finance Market Benchmarking Report*.

Chemmanur, T. J., E. Loutskina, and X. Tian (2014), 'Corporate venture capital, value creation, and innovation', *The Review of Financial Studies*, 27(8), pp. 2434-2473.

Crisanti, A., Krantz, J., Pavlova, E. and Signore, S. (2021), *The VC factor. Pandemic edition. Data driven insights into European VC and its resilience to the COVID-19 crisis*, Joint EIF – Invest Europe study, First online 23 September 2021.

Crunchbase (2020), *Funding to the Female Founders*.

Demmou, L. and G. Franco (2021), *Mind the financing gap: Enhancing the contribution of intangible assets to productivity*, OECD Economics Department Working Papers, No. 1681, OECD Publishing, Paris, https://doi.org/10.1787/7aefd0d9-en.

Duruflé, G., Hellmann, T. and Wilson, K. (2017), *From Start-up to Scale-up: Examining Public Policies for the Financing of High-Growth Ventures*, Bruegel, Issue 04, 201.

EIF (2020), *European Small Business Finance Outlook 2020: The impact of COVID-19 on SME Financing markets*.

European Commission (2018), Action Plan: Financing Sustainable Growth, COM/2018/097 final.

European Commission (2021a), 'Fit for 55': delivering the EU's 2030 Climate Target on the way to climate neutrality, COM(2021) 550 final.

European Commission (2021b), Progress on competitiveness of clean energy technologies, COM(2020) 953 final.

Flachenecker, F., Gavigan, J. P. Goenaga Beldarrain, X., Pasi, G., Preziosi, N., Stamenov, B. and Testa, G. (2020), *High Growth Enterprises: demographics, finance and policy measures*, EUR 30077 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-10615-9, doi:10.2760/34219, JRC119788.

Grassano, N., Hernandez Guevara, H., Fako, P., Tuebke, A., Amoroso, A., Georgakaki, A., Napolitano, L., Pasimeni, F., Rentocchini, F., Compaño, R., Fatica, S. and Panzica, R. (2021), *The 2021 EU Industrial R&D Investment Scoreboard – Executive Summary*, EUR 30902EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-76-44455-8, doi: 10.2760/248161, JRC127360.

Hahn, Davide; Tommaso Minola, Silvio Vismara and Vincenzo De Stasio (2019), 'Financing Innovation: Challenges, Opportunities, and Trends', *Foundations and Trends® in Entrepreneurship*, 15(3-4), pp. 328-367. http://dx.doi.org/10.1561/0300000085-1.

Hall, B. H., & Lerner, J. (2010), *The financing of R&D and innovation*, In Handbook of the Economics of Innovation, 1, pp. 609-639. North-Holland.

Hall, B. H., P. Moncada-Paternò-Castello, S. Montresor, and A. Vezzani (2016), 'Financing constraints, R&D investments and innovative performances: New empirical evidence at the firm level for Europe', *Economics of Innovation and New Technology*, 25(3), pp. 183-196.

Harrison RT, Mason CM (2007), 'Does Gender Matter? Women Business Angels and the Supply of Entrepreneurial Finance', *Entrepreneurship Theory and Practice*, 31(3), pp. 445-472, doi:10.1111/j.1540-6520.2007.00182.x.

Kraemer-Eis, H. and Conforti, A. (2009), *Microfinance in Europe. A market overview*, EIF Working Paper 2009/001, EIF Research & Market Analysis, November 2009.

Kraemer-Eis, H., and Lang F. (2017), 'Access to funds: how could CMU support SME financing?', *Vierteljahrshefte zur Wirtschaftsforschung*, 86(1), pp. 95-110.

Kraemer-Eis, H., Botsari, A., Gvetadze, S., Lang, F. and Torfs, W. (2020), *European Small Business Finance Outlook*, EIF Working Paper 2020/67, EIF Research & Market Analysis, September 2020.

Kraemer-Eis, H., Botsari, A., Gvetadze, S., Lang, F. and Torfs, W. (2021), *The European Small Business Finance Outlook 2021*, EIF Working Paper 2021/75, EIF Research & Market Analysis.

Kraemer-Eis, H., Signore, S., and Prencipe, D. (2016), *The European venture capital landscape: an EIF perspective*, EIF Research & Market Analysis.

Mason, C. (2020), *The Coronavirus Economic Crisis: Its Impact on Venture Capital and High Growth Enterprises*, Gavigan, J. editor, Publications Office of the European Union, Luxembourg , ISBN 978-92-76-18432-4, doi:10.2760/408017, JRC120612.

Mazzucato M. (2016), 'Innovation, the State and Patient Capital', *The Political Quarterly*, 86, pp. 98-118, https://doi.org/10.1111/1467-923X.12235.

Napp, J. J., and Minshall, T. (2011), 'Corporate Venture Capital Investments for Enhancing Innovation: Challenges and Solutions', *Research-Technology Management*, 54(2), pp. 27-36, DOI: 10.5437/08953608X5402004.

OECD (2015), *New Approaches to SME and Entrepreneurship Financing: Broadening the Range of Instruments*, OECD Publishing, Paris. http://dx.doi.org/10.1787/9789264240957-en.

Quas, A., Mason, C., Compano, R., Gavigan, J. and Testa, G. (2021), *Tackling the Scale-up Gap*, EUR 30948 EN, Publications Office of the European Union, Luxembourg, ISBN 978-92-76-46712-0, doi:10.2760/982079, JRC127232.

Reypens, C., Delanote, J. & Rückert, D. (2020), *From* Starting to Scaling: *How to foster startup growth in Europe*, EIB, May 2020.

Testa, G., Compano, R., Correia, A. and Rückert, E. (2022), *In search of EU unicorns -What do we know about them*, EUR 30978 EN, Publications Office of the European Union, Luxembourg, 2022, ISBN 978-92-76-47058-8, doi:10.2760/843368, JRC127712.

Wa4e (2018), *The Barriers and Opportunities for Women Angel Investing in Europe*.

CHAPTER 7.2

OTHER FRAMEWORK CONDITIONS

KEY QUESTIONS WE ARE ADDRESSING

- How does the functioning of institutions and markets affect R&I?
- What does 'institutional quality' mean?

KEY MESSAGES

What did we learn?

- Good institutions are characterised by political stability, transparency and accountability, and show solid rule-of-law guarantees with a low risk of expropriation and corruption.
- Regulation can be a powerful instrument to foster innovation in the EU.
- Access to efficient digital infrastructure and data is essential to foster the EU digital transition, but the ability of EU firms to invest in digitalisation varies significantly across EU regions.
- The engagement of civil society in science has been a key focus of R&I policies at the EU level.

What does it mean for policy?

- The emergence of new practices, technologies and business models and the pacing problem due to the acceleration of innovation call for more flexible and experimental approaches to regulation, such as regulatory sandboxes.
- A wide use of public procurement on innovation by EU public authorities is hampered by implementation barriers.
- To fully reap the benefits of the digital transformation, it is necessary to create a safe and inclusive digital space for both citizens and EU enterprises.
- Citizens need to be engaged in R&I, as they are critical to enriching it, reinforcing trust in science and facilitating the innovation process and its uptake by industry and citizens.

1. Institutional and regulatory environment

The quality of countries' institutions shapes their innovation and economic performance. Institutions are the 'rules of the game' in a society or, more formally, the humanly devised constraints that shape human interaction (North, 1981). A growing branch of the literature is studying the impact of institutions on economic growth and technological change. The main argument is that since institutions (such as property rights, balance of political power, organisation of markets, democracy, etc.) determine the incentives and constraints of economic actors, they will shape individual behaviour and economic outcomes[20].

Good institutions are characterised by political stability, transparency, accountability, and show high degrees of rule of law with low risk of expropriation and corruption. The economic gains of secure property rights stem from the fact that they lower the transaction costs of trade and the costs of monitoring and enforcing contracts. A lack of property right enforcement will increase the likelihood that future profits from current investments may be lost, either through theft or outright government expropriation (Olson, 2000). Individuals and firms are unlikely to risk their own capital and resources if they are unsure about the returns. Countries with strong property rights protection tend to show better economic performance[21]. Nonetheless, China has been able to achieve remarkable economic results despite the absence of credible property rights protection (Li, 2015). Private ownership has drastically increased over the years without the rule of law to provide reassurance on the protection of such ownership. With a one-party political set up and no independent judicial system to protect property rights, private investors seem to be taking big risks. Several explanations have been proposed for how China has been able to compensate its institutional deficiencies and make credible commitments to investors. Research on property rights in China often refers to social networks (Nee and Opper, 2012; Wang, 2014; Tsai, 2002; Wang, 2002; Wank, 2001), fiscal federalism (Oi and Walder, 1999; Qian and Weingast, 1997; Weingast, 1995), or the personnel control system (Li and Zhou, 2005).

During the COVID-19 pandemic, there was a rising consensus among countries to request a temporary waiver of intellectual property rights for COVID-19 vaccines. India and South Africa were among the first proponents[22], however the United States also affirmed its support in principle. The European Union and the United Kingdom opposed the proposal. They argued that intellectual property right played a 'positive role' in generating innovative vaccines and provide an incentive to further work to address new variants of the virus. They suggested less

20 See North (1981), Spolaore and Wacziarg (2013), Acemoglu et al. (2002, 2005), Besley and Persson (2011), Robinson and Acemoglu (2012).

21 Acemoglu et al. (2001) showed empirically how the colonies where European colonisers tried to replicate European institutions, with strong emphasis on private property rights and checks against government power (e.g. Australia, New Zealand, Canada, the United States), performed much better after independence than the colonies where the European settlers established extractive systems without attempting the introduction of similar institutions.

22 See https://timesofindia.indiatimes.com/india/india-south-africa-moot-3-year-covid-patent-waiver/articleshow/82868816.cms

radical measures such as encouraging the voluntary licensing of vaccines to allow others to manufacture doses. Thanks to the remarkable rise in COVID-19 vaccine production, there is currently more of an allocation problem than a supply problem[23], with the rollout of vaccination campaigns in lower-income countries being one of the greatest challenges[24].

Strong institutions help to generate a more innovative environment. Institutional quality is strongly associated to innovation capacity, and this relationship is confirmed for different country samples[25]. Figure 7.2-1 depicts the positive relationship between the Global Innovation Index[26], as well as GDP per capita, and various measures of institutional quality: rule of law[27], regulatory quality[28] and control of corruption[29]. The scatterplots contain cross-country-level data for around 180 nations, from the last available year. Figure 7.2-1 highlights how countries with better performance as regards the rule of law, property rights enforcement and control of government corruption also tend to show better innovation and economic outcomes. Even though the presented plots do not represent causal evidence, they are an instructive descriptive depiction of the relationships at play.

Northern European countries such as Finland, Denmark and Sweden are among the best performers in the world as regards rule of law, private property enforcement and judicial efficiency, ranking above the other EU Member States, as well as many international competitors such as the US, the UK, Japan and South Korea. Among the countries with weaker performance in this respect are Bulgaria and Italy. On average, the EU has a very similar level of rule of law to that of the US. China is a special case, managing to obtain significant economic and innovation success while maintaining relatively low (according to the proposed definition) institutional quality. The explanation behind this is still being debated, from those claiming that it is a short-term exception to those calling for a new paradigm of analysis.

23 See https://www.who.int/campaigns/vaccine-equity

24 See https://www.oecd.org/coronavirus/policy-responses/coronavirus-covid-19-vaccines-for-developing-countries-an-equal-shot-at-recovery-6b0771e6/#endnotea0z8

25 Rodríguez-Pose and Di Cataldo (2015) focus on EU countries; Tebaldi and Elmsie (2013) on a sample of OECD and non-OECD countries; Hussen and Çokgezen (2021) on a sample of African countries.

26 The Global Innovation Index ranks the innovation ecosystem performance of economies around the globe, relying on 81 different indicators ranging from R&D intensity, education, patenting, ICT and infrastructure to political institutions.

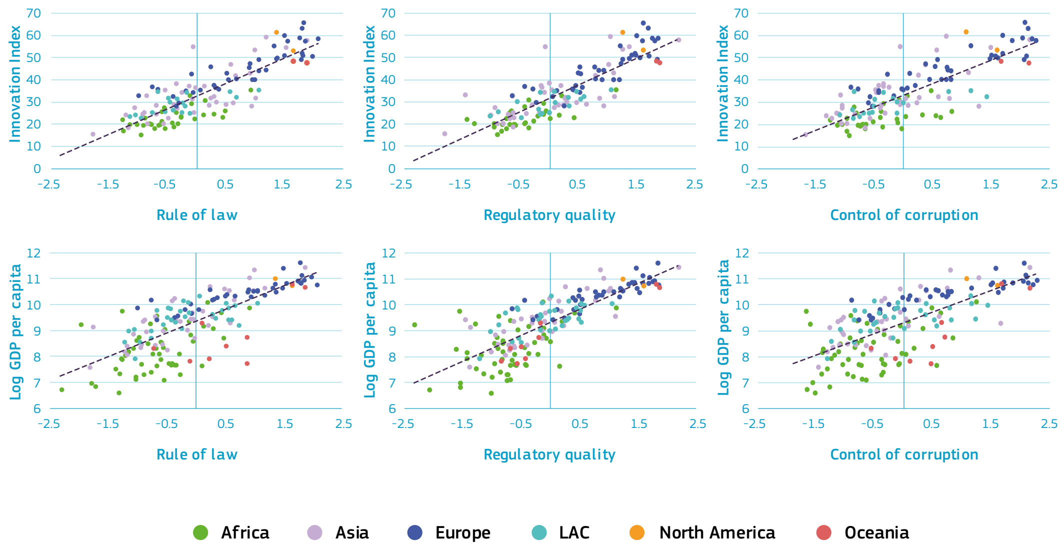
27 'Rule of law' measures the extent to which agents have confidence in and abide by the rules of society, and in particular the quality of contract enforcement, property rights, the police and the courts, as well as the likelihood of crime and violence.

28 'Regulatory quality' measures the ability of the government to formulate and implement sound policies and regulations that permit and promote private-sector development.

29 'Control of corruption' measures the extent to which public power is exercised for private gain, including both petty and grand forms of corruption, as well as capture of the state by elites and private interests.

Regulation can both hinder and encourage innovation. Regulation matters at all stages of the innovation process, but the relation between regulation and innovation is complex (Porter, 1990; Porter and van der Linde, 1995; Ashford and Hall, 2011; Pelkmans and Renda, 2014). On the one hand, regulation can be a **barrier to innovation when it is not properly designed.** Ineffective regulation raises compliance costs, using up entrepreneurs' resources and time. Inflexible regulation or regulation that lags behind innovation cycles can, for example, prevent the commercial introduction of an innovative product or its scaling up. Prescriptive regulation may also not generate sufficient incentives for firms to seek improvement of their product or service beyond what is specified in the regulation.

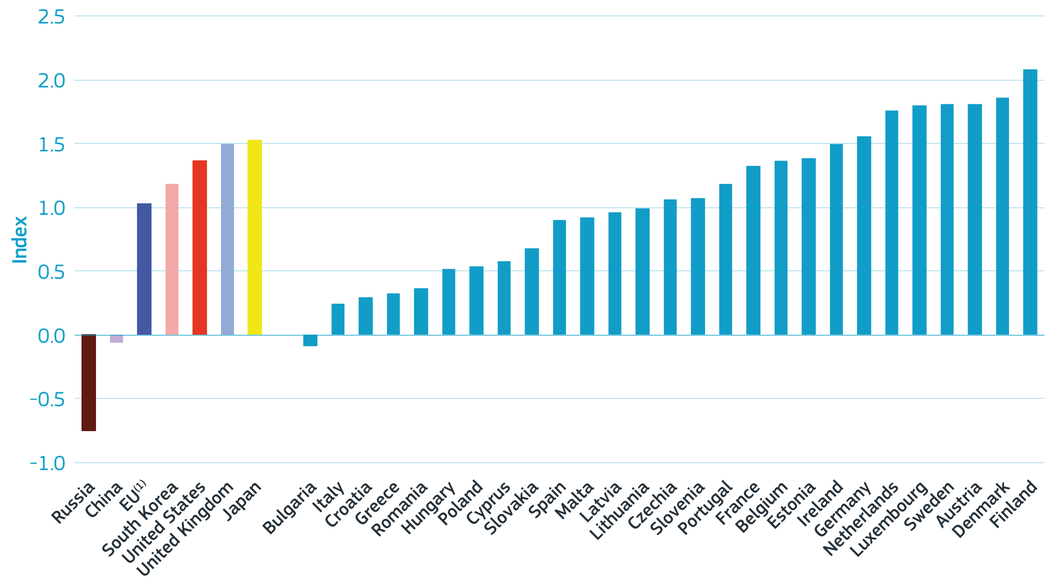
Figure 7.2-1: Institutions vs Economic and Innovation output, 2020



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Unit Service – Chief Economist Unit, own elaboration.
Note: The Global Innovation Index is produced by Cornell University, INSEAD and the World Intellectual Property Organization. GDP per capita, PPP (constant 2017 international dollars) is collected from the World Bank database. The rule of law, regulatory quality and control of corruption measurements are taken from the Worldwide Governance Indicators (WGI) of the World Bank.
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-7-2-1.xlsx

Figure 7.2-2: Rule of law, 2020



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Unit Service – Chief Economist Unit, own elaboration based on 'Rule of law' measurements from the WGI of the World Bank

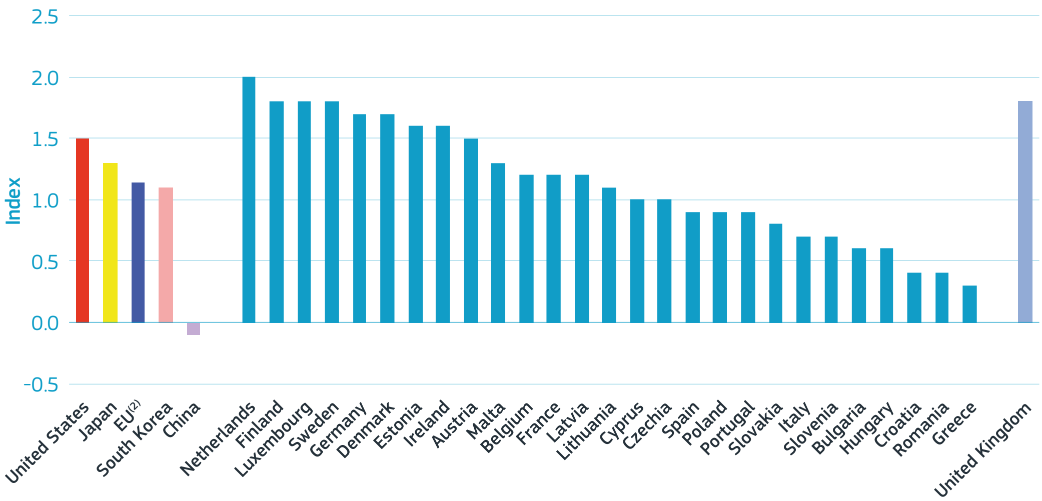
Note: [1]EU is an unweighted average of the 27 Member States.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-7-2-2.xlsx

On the other hand, regulation can act as a **major driver of innovation**. It brings stability and certainty, which matter for investment and planning and enable firms to work on safe legal ground. It can also create strong stimulus for innovation through standard setting or regulatory stringency. Standard setting may improve market functioning as it provides guidance to producers for the design of a new and innovative product, while increasing trust among customers in a product that is yet unknown. Stringency can provide strong incentives to businesses to innovate and shift from outdated techniques and procedures to new ones (EPSC, 2016). In particular, strict environmental regulations can encourage innovations that help to improve commercial competitiveness (Porter and van der Linde, 1995). Regulation may also have impacts on innovation at the systemic level, when it shifts investment opportunities to different actors. This could occur, for example, in the context of the twin transition, supported by the European Green Deal and the digital-transformation priorities.

Hence, regulation can be a powerful instrument to foster innovation in the EU. However, several factors can prevent this. On the one hand, the EU is faced with challenges common to other regulatory systems, e.g.: how to ensure that regulation is agile enough to adapt rather than react to the pace of innovation; and when and how to regulate disruptive innovation, while only limited evidence is available. In addition, EU-specific challenges may also come into play. These include the length of the legislative process, risks of market fragmentation if the same innovation is treated differently across Member States, and problems in national implementation of EU regulation (inadequate transposition

Figure 7.2-3: Regulatory quality index(1), 2020



Science, Research and Innovation Performance of the EU 2022

Source: Global Innovation Index, World Bank.

Note: (1)Regulatory quality is a sub-index of the Global Innovation Index, which captures perceptions of the government's ability to formulate and implement sound policies and regulations that permit and promote private-sector development. (2)The figure for EU is an unweighted average of the 27 Member States.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-7-2-3.xlsx

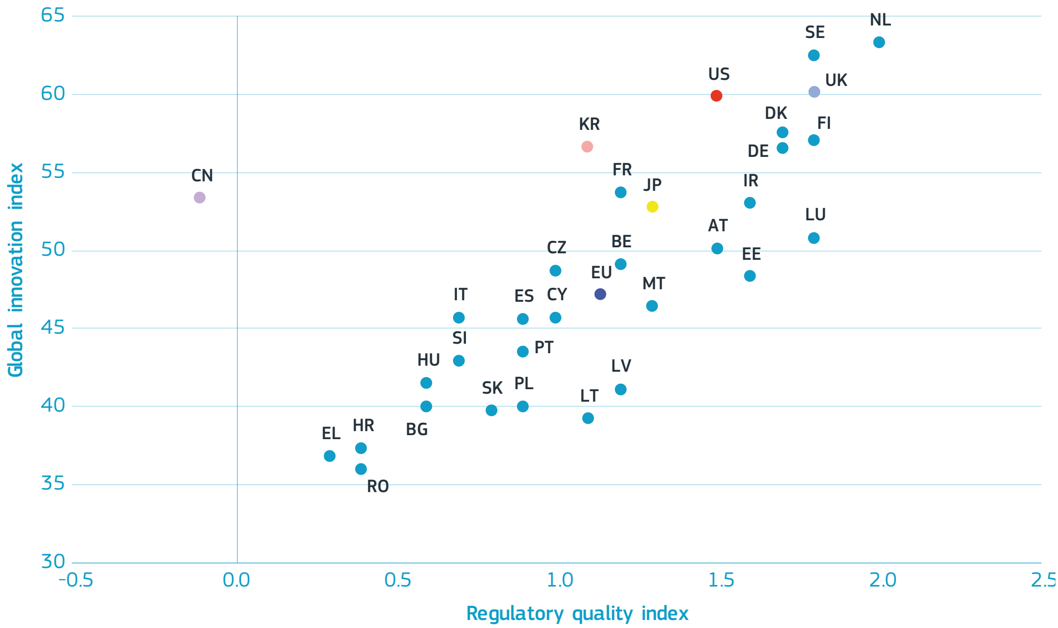
or implementation, gold-plating, burdens or obstacles to the delivery phase of the legislation) (Pelkmans and Renda, 2014; Ashford and Renda, 2016; Peter et al., 2017). These factors can also discourage investment and limit innovation.

Moreover, regulatory quality seems to differ significantly across EU Member States. The (perceived) government ability to formulate and implement sound policies and regulations for promoting private-sector development is highest in the Netherlands, Finland, Luxembourg, Sweden, Germany and Denmark, which also show stronger R&I performance compared to other countries (according to the Global Innovation Index). Countries with lower regulatory quality, such as Greece, Romania, Croatia and Bulgaria, also tend to perform less well in terms of R&I. Compared to the US, EU countries present on average a lower perceived regulatory quality. China shows the lowest score on this indicator, while still presenting a strong R&I performance.

Innovation plays a role in the design of EU legislation. Recent efforts aim to reinforce innovation-related considerations, both in terms of possible impacts of policies on innovation but also the influence that innovation itself can have on the design and implementation of EU policies and legislation. In particular, DG Research and Innovation is stepping up efforts within the European Commission to implement the **innovation principle**[30] at all relevant stages of policymaking and to create future-proof framework conditions for achieving sustainable development. The innovation principle is an approach ensuring that the processes of preparing, revising and implementing EU legislation take into account emerging innovations that are in line with EU policy objectives, facilitating their

30 https://ec.europa.eu/info/research-and-innovation/law-and-regulations/innovation-friendly-legislation_en

Figure 7.2-4: Regulatory quality index and global innovation index, 2020



Science, Research and Innovation Performance of the EU 2022

Source: Global Innovation Index, World Bank
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-7-2-4.xlsx

development and adoption. This simultaneously requires policy to become more agile – able to adapt and adjust to changing circumstances – while introducing regulatory certainty and relevant legal protection where necessary.

The pacing problem, due to the acceleration of innovation, calls for more flexible and experimental approaches to regulation, such as regulatory sandboxes, which aim to test new solutions or alternative business models in a controlled real-world environment before admitting them to the market. Current regulatory sandboxes in the EU context cover genuine innovations that are expected to deliver consumer and/or wide societal benefits. They allow the regulator some flexibility while maintaining regulatory standards, and they facilitate learning, keeping up with developments in the sector and strengthening ties between regulators from different policy fields (see Box 7.2-1).

In 2021, the European Commission launched the "EU Startup Nations Standard" initiative with the support of Ministers in 27 countries (26 Member States and Iceland. This initiative identified 8 areas of action to ensure that innovators in Europe are provided with framework conditions capable of optimising growth. Among these areas there are regulatory sandboxes, wider use of innovation public procurement, and inclusive digital spaces.

Box 7.2-1: Regulatory sandboxes and other forms of experimentation

Broadly speaking, a regulatory sandbox is a scheme that enables the testing of innovations in a controlled real-world environment, under a specific plan developed and monitored by a competent authority. Sandboxes usually entail a temporary loosening of applicable rules, and feature safeguards to preserve overarching regulatory objectives, such as safety and consumer protection[31]. They are a relatively new phenomenon in most regulatory systems, and experience with implementation of such sandboxes is still limited. At the EU level, initiatives paving the way for sandboxes include the Commission proposal for a regulation on AI[32] and the pilot regime for market infrastructures based on distributed ledger technology (DLT)[33]. At national level, over half of the Member States have set up sandboxes and additional ones are in the pipeline. Applications of sandboxes are mostly in the areas of finance, transport and energy.

Closely connected to sandboxes are experimentation clauses: these enable authorities tasked with implementing and enforcing legislation to exercise a degree of flexibility in relation to innovative technologies, products or approaches, even if they do not conform to all existing legal requirements. Experimentation clauses can serve as the legal basis for sandboxes or simply allow for flexibility under certain circumstances. Other forms of experimentation exist without being a fully-fledged sandbox. Worth mentioning are test beds, living labs[34] and the European Blockchain Services Infrastructure (EBSI) to build a pan-European blockchain infrastructure for the delivery of public services. Finally, innovation deals offer another possibility to tackle real or perceived barriers to innovation[35]. They contribute to future-proof EU legislation by addressing perceived EU regulatory obstacles to innovative solutions. By fostering learning and facilitating the uptake of innovation in line with key policy objectives such as consumer safety and environmental protection, all the above tools can usefully complement traditional efforts to improve regulatory quality.

31 For further details, see, among others, the Council conclusions of 16 November 2020 on regulatory sandboxes and experimentation clauses.

32 The proposal provides a common framework for the establishment and implementation of AI regulatory sandboxes by one or more Member-State competent authorities or the European Data Protection Supervisor, and the coordination of those schemes within the European Artificial Intelligence Board (Article 53). Article 54 also provides the legal basis for the further processing of personal data for the development of certain innovative AI systems in the public interest subject to certain conditions.

33 Proposal for a Regulation of the European Parliament and of the Council of 24 September 2020 on a pilot regime for market infrastructures based on distributed ledger technology (COM(2020) 594). This proposal is part of a package of measures to further enable and support the potential of digital finance in terms of innovation and competition, while mitigating the risks. Together with a bespoke regime for crypto-assets (proposal for a regulation of the European Parliament and of the Council of 24 September 2020 on markets in crypto-assets, and amending Directive (EU) 2019/1937, (COM(2020) 593)), they represent the first concrete actions in this area, seeking to provide appropriate levels of consumer and investor protection, legal certainty for crypto-assets, to enable innovative firms to make use of blockchain, DLT and crypto-assets, and to ensure financial stability.

34 For an overview, see Alonso Raposo et al. (2021).

35 Innovation deals are a stakeholder-led voluntary process to create a shared understanding between innovators and policymakers on to what extent existing EU legislation accommodates beneficial innovations. For further details, see Tool #22 on research and innovation in the 'better regulation' toolbox.

The European Commission is set to analyse the state of play regarding regulatory sandboxes and to create an overview of main experimentation clauses in EU law. A stocktaking exercise[36] was completed under the Slovenian Presidency of the EU. Experimentation clauses and regulatory sandboxes are already mentioned in the 'better regulation' toolbox as a means of encouraging innovation. At the same time, experimentation in innovation agencies was supported by pilot projects under the Horizon 2020 programme. Experimentation for policy development is also included in the Horizon Europe Strategic Plan 2021-2024. Finally, it is tackled under the widening of the European Research Area agenda.

Competition law is a key element of ensuring well-functioning markets and innovation. Markets need rules to operate well and to be competitive. Competition law helps to foster free and open competition. The functioning of markets is closely interlinked with innovation performance. Aghion et al. (2005) find strong evidence of an inverted-U relationship between product market competition and innovation, with most sectors being located at the upward sloping segment of the curve, where increased competition fosters innovation. Non-competitive markets, with barriers to starting and operating a business, hamper the innovation potential of economies. The negative impact of malfunctioning markets on innovation becomes more pronounced when financial markets are not sufficiently developed and cannot provide alternative financing to young and new companies, especially those based on intangible assets that face more difficulties in providing collateral. At the same time, innovative activities require adequate protection through intellectual property rights. Although intellectual property can be overused and misused (see Boldrin and Levine, 2002), it remains an important pillar of successful innovation policies.

Competition policy has contributed to preserving and fostering the EU's economic prosperity. Vigorous competition enforcement has served European consumers, citizens and businesses, by empowering them to make choices in the marketplace and benefit from innovative products and services at affordable prices. The European Single Market, together with the continuous use of all competition instruments (merger law, antitrust law and state-aid control) will be crucial in leading EU industries toward the twin transitions while allowing consumers a fair share of the resulting benefits. EU competition policy helps to set the right incentives for companies to use resources efficiently, avoid stranded assets and innovate their production processes towards greater sustainability. Indeed, regulators need to remain vigilant, including in light of the increasing market power of some firms and the acceleration of this trend during the COVID-19 pandemic.

The potential of public procurement to bring innovative solutions to the market is not fully exploited in Europe. Public buyers in the EU spend around 17% of GDP on public procurement every year, amounting for more than €2.3 trillion per year[37]. Procurement represents a key source of demand for firms in sectors such as construction, health care, space and defence systems, energy and transport. The public sector can employ innovation procurement as a powerful demand-side instrument for tackling societal challenges (Lember et al., 2014), and this use of public demand as an engine for the development, uptake and diffusion of innovation has attracted interest both at EU and national levels. In 2004, France,

36 https://data.consilium.europa.eu/doc/document/ST-10338-2021-INIT/en/pdf.

37 www.eafip.eu. This spending consists of €1 765 billion (13% GDP) of public procurement performed by public authorities, €436 billion (3,5% GDP) by public procurers in the energy, transport, postal, water and waste management sector and €75 billion (0,5% GDP) by defence procurers.

Germany and the UK issued a position paper (French, German, UK Governments, 2004) to the European Council calling for the use of public procurement across Europe to spur innovation, which was continued by various calls of the Council of the European Union[38]. In 2015, the European Research Area and Innovation Committee (ERAC) in the Council adopted a position with 5 concrete recommendations to mainstream innovation procurement across Europe: creating national strategies and action plans, financial incentives, national competence centres, EU wide knowledge sharing and an EU wide monitoring system for innovation procurement with an indicator in the EU Innovation Scoreboard.

In order to address these challenges, several actions have already been taken at national and EU level. At national level, 10 Member States have meanwhile setup **national action plans or strategies for innovation procurement**, 12 have national competence centres, 13 provide national financial incentives and 9 setup national monitoring. 11 Member States have already implemented policies that encourage public buyers to leave IPR ownership in public procurements as much as possible with contractors in line with the recommendation of the EU IPR action plan. At EU level, the European Commission has gradually reinforced since 2013 **EU financial incentives for innovation procurement**. Grants in EU funding programmes such as Horizon 2020, Horizon Europe, COSME, Innovation Fund, CEF, Digital Europe Program and the European Structural Funds have already co-financed hundreds of innovation procurements and the new Recovery and Resilience Facility will fund many more to come. The EIB has also provided loans to Member States for innovation procurement programs. The Commission also funded the creation of a **European network of national competence centres on innovation procurement[39]** and a **European Assistance For Innovation Procurement[40]**. In 2021, the Commission also published the first **EU-wide benchmarking on national policy framework and investments on innovation procurement** and is preparing to launch the second one to take stock of progress made meanwhile[41] and is preparing to launch the second one to take stock of progress made meanwhile.

Evidence has also been building up on the positive impacts of innovation procurement both for public buyers and participating companies and researchers. Literature suggests that innovation procurement has a positive impact on private spending on research and innovation activities and innovation commercialisation success (Edquist and Zabala-Iturriagagoitia, 2012), and it also appears that innovative public procurement may be more effective than R&D grants in stimulating private expenditure on innovation (Guerzoni and Raiteri, 2015). EU funded pre-commercial procurements have proven to decrease costs of innovative solutions with 20% for public buyers, increase interoperability of solutions with 50%, open up 20 times more cross-border sales opportunities for companies, almost triple the amount of contracting from SMEs and more than double their commercialisation success rate[42]. Similar effects have been observed in such procurements across Europe[43]. A 2004 Eurobarometer survey also showed that com-

38 See in particular: COMP Council Conclusions (30 May 2008, 26 May 2010, 21 Feb 2014, 27 May 2016), EU Council Conclusions (4 Feb 2011, 26 April 2012 and 25 October 2013) and EP resolution on PCP (3 Feb 2009)

39 https://procure2innovate.eu/home/.

40 www.eafip.eu provides local innovation procurement assistance to public buyers across EU Member States.

41 Impacts of EU funded Pre-Commercial Procurements, published on EU webpages

42 Impacts of EU funded Pre-Commercial Procurements, published on EU webpages

43 Comparison of impacts of national and EU level pre-commercial procurements, published on EU webpages

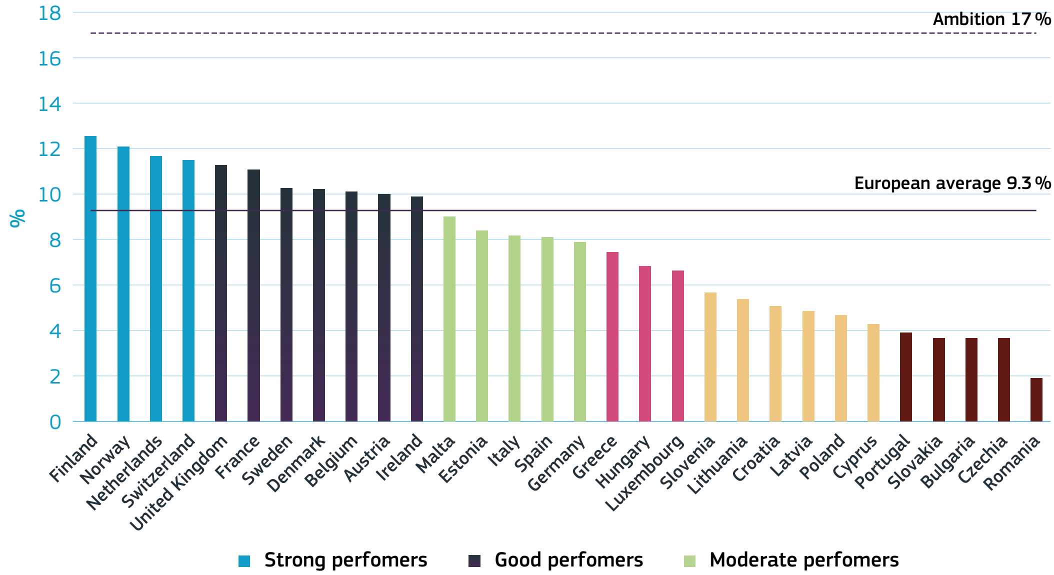
panies that participated in a public procurement of innovative solutions, were four times more likely to win additional procurement contracts later (European Commission, 2004). It is also argued that a healthy economy needs approximately 20% of its public procurement expenditure to be devoted to innovation procurement investments in order to reach a sufficient level of early adopters that are needed to encourage the rest of the market to widely adopt the innovations afterwards (3% to public procurement of R&D to trigger the development, pilot deployment and testing of innovations, and 17% to public procurement of innovative solutions to stimulate early adoption of solutions)[44].

Despite the efforts, public buyers across Europe are still not widely implementing innovation procurement (Figure XX). Benchmarking across 30 European countries212 demonstrated that in 2018 these countries devoted 9.6% of their total public procurement expenditure (10.6% when including defence) to the purchase of innovative solutions, an equivalent of €265 billion excluding defence and €305 billion including defence. This consisted of €16,6 billion of R&D procurement (€10,2 billion excluding defence) and €288 billion of procurement of innovative solutions (€255 billion excluding defence). This means that R&D procurement investments were still only at 0,6% instead of 3% of total public procurement expenditure, while investments in public procurement of innovative solutions were at 9,3% instead of 17% of total public procurement. While a doubling of overall innovation procurement investments is needed to reach 20% of public procurement expenditure, the biggest increase (with a factor 5) is needed for R&D procurements.

The underlying factors explaining underinvestment are linked to the status of development of national policy frameworks for innovation procurement. On average, the 30 countries around Europe have so far only deployed one quarter (26,6%) of the potential measures to stimulate innovation procurement. However, countries with stronger national policy frameworks that have deployed a more comprehensive set of policy measures also achieve higher national investments in innovation procurement, and as a result faster public sector modernisation and faster industrial growth. The benchmarking therefore concluded that additional EU and national efforts are needed to substantially reinforce both policy frameworks and investments in innovation procurement.

44 See Commission notice on innovation procurement C(2018)3051, based on the Bell innovation curve for conservative sectors

Figure 7.2-5: **Benchmarking of national procurement for innovative solutions out of total public procurement expenditure (including defence), 2018**



Science, Research and Innovation Performance of the EU 2022

Source: European Commission (2021a).

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-7-2-5.xlsx

2. Economic freedom and the flexibility of the labour market

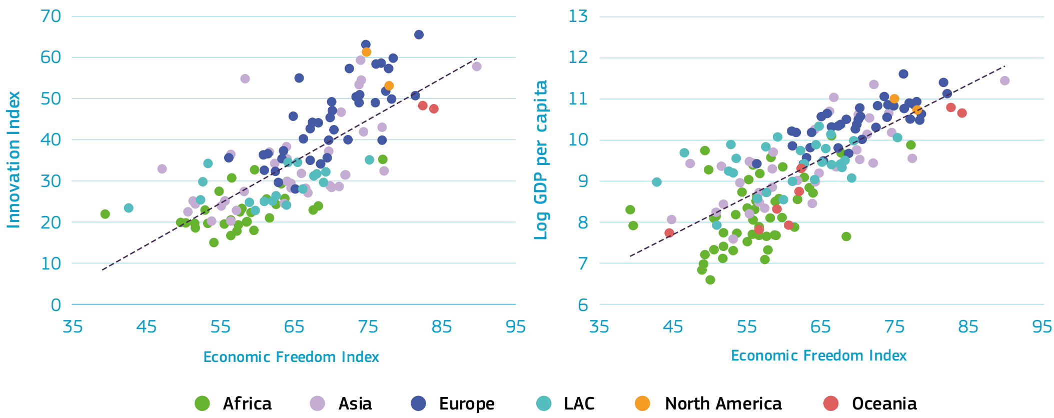
Economic freedom[45] leads to greater prosperity and innovation. The freedom of individuals to work, produce, consume and invest according to their preferences, within a clear, simple and supportive regulatory environment and with cohesive political institutions promoting common interests, is a crucial prerequisite for socioeconomic growth (Robinson and Acemoglu, 2012; Besley and Persson, 2011). The empirical literature on the impact of economic freedom on economic growth is wide, with most studies finding a positive association between measures of economic freedom and economic growth (Berggren, 2003; De Haan et al., 2006). Other studies report evidence on the relationship between economic freedom and innovation. For example, Zhu and Zhu (2017) uses firm-level data in the US to find a positive association between economic freedom and corporate innovation (measured by patent filings and citations), while controlling for other factors. At the same time, Kuckertz et al. (2016) shows how economic freedom has a greater explanatory power for economies in the earlier stages of development than for innovation-driven economies. According to the authors, this happens because economic freedom eases necessity-driven entrepreneurship (NDE) more than opportunity-driven entrepreneurship (ODE).

Figure 7.2-6 depicts the positive relationship between the Index of Economic Freedom[46] and the Global Innovation Index, as well as GDP per capita. The scatterplots contain cross-country level data for around 180 nations, highlighting how countries with a higher overall degree of economic freedom perform better in terms of prosperity and innovation. Even though the presented plots do not represent causal evidence, they are an instructive descriptive depiction of the relationships at play.

45 Gwartney and Lawson (2003) define economic freedom as a multidimensional concept composed of 'personal choice, voluntary exchange, freedom to compete, and protection of persons and property'. Gwartney and Lawson (2008) extend the concept of economic freedom to consist of five elements: (1) the size of government (government spending, taxes and government enterprises), (2) property rights enforcement, (3) sound money (monetary and inflationary policies), (4) open trade policies, and (5) regulation of business, labour and credit markets. An explanation of the theoretical mechanisms according to which each of these components may affect economic performance can be found in Justesen (2008).

46 The Economic Freedom Index is a composite index produced by The Heritage Foundation in collaboration with The Wall Street Journal. It ranks countries based on their degree of economic freedom using 12 variables that can be grouped into four broad categories: (1) rule of law (property rights, government integrity and judicial effectiveness), (2) government size (government spending, tax burden, fiscal health), (3) regulatory efficiency (business freedom, labour freedom and monetary freedom), (4) open markets (trade freedom, investment freedom, financial freedom). In a similar analysis, Carlsson and Lundström (2002) discuss critically the benefits and drawbacks of using such composite indices of freedom.

Figure 7.2-6: Economic Freedom Index(1) and Global Innovation Index(2) (left panel), and GDP per capita(3) (right panel), 2020



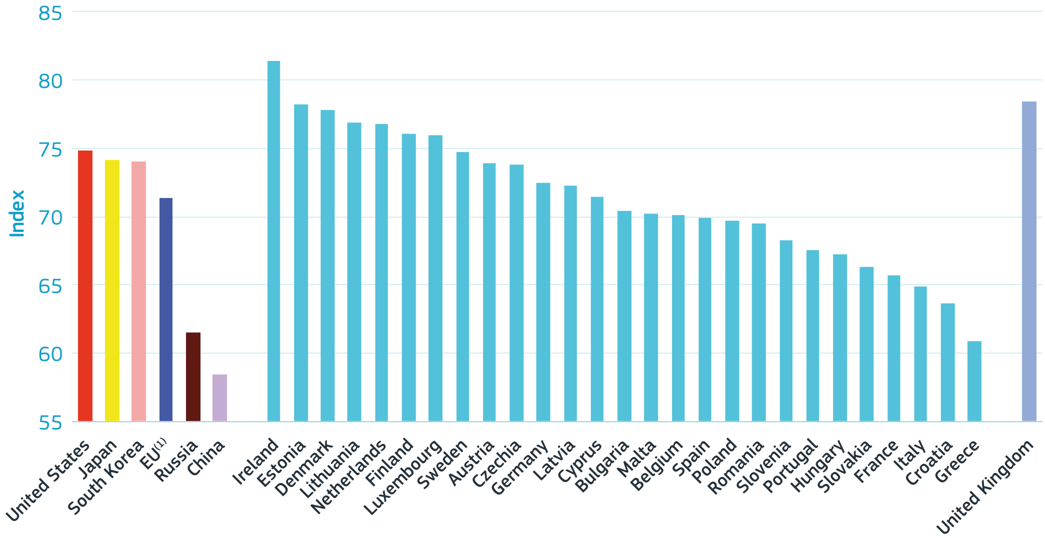
Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Unit Service – Chief Economist Unit, own elaboration.
Note: (1)"Economic freedom index" measurement is taken from The Heritage Foundation in collaboration with The Wall Street Journal (2021 edition). (2)The Global Innovation Index is produced by the Cornell University, INSEAD, and the World Intellectual Property Organization. (3)GDP per capita, in PPP (constant 2017 international $) is collected from the World Bank database.
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-7-2-6.xlsx

Ireland and the UK present the highest level of economic freedom in Europe, closely followed by Nordic countries such as Denmark, Lithuania, the Netherlands and Finland. Noticeably, northern European countries present higher levels of economic freedom than the US, Japan and South Korea. The social contract in these Nordic countries combines relatively high taxation and generous welfare state provisions with highly liberalised markets, secure property rights and rigorous public-spending discipline. European nations with less economic freedom are Greece, Croatia and Italy. Contrary to the general pattern, China has a strong innovation and economic performance despite its low degree of economic freedom.

A more flexible labour market is generally associated with more efficient resource allocation, higher employment and productivity. The facilitation of hiring and reduction of dismissal costs provides firms with incentives to hire workers and invest, especially when engaging in innovative activities with highly uncertain outcomes. Rigidities in salary structures and complex firing practices have negative bearings on firms' investments and may discourage the adoption of innovation, hampering growth prospects (Tressel and Scarpetta, 2004; Thum-Thysen et al., 2017). At the same time, it is necessary to underline that 'flexible' shall not be misunderstood as 'unregulated' or 'unfair', as unregulated markets rarely lead to optimal outcomes.

Figure 7.2-7: Economic Freedom index, 2020



Science, Research and Innovation Performance of the EU 2022

Source: DG Research and Innovation – Common R&I Strategy and Foresight Unit Service – Chief Economist Unit, own elaboration based on the economic freedom measurement from The Heritage Foundation in collaboration with The Wall Street Journal (2021 edition).

Note: [1]EU is an unweighted average of the 27 Member States.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-7-2-7.xlsx

The relationship between labour market flexibility and innovation is more nuanced. On the one hand, a more flexible and competitive labour market may allow more efficient allocation of resources and reduction of barriers to entry, possibly leading to more innovation activity. On the other hand, more employment security can facilitate research projects that typically require longer-term commitments from researchers and management. Empirical research has found that the impact of labour market flexibility on innovation depends on the type of innovation and the sector (Bassanini and Ernst, 2002; Arvanitis, 2005; Lucidi and Kleinknecht, 2010; Wachsen and Blind, 2016; Hoxha and Kleinknecht, 2020). For example, Cetrulo et al. (2019) find a negative correlation between temporary employment and innovation in those sectors where tacit firm-specific knowledge is crucial for the innovation process.

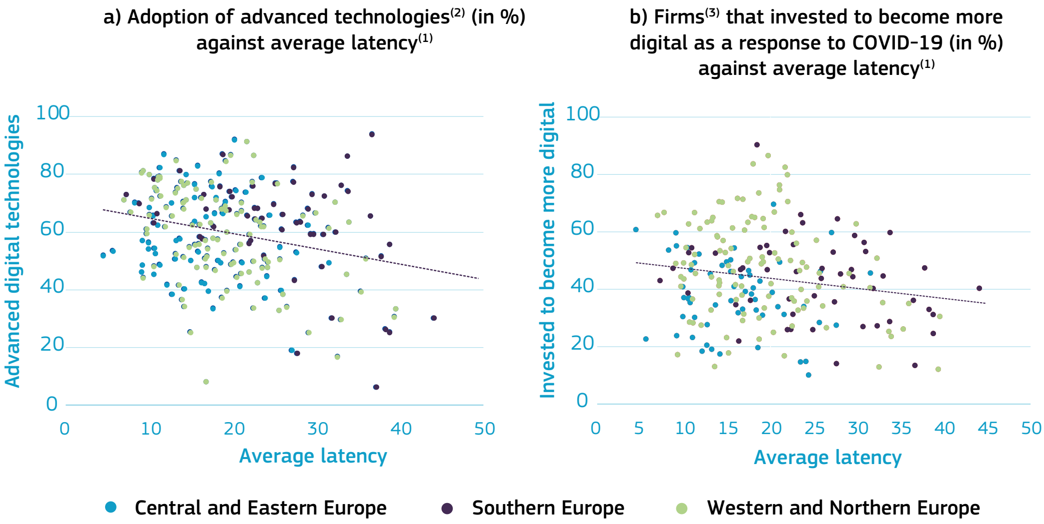
Labour mobility, particularly mobility of R&D workers, can positively impact innovation. Mobility of researchers facilitates knowledge circulation and expansion of research networks. For example, for Sweden, Braunerhjelm et al. (2020) find that knowledge workers' mobility has a positive and strongly significant impact on innovation output, as measured by firms' patent applications. Kaiser et al. (2015) also find positive effects on innovation (measured as patenting) of R&D workers' mobility, in Denmark. Furthermore, knowledge flows to inventors' former workplaces are approximately 50% greater than to other firms, indicating the importance of networks (Agrawal et al., 2006).

3. Digital infrastructures and access to data

The pandemic pushed forward the digitalisation process of many EU businesses, accelerating the uptake of digital technologies (see Chapter 5.3 – The ICT sector and digitalisation). To fully reap the benefits of the digital transformation, it is necessary to create a safe and inclusive digital space for both citizens and EU enterprises, safeguarding EU values and protecting citizens' fundamental rights, while enhancing Europe's digital sovereignty.

In this regard, access to efficient digital infrastructures is essential to foster the digital transition. This is particularly relevant in the context of the EU post-pandemic economic recovery. According to the EIBIS 2022 carried out by the EIB between April and July 2021, 16 % of EU firms indicated that access to digital infrastructure was the main obstacle to investment (EIB, 2022).

Figure 7.2-8: The quality of digital infrastructure and digital adoption in the EU during the COVID-19 pandemic, by NUTS region



Source: EIBIS (2021), firms in EU and European Data Journalism Network (2021)

Note: [1]Latency is the time it takes for data to be transferred between its original source and its destination, measured in milliseconds. [2]See note to Figure 3 in the report for the definition of the adoption of advanced digital technologies. [3]Firms are weighted with value added.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-7-2-8.xlsx

The ability of firms to invest in digitalisation varies significantly across EU regions, depending on the quality of the underlying operating environment. Using average latency[47] as a proxy for quality of the internet connection, the results from EIBIS 2022 show that EU regions having low average latency typically report higher uptake of digital technologies. As illustrated by Figure 7.2-8, firms operating in regions with better access to digital infrastructure also invested more in digitalisation after the onset of the pandemic, confirming that the presence of a well-functioning operating environment plays a key role in steering firms' investments into digital solutions (EIB, 2022).

A second important enabling condition for the digital transformation concerns the availability of people with appropriate levels of digital literacy. Firms active in countries in which a higher share of the population have digital skills tend to report a higher uptake of advanced digital technologies, as well as a higher level of digital investment (EIB, 2022). As such, improving digital education and training systems is essential to foster the digital transition in the EU (for more on digital skills, please refer to Chapter 4.3 – Skills in the digital age).

As new digital technologies become available, so does the amount of data to manage and process. In this regard, **the creation of a secure digital market in which data sharing and USge is performed in accordance with EU common values is at the top of the EU policy agenda.** In November 2020, the European Commission presented its first legislative initiative in this sense, the Data Governance Act (DGA). This act aims to promote data availability and reuse across sectors and EU borders, thereby guiding the creation of EU-wide common interoperable data spaces in strategic sectors such as energy, mobility and health.

In building an inclusive and secure digital market, increased attention is paid to the role and functioning of online platforms. Increasing the transparency of the rules governing digital services is the underlying objective of both the Digital Services Act (DSA) and the Digital Markets Act (DMA). These two legislative acts ultimately aim to create a safe digital space in which EU citizens' fundamental rights are also protected online, and to regulate the behaviour of large online platform, thereby ensuring a level playing field for EU businesses, which is essential to boost innovation and growth.

47 Latency is defined as the time necessary for data to be transferred between its original source and its destination, measured in milliseconds (EIB, 2022).

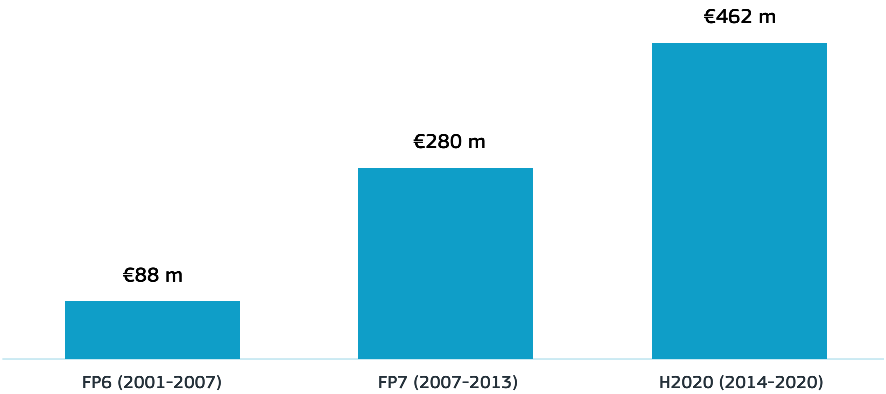
4. Towards a framework for open science and engagement of citizens

Engagement of civil society in science is critical to enrich science, reinforce trust in it and facilitate innovations and their uptake by industry and citizens. Finding the relevant framework conditions to encourage and develop the engagement of society in science is a key part of the success of R&I policy programmes. As recalled by Mariya Gabriel, the European Commissioner for Innovation, Research, Culture, Education and Youth, 'interaction between citizens, scientists and policymakers is essential to enrich research and innovation and reinforce trust of society in science' (European Commission, 2020a). It requires opening up the R&I system to the participation and collective intelligence of society, embedding high integrity and ethics standards, raising interest in science and supporting Europe's brightest minds to engage in scientific careers. Europe cannot thrive without ensuring the best possible match between the immense potential achievements science has to offer and the needs, values and aspirations of citizens (European Commission, 2020b).

Co-creation and engagement of civil society are key pillars of Industry 4.0 and 5.0. An open and ecosystem-based approach, embedding co-creation rather than a linear supply-chain approach has been proven more relevant when dealing with Industry 4.0 solutions (Benitez et al., 2020). Besides, adding co-creation as an antecedent condition leads to trust in business-to-business relationships (Franklin and Marshall, 2019). To address the inherent complexity in innovation ecosystems, economists, sociologists, policy analysts, management scholars and technologists will find it to their advantage to increase collaboration for joint elaboration of conceptual categories, as well as theoretical and empirical approaches that can better describe emergent phenomena, parameters and patterns. The interdependence between technological and social changes and the growing complexity in technological systems, generating complexity in societies and economies, calls for more cocreation (Russell and Smorodinskaya, 2018).

Engagement of civil society in science is a key focus of R&I policies at the EU level, and is included in the R&I framework programmes of the European Commission, as well as in the European Research Area. Citizen science is a powerful tool for public engagement and empowerment in policymaking and for raising awareness, notably when environmental issues and policies are concerned (European Commission, 2020). Under the seventh framework programme for R&I (FP7) (2007-2013), the Commission funded several projects involving citizen science, including Socientize, an initiative to promote and support citizen science. Under the eighth framework programme (2014-2020), **the Horizon 2020 'Science with and for Society' sub-programme aimed to build effective cooperation between science and society, foster the recruitment of new talent for science and couple scientific excellence with social awareness and responsibility.** A budget of EUR 462 million was allocated to this sub-programme. Since its start, 150 projects have been funded for a total budget of EUR 319 million.

Figure 7.2-10: Evolution of budget allocated to 'Science with and for Society' in EU R&I framework programmes



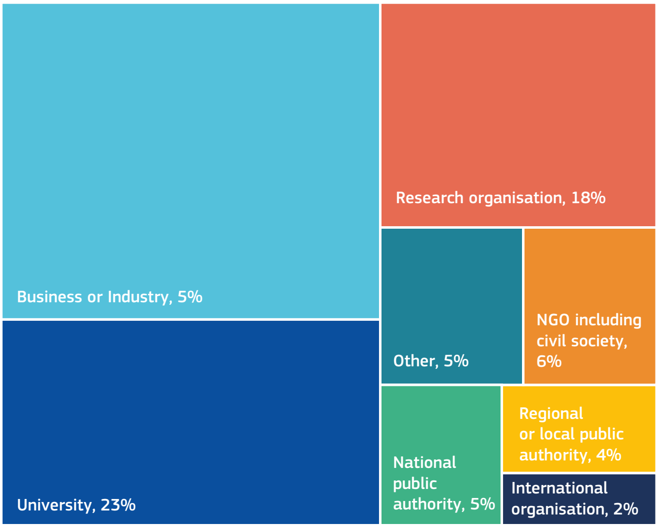
Science, Research and Innovation Performance of the EU 2022
Source: European Commission. Warin C., Delaney N. (2020). Citizen Science and Citizen Engagement - Achievements in Horizon 2020 and recommendations on the way forward.
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-7-2-10.xlsx

Horizon 2020 also funded citizen science under its ICT programme, in particular through collective awareness platforms for sustainable and social innovation (CAPs). This included crowd and citizen-sensing initiatives such as the Making Sense project, supporting the creation of online platforms to raise awareness of sustainability problems and to put in place collective, cooperative solutions by enabling people to share knowledge, make better-informed decisions as consumers, nudge collective environment-aware behavioural change and establish more participatory democratic processes. Another important example is **the 'citizens' observatories' and their second generation, which were funded under the 'Earth observation' topic in Horizon 2020**. The observatories are community-based environmental monitoring and information systems covering, e.g., air pollution, flooding, drought or water quality. They enable the public to monitor the quality of the environment, e.g., through innovative Earth-observation apps.

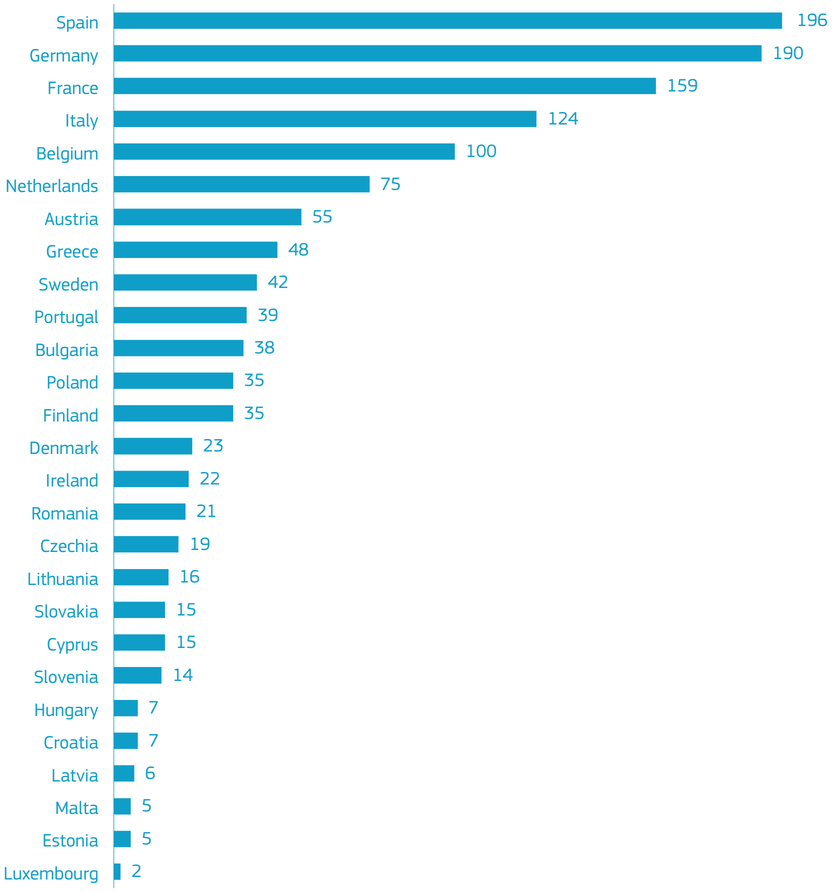
In Horizon Europe, citizen engagement has become even more prominent. It has been envisioned as taking place in terms of co-design (e.g. developing research agendas), co-creation (e.g. involving citizens and/or end-users in developing new knowledge and innovations), **and co-assessment** (e.g. continual contribution to governance), taking the concept of responsible R&I further. The strategic plan of Horizon Europe has been co-designed, in particular through a web-based consultation and views expressed by participants in the European Research and Innovation Days. In total, the views of more than 10 000 respondents across 64 countries – from universities, research organisations, industry and civil society and covering all Member States – were integrated into the strategic planning (European Commission, 2019).

Figure 7.2-9: Co-design of the strategic plan for Horizon Europe, origin of respondents in the EU and across sectors to the web-based consultation, 2019

a) Share of sectors in the co-design of the strategic plan for Horizon Europe



b) Origin of the respondents in the EU (absolute number)



Source : DG R&I based on reports from the European Commission on Horizon Europe Co-design
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-7-2-9.xlsx

Since its development, open innovation has been described as a 'new imperative for creating and profiting from technology' (Chesbrough, 2003). In a closed innovation model, firms internalise their firm-specific R&D activities, and commercialise them through internal development, manufacturing and distribution processes. In contrast, an open innovation model is characterised by the use of purposive inflows and outflows of knowledge to accelerate internal innovation and to expand the markets for external use of innovation, respectively. West and Gallagher (2006) identified three fundamental challenges for firms in applying the concept of open innovation: finding creative ways to exploit internal innovation, incorporating external innovation into internal development, and motivating outsiders to supply an ongoing stream of external innovations.

Table 7.2-1: Models of innovation and resulting managerial issues

Innovation model	Management challenges	Resulting management techniques
Proprietary (or internal or 'closed')	1. Attracting the 'best and brightest' 2. Moving research results to development	1. Provide excellent compensation, resources, and freedom. 2. Provide dedicated development functions to exploit research and link it to market knowledge.
External	1. Exploring a wide range of sources for innovation. 2. Integrating external knowledge with firm resources and capabilities	1. Carefully scan the environment. 2. Develop absorptive capacity and/or use alliances, networks and related consortia.
Open	1. Motivating the generation and contribution of external knowledge (motivating) 2. Integrating those sources with firm resources and capabilities (incorporating) 3. Diversifying the exploitation of IP resources (maximising)	1. Provide intrinsic rewards (e.g. recognition) and structure (instrumentality) for contributions. 2. As above 3. Share or give away IP to maximise returns from entire innovation portfolio.

Source: West and Gallagher (2006).

Open science through the sharing of knowledge, data and tools in the R&I process, in open collaboration with all relevant knowledge actors, is another key element of Horizon Europe. Horizon Europe features 'research infrastructures', which will support the development and consolidation of the European Open Science Cloud (EOSC) through a dedicated Partnership (European Commission, 2021b). Marie Skłodowska-Curie Actions will also promote the diffusion of open-science practices and will support the development of appropriate skills among researchers. **The European Missions of Horizon Europe will connect all relevant actors through new forms of partnerships for co-design and co-creation and involvement of multiple sectors and actors.** Horizon Europe will also support European partnerships with EU countries, the private sector, foundations and other stakeholders. The aim is to deliver on global challenges and industrial modernisation through co-creation and concerted research and innovation efforts.

The European Research Area will also increase coordination, exchange of good practices and tools, development of guidance and training, implementation of institutional changes, and consolidation of evidence on impacts. Furthermore, the Widening Participation and Strengthening the European Research Area part of Horizon Europe will support the further development of the open-science policy and adoption of open-science practices. **The Open Research Europe (ORE) publishing platform will also provide Horizon 2020 and Horizon Europe beneficiaries with the possibility of using a high-quality open-access peer-reviewed publishing venue, at no cost to them, during and after the end of their grants.** This will not only help beneficiaries to meet their open-access obligations, it also will further incentivise pre-prints and open peer-review. It is also expected that a new multidisciplinary, cloud-based and open repository for research materials from Horizon Europe projects will be developed, offering services at no cost to its beneficiaries.

Finally, **one of the nine Key Impact Pathways of Horizon Europe, 'strengthening the uptake of innovation in society', starts with projects in which members of the public and end-users co-create R&I content**. A section under 'reforming and enhancing the European R&I system' focuses on citizen science.

5. Conclusions: an innovation-friendly environment

Setting the correct framework conditions to allow innovation and knowledge to flourish is an important prerequisite for success in R&I in Europe. The overall framework conditions in which companies operate are fundamental as they set business incentives and shape the innovation capacity of economies. Good framework conditions positively affect business-investment decisions, ease access to markets for new and innovative companies, and contribute to reallocating resources towards more productive and innovative activities. Political stability, transparency, accountability, and a high degree of rule of law with a low risk of expropriation and corruption allow transaction costs of trade and the costs of monitoring and enforcing contracts to be reduced. Within such an environment, firms are incentivised to innovate and to take calculated risks for innovation.

Economic freedom, within a clear and simple regulatory environment and with cohesive political institutions promoting common interests, is essential to foster prosperity and innovation. Regulation can act as a major driver of innovation, as it brings stability and certainty, which foster investment and planning and enable firms to work on safe legal ground. Flexible labour markets are more efficient at allocating resources, leading to higher employment and productivity. However, 'flexible' is not to be misunderstood as 'unregulated', as unregulated markets rarely lead to optimal outcomes.

The emergence of new practices, technologies and business models and the pacing problem due to the acceleration of innovation call for more flexible and experimental approaches to regulation. Furthermore, citizens need to be engaged in R&I as they are critical to enriching it, reinforcing trust in science and facilitating the innovation process and its uptake by industry and citizens. To ease citizens' participation, it is necessary to create a safe and inclusive digital space for both citizens and EU enterprises, fostering up-skilling, reskilling and life-long learning.

References

Acemoglu, D., Johnson, S., Robinson, J. A. (2001), 'The colonial origins of comparative development: An empirical investigation', American economic review, 91(5), pp. 1369-1401.

Acemoglu, D., Johnson, S., Robinson, J. A. (2002), 'Reversal of fortune: Geography and institutions in the making of the modern world income distribution', The Quarterly journal of economics, 117(4), 1231-1294.

Acemoglu, D., Johnson, S., Robinson, J. A. (2005), 'Institutions as a fundamental cause of long-run growth', Handbook of economic growth, 1, pp. 385-472.

Aghion, P., Bloom, N., Blundell, R., Griffith, R., Howitt, P. (2005), 'Competition and innovation: An inverted-U relationship', The quarterly journal of economics, 120(2), pp. 701-728.

Agrawal, A., Cockburn, I., McHale, J. (2006), 'Gone but not forgotten: knowledge flows, labor mobility, and enduring social relationships', Journal of Economic Geography, 6(5), pp. 571-591.Alonso Raposo, M., Mourtzouchou, A., Garus, A., Brinkhoff-Button, N., Kert, K., Ciuffo, B., (2021), JRC Future Mobility Solutions Living Lab (FMS-Lab): conceptual framework, state of play and way forward, Publications Office of the European Union, Luxembourg.

Arvanitis, S. (2005), 'Modes of labor flexibility at firm level: Are there any implications for performance and innovation? Evidence for the Swiss economy', Industrial and Corporate Change, 14(6), pp. 993-1016. Ashford, N., Hall, R. (2011), 'The Importance of Regulation-Induced Innovation for Sustainable Development', Sustainability, 3, pp. 270-292.

Ashford, N.A., Renda, A. (2016), Aligning Policies for Low-Carbon Systemic Innovation in Europe, CEPS and i24c Report.

Bassanini, A. E. Ernst (2002), Labour Market Institutions, Product Market Regulation, and Innovation: Cross-Country Evidence, OECD Economics Department Working Papers, No. 316, OECD Publishing, Paris.

Benitez G.B., Ayala N.F., Frank A.G. (2020), 'Industry 4.0 innovation ecosystems: An evolutionary perspective on value cocreation', International Journal of Production Economics, 228, 107735.

Berggren, N. (2003), 'The benefits of economic freedom: a survey', The independent review, 8(2), pp. 193-211.

Besley, T., Persson, T. (2011), Pillars of prosperity, Princeton University Press.

Boldrin, M., Levine, D. (2002), 'The case against intellectual property', American Economic Review, 92(2), pp. 209-212.

Braunerhjelm, P., Ding, D., Thulin, P. (2020), 'Labour market mobility, knowledge diffusion and innovation', European Economic Review, 123, 103386.

Carlsson, F., Lundström, S. (2002), 'Economic freedom and growth: Decomposing the effects', Public choice, 112(3), pp. 335-344.

Cetrulo, A., Cirillo, V., & Guarascio, D. (2019), 'Weaker jobs, weaker innovation. Exploring the effects of temporary employment on new products', Applied Economics, 51(59), pp. 6350-6375.

Council of the European Union, (2021), *State of play on the use of regulatory sandboxes in the EU Member States*, Brussels, 5 July 2021 (OR. en) 10338/21

De Haan, J., Lundström, S., Sturm, J. E. (2006), 'Market-oriented institutions and policies and economic growth: A critical survey', Journal of economic surveys, 20(2), pp. 157-191.
Edquist, C., Hommen, L., (1999),' Public technology procurement and innovation theory', Public Technology Procurement and Innovation, 16, pp. 5–70.

Edquist C., Zabala-Iturriagagoitia J-K. (2012), 'Public Procurement for Innovation as mission-oriented innovation policy', Research Policy, 41(10), pp. 1757–1769

EPSC (2016), Towards an Innovation Principle Endorsed by Better Regulation, EPSC Strategic Notes.European Commission. (2019), *Horizon Europe co-design – implementation report on the results of the online consultation and the European research & innovation days event.*

European Commission. Warin C., Delaney N. (2020), *Citizen Science and Citizen Engagement - Achievements in Horizon 2020 and recommendations on the way forward*, Publications Office of the European Union, Luxembourg.

European Commission (2020a), *Citizen Science - Elevating research an innovation through societal engagement*, Publications Office of the European Union, Luxembourg.

European Commission (2020b), Best Practices in Citizen Science for Environmental Monitoring. Brussels, Commission staff working document, SWD (2020) 149 final.

European Commission, (2021a), *The strategic use of public procurement for innovation in the digital economy: executive summary in English, French and German*, Directorate-General for Communications Networks, Content and Technology, Publications Office, 2021.

European Commission (2021b), *Open science early knowledge and data sharing, and open collaboration*, Publications Office of the European Union, Luxembourg.

European Investment Bank (2022), EIB Investment Report 2021/2022.

Franklin D., Marshall R., (2019), 'Adding co-creation as an antecedent condition leading to trust in business-to-business relationships', Industrial Marketing Management, 77, pp. 170-181.

French, German, UK Governments, 2004. Towards and innovative Europe. A Paper by the French, German and UK Governments. 20 February 2004

Guerzoni M., Raiteri.E. (2015), 'Demand-side vs. supply-side technology policies: Hidden treatment and new empirical evidence on the policy mix', Research Policy 44(3), pp. 726–747.

Gwartney, J., Lawson, R. (2003), 'The concept and measurement of economic freedom', European Journal of Political Economy, 19(3), pp. 405-430.

Gwartney, J., Lawson, R., Norton, S. (2008), Economic freedom of the world: 2008 annual report, The Fraser Institute.

Hoxha, S., & Kleinknecht, A. (2020), 'When labour market rigidities are useful for innovation. Evidence from German IAB firm-level data', Research Policy, 49(7), 104066.

Hussen, M. S., & Çokgezen, M. (2021), 'The impact of regional institutional quality on firm innovation: evidence from Africa', Innovation and Development, 11(1), pp. 69-90.

Justesen, M. K. (2008), 'The effect of economic freedom on growth revisited: New evidence on causality from a panel of countries 1970–1999', European journal of political economy, 24(3), pp. 642-660.

Kaiser, U., Kongsted, H. C., Rønde, T. (2015), 'Does the mobility of R&D labor increase innovation?. Journal of Economic Behavior & Organization', 110, pp. 91-105.

Kuckertz, A., Berger, E. S., Mpeqa, A. (2016), 'The more the merrier? Economic freedom and entrepreneurial activity', Journal of Business Research, 69(4), pp. 1288-1293.

Lember V., Kattel R., Kalvet T. (2014), How Governments Support Innovation Through Public Procurement: Comparing Evidence from 11 Countries, in: Lember V., Kattel R., Kalvet T. (eds), Public Procurement, Innovation and Policy, Springer, Berlin, Heidelberg.

Li, H., Zhou, L. A. (2005), 'Political turnover and economic performance: the incentive role of personnel control in China', Journal of public economics, 89(9-10), pp. 1743-1762.

Li, I. Y. (2015), The Political Economy of Property Rights In China: Local Officials, Incentive Structure, And Private Enterprises, mimeo.

Lucidi, F., Kleinknecht, A. (2010), 'Little innovation, many jobs: An econometric analysis of the Italian labour productivity crisis', Cambridge Journal of Economics, 34(3), pp. 525-546.

Nee, V., Opper, S. (2012), Capitalism from below, Harvard University Press.

North, D. C. (1981), Structure and change in economic history. Norton, New York.

Oi, J. C., Walder, A. G. (1999), Property rights and economic reform in China, Stanford University Press.

Olson, M. (2000), Power and prosperity: Outgrowing communist and capitalist dictatorships, Basic Books.

Pelkmans, J., Renda, A. (2014), Does EU regulation hinder or stimulate innovation? CEPS Special Report No.96.

Peter, V., Ravet, J., Roman, L., Enzing C., Venjakob, M., Adisorn, T., Seibt, C., Dates, M. (2017), Assessing the Impacts of EU Regulatory Barriers on Innovation, Publications Office of the European Union, Luxembourg.

Porter, M.E. (1990), The Competitive Advantage of Nations, Free Press, New York.

Porter, M.E., van der Linde, C. (1995), 'Toward a New Conception of the Environment Competitiveness Relationship', Journal of Economic Perspectives, 9(4).

Qian, Y., Weingast, B. R. (1997), 'Federalism as a commitment to reserving market incentives', Journal of Economic perspectives, 11(4), pp. 83-92.

Robinson, J. A., Acemoglu, D. (2012), Why nations fail: The origins of power, prosperity and poverty, Profile, London.

Rodríguez-Pose, A., Di Cataldo, M. (2015), 'Quality of government and innovative performance in the regions of Europe', Journal of Economic Geography, 15(4), pp. 673-706.

Russell M, Smorodinskaya N. V. (2018), 'Leveraging complexity for ecosystemic innovation, Technological Forecasting and Social Change', 136, pp. 114-131.

Spolaore, E., Wacziarg, R. (2013), 'How deep are the roots of economic development?', Journal of economic literature, 51(2), pp. 325-69.

Tebaldi, E., Elmslie, B. (2013), 'Does institutional quality impact innovation? Evidence from cross-country patent grant data', Applied Economics, 45(7), pp. 887-900.

Thum-Thysen, A., Voigt, P., Maier, C., Bilbao-Osorio, B., Ognyanova, D. (2017), 'Unlocking investment in intangible assets in Europe', Quarterly report on the euro area, 16(1), pp. 23-35.

Tressel, T., & Scarpetta, S. (2004), Boosting productivity via innovation and adoption of new technologies: any role for labor market institutions? Vol. 3273, World Bank Publications.

Tsai, K. S., (2002), Back-Alley Banking: Private Entrepreneurs in China. Ithaca, Cornell University, New York.Wachsen, E., Blind, K. (2016), 'More labour market flexibility for more innovation? Evidence from employer–employee linked micro data', Research Policy, 45(5), pp. 941-950.

Wang, H. (2002), Weak State, Strong Networks: The Institutional Dynamics of Foreign Investment in China, Oxford University Press, Oxford.

Wang, Y. (2014), 'Institutions and bribery in an authoritarian state', Studies in Comparative International Development, 49(2), pp. 217-241.

Wank, D. L. (2001), Commodifying communism: Business, trust, and politics in a Chinese city (Vol. 14), Cambridge University Press.

Weingast, B. R. (1995), 'The economic role of political institutions: Market-preserving federalism and economic development', Journal of Law Economics and Organization 11(1), pp. 1-31.

West, J., Gallagher, S. (2006), 'Challenges of Open Innovation: The Paradox of Firm Investment in Open-Source Software', R&D Management, 36(3), pp. 319-331.

Zhu, H., Zhu, S. X. (2017), 'Corporate innovation and economic freedom: Cross-country comparisons', The Quarterly Review of Economics and Finance, 63, pp. 50-65.

PART II

CHAPTER 8

A POLICY TOOLKIT TO INCREASE RESEARCH AND INNOVATION IN THE EUROPEAN UNION

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Summary

What R&I policies should the EU adopt? The world faces a challenge to rebuild after the pandemic, but also faces the same structural slowdown of productivity growth that occurred in the decades before the COVID-19 crisis. The EU needs a plan around innovation policy to address the challenge. We show that Europe is less innovative on many dimensions compared to other advanced regions, such as the USA and parts of Asia. We review the econometric evidence on R&I policies and argue that there is good evidence for the efficacy of many of them. A mix of R&D subsidies, reinvigorated competition and a big push on expanding the quantity and quality of human capital is needed. These could be bound together around the need for green innovation to achieve the mission to radically reduce carbon emissions.

1. Introduction

Rebuilding our societies after the COVID-19 pandemic is a huge task, reminiscent of the challenges facing Europe after the Second World War. The fall of output in 2020 due to the pandemic and the necessary policy response of lockdowns was substantial – of the order of 13 % across the EU as a whole[1]. This was more than twice the GDP loss in the depths of the global financial crisis in 2008-09. To tackle the crisis, we need a serious plan for growth using the best innovation policies. This will be no easy task, of course. Not only was the crisis deep – and continues at the time of writing – but economic performance was poor in the decades even prior to COVID-19.

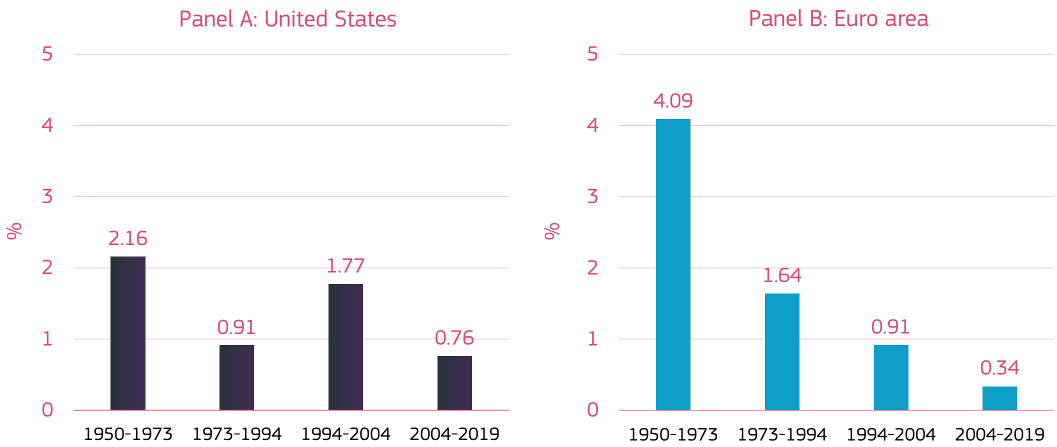
Figure 1 shows the growth in total factor productivity (TFP) since 1950 for the USA (Panel A) and the euro area[2] (Panel B). TFP is a proxy for technical change – the improvement in the efficiency with which an economy uses production inputs such as labour and capital. The picture is grim. TFP growth has been on a declining path over the last 70 years.

Productivity growth was strongest during the post-war reconstruction period (1950-73); in fact, even stronger in Europe than the USA (4 % per annum vs 2 %) as the damage was greater in war-torn Europe. After the OPEC oil shocks of the 1970s, productivity growth more than halved from 1973 to 1994, but still remained higher in Europe (1.6 %) than in the USA (0.91 %). Although Europe continued on a downward path after the mid-1990s, the USA experienced a brief 'productivity miracle' between 1994 and 2004 based around the rapid fall in quality-adjusted prices of information and communication technologies (ICT) enhanced by the growth of the internet (see Draca, Sadun and Van Reenen, 2007; Bloom, Sadun and Van Reenen, 2012). Nevertheless, over 2004-19, TFP growth has been only 0.76 % a year in the USA and 0.34 % in Europe. Although this dismal performance is influenced by the global financial crisis and its aftermath, such as the euro crisis, the fact that the productivity slowdown began well before Lehman's collapse implies that there are more structural forces at play.

1 Eurostat: https://ec.europa.eu/eurostat/documents/2995521/11563211/2-30072021-BP-EN.pdf/0567c280-b56c-2734-2a4b-e4af85a55bf5?t=1627630313030 (last accessed on 30 July 2021).

2 We define the euro area (or 'Europe' for short) in this chapter as DE, FR, IT, ES, NL and FI, using data updated from Bergeaud, Cette and Lecat (2016). These countries made up 82 % of the euro area's GDP in 2012.

Figure 8-1: Average annual TFP growth in the United States and the Euro area in different time periods



Science, Research and Innovation Performance of the EU 2022

Source: Data updated from Bergeaud, Cette, and Lecat (2016). Data publicly available at http://www.longtermproductivity.com/
Note: The average annual TFP growth in the US (panel A) and Euro area (panel B) is shown. There is insufficient data for the whole EU, so we use Germany, France, Italy, Spain, the Netherlands and Finland to represent the euro area.
Stats.: link

Productivity growth matters because it determines wage growth in the long-run. It expands the economic pie, which enables a society to pursue its goals, whether this be greater consumption or spending on public goods such as the environment, health, education or defence. Without productivity growth, the effective economic pie is fixed in size, so some groups have to be made strictly worse off if we want to redistribute resources to others, which is no politically easy task.

TFP growth can be driven by several proximate causes. One is **frontier innovation**, defined as commercially applicable new ideas that are new to the world (not just to a country, industry or firm) that push forward the production possibility frontier. Frontier innovation is the most important factor for advanced economies such as Europe and the USA. A second factor driving aggregate TFP growth is **diffusion**, the spread of these frontier technologies across people, firms, industries and countries. A third factor is **reallocation**, the degree to which an economy allocates more output to high-productivity firms and away from low-productivity firms. Diffusion and misallocation are very important in rich countries and are the overwhelmingly dominant force in poorer nations. In this chapter, we focus on frontier R&I policies in order to keep the discussion within manageable limits[3].

Technological innovation is vital for growth, but it is also crucial in order to address the major challenges we face in many other dimensions.

3 For a discussion of diffusion policies, particularly around management practices see Scur et al. (2021). Note that the policies interact: higher R&D might enable faster catch up to the frontier as well as frontier innovations (see Griffith, Redding and Van Reenen, 2004, for evidence on these 'two faces' of R&D).

Above all, combating the existential threat of climate change will require green innovation. Taxes and regulation by themselves will not be enough. Importantly, there are many targets for innovation – for example the environment more broadly (e.g. plastics in the ocean), health (e.g. future pandemics) and inclusion (as inequality has risen within many countries over the last few decades).

In this chapter, we argue for a new plan around innovation policy to foster economic growth. This would have to be based on good evidence, and an important aim of this chapter is to provide the theoretical and empirical evidence upon which such a plan could be based. The EU has already made some progress in this regard. In particular, the Horizon 2020 programme (launched in 2014) had a reinforced focus on innovation in addition to supporting frontier research and collaborative research projects – making funding available to researchers and innovators in the form of grants, prizes and procurement[4]. Horizon Europe is the next phase of this initiative, covering the 2021-2027 period with a budget of EUR 95.49 billion[5]. Compared to Horizon 2020, this amounts to a 30% increase in spending[6]. Based on the evidence we provide in this chapter, this substantial increase is clearly a step in the right direction. However, we think that theory and evidence support an even higher increase in resources. And obviously, not only is the **amount** of money spent important; it is **how** it is to be spent.

The budget should not solely be used as a short-term demand boost, but rather be designed to induce structural changes in the EU economy that will lead to long-lasting productivity increases[7]. We will lay out evidence for a mix of such policies in this chapter.

Horizon Europe is mainly aimed to help researchers, inventors and research institutions through grants. For example, one policy is the Marie Sklodowska-Curie Actions (MSCA), which include postdoctoral fellowships for researchers who recently obtained their PhD. Another is support from the European Research Council for promising early-career and experienced researchers. Additionally, researchers can generally apply for funding of collaborative projects in pre-specified areas (or 'clusters'), with particular emphasis being put in terms of budget on climate, energy, mobility and digital areas, industry and space[8]. Horizon Europe is only a small part of the EU's overall EUR 2.02 trillion budget[9]. Part of this larger budget is the Recovery and Resilience Facility worth a substantial EUR 723.8 billion (47% in grants and 53% in loans) to help Member States to recover from the pandemic. The allocation of the money to individual areas is generally delegated to individual Member States, although particular quotas have to be met (e.g. at least 20% of the total Rescue and Resilience Facility is to be spent on digital transformation) and the plans have to be formally signed off by the Commission.

4 The Horizon 2020 budget was EUR 80 billion over 2014-2020 https://ec.europa.eu/info/research-and-innovation/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe_en (last accessed 02 September 2021)

5 The majority of this (EUR 86.1 billion) is from the main budget, with EUR 5.41 billion from the NextGenerationEU instrument and smaller amounts from elsewhere.

6 This excludes data on the UK beneficiaries from the previous programme so that the numbers are on a consistent basis pre- and post-Brexit. The increase is measured in real terms. https://op.europa.eu/en/publication-detail/-/publication/1f107d76-acbe-11eb-9767-01aa75ed71a1 (last accessed 03 September 2021)

7 For example, see the intervention by Luis Garicano at the LSE event on 'Europe's Recovery Programmes': https://www.lse.ac.uk/Events/2021/11/202111181830/europe

8 https://op.europa.eu/en/publication-detail/-/publication/1f107d76-acbe-11eb-9767-01aa75ed71a1 (last accessed 03 September 2021)

9 This covers 2021-2027 (passed in 2020) and is composed of the long-term budget (EUR 1.210 trillion) and NextGenerationEU (EUR 806.9 billion).

Some of the country-specific plans clearly seem to involve spending on innovation. For example, Italy explicitly states 'innovation in the production system' as one policy area[10], and Germany plans to support disadvantaged students[11]. Although the latter is not a classical innovation policy, we will argue below that this kind of human capital support can be a successful supply-side innovation policy (Aghion et al., 2017; Bell et al., 2019a; Van Reenen, 2021).

The structure of the chapter is as follows. We provide some background innovation statistics in section 2. In section 3, we discuss the rationale for state intervention in innovation and present a review of evidence on these policies in section 4, before offering concluding comments in section 5. Further analysis is available in the Online Appendix.

10 For more detailed information on the Italian recovery plan, see https://www.mef.gov.it/en/focus/The-National-Recovery-and-Resilience-Plan-NRRP/ (last accessed 3 September 2021).

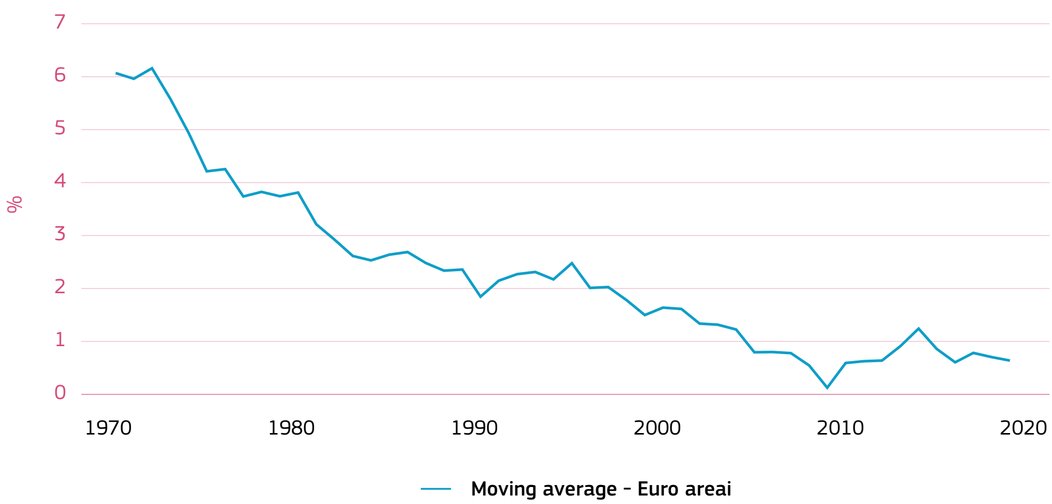
11 This and additional information on the German recovery plan can be found here: https://ec.europa.eu/commission/presscorner/detail/en/ip_21_3133 (last accessed 03 September 2021).

2. Background: R&I facts

Productivity trends

As we documented in the previous section, TFP growth has slowed down in the USA and Europe since the mid-1970s. Figure 1 presented this for TFP and Figure 2 does the same for labour productivity (GDP per hour) in the 'euro area'. Growth rates of labour productivity have been falling relatively consistently between 1970 and the financial crisis and have stagnated on a relatively low level since the crisis (growth of less than 1 % in most years).

Figure 8-2: Annual growth of labour productivity in a subset of EU countries (1970-2019)



Source: Data updated from Bergeaud, Cette, and Lecat (2016). Data publicly available at: http://www.longtermproductivity.com/

Note: The line shows annual growth of real GDP per hour in a subset of EU countries (Germany, France, Italy, Spain, Netherlands, and Finland). Data are shown as 5-year moving averages (i.e. 1970 includes the 1970 change and the previous four yearly changes).

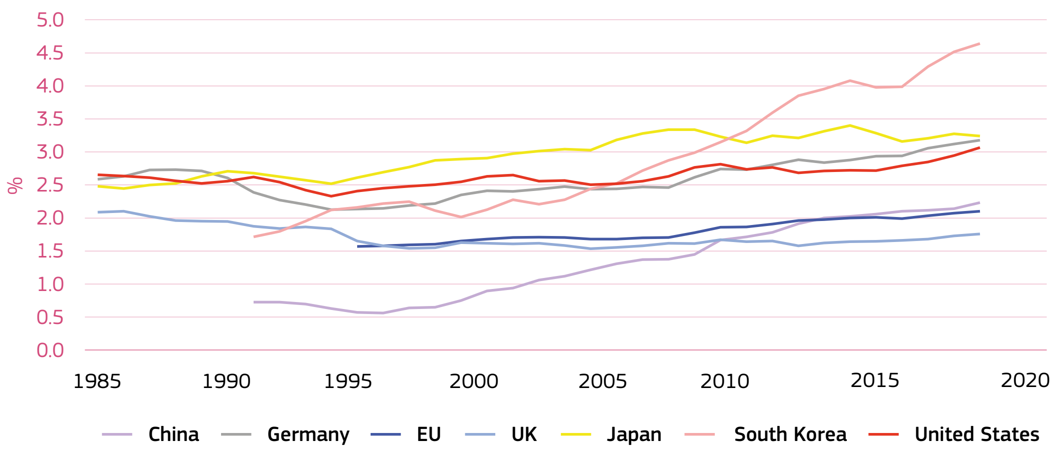
Stats.: link

R&I statistics

As innovation is vital to restore productivity growth, we now turn to different innovation statistics. There are many different indicators of innovation, and we present only some of them here. We give an overview of the time-series patterns of innovation in the EU compared to other major industrialised economies.

In 2019, total R&D spending in the EU-27 amounted to EUR 308 billion[12]. This is about 60% of the value in the USA (which spends more money on R&D than any other country), and more than twice the value of Japan. In part, these differences are related to the size of the different economies, so we consider R&D intensity (R&D spending as a fraction of GDP) in Figure 3 for selected countries. This shows that R&D intensity has generally increased over time in the EU (from 1.6% in 1995 to 2.1% in 2019, with most of this increase occurring since 2007). This fraction lies well below the EU's own target of 3%, which was supposed to be reached by 2020[13]. Compared to other OECD countries, the EU's R&D intensity is relatively low. The USA, Germany and Japan all have R&D intensities closer to 3% or more – a whole percentage point higher. South Korea's R&D intensity is more than double that of the EU (about 4.5%). China

Figure 8-3: R&D spending as a share of GDP in selected countries (1985-2019)



Science, Research and Innovation Performance of the EU 2022

Source: OECD. https://data.oecd.org/rd/gross-domestic-spending-on-r-d.htm

Note: The respective lines show R&D spending as a share of GDP in different countries. R&D spending from abroad is included, but domestic funds for R&D that are not used within the domestic economy are excluded. EU-27 refers to the EU Member States as of 2020 (i.e. not the UK). The EU-27, China and South Korea series start later due to limited data availability.

Stats.: link

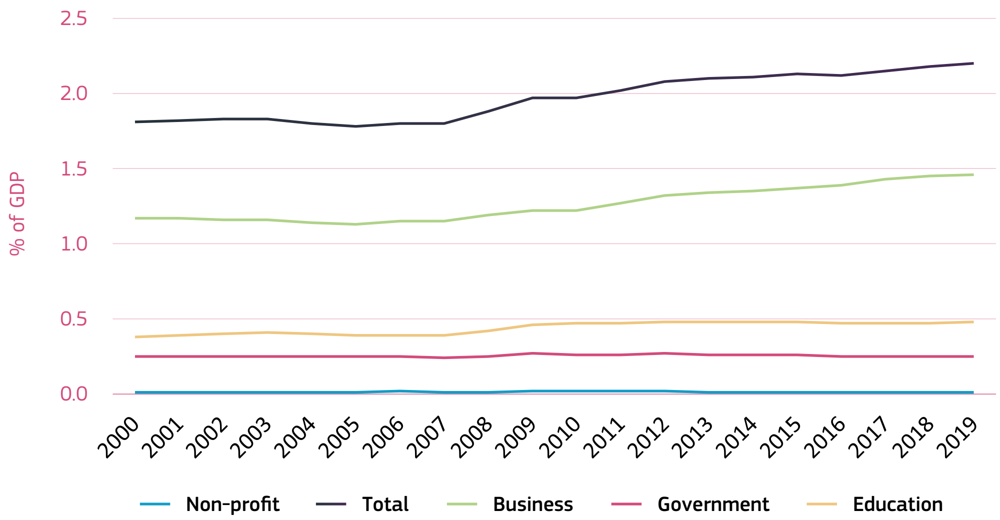
12 Eurostat Science, Technology and Innovation data base: https://ec.europa.eu/eurostat/databrowser/view/RD_E_GERDSC__custom_1392084/default/table?lang=en (last accessed on 11 October 2021).

13 This target was part of the EU's 2020 strategy. For more information, see https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Archive:Europe_2020_indicators_-_R%26D_and_innovation&oldid=383721 (last accessed on 02 September 2021).

has seen massive increases in its R&D intensity since the mid-1990s, and it is now slightly higher than that of the EU. The EU average conceals huge heterogeneity among Member States. Whereas countries such as Germany, Austria and Sweden had R&D intensities of more than 3% in 2019, other Member States spent less than 1% (e.g. late joiners such as Latvia, Romania and Slovakia.

Figure 4 shows how R&D expenditure of the EU-27 breaks down into the broad sectors that conduct the R&D. Two-thirds of R&D is conducted by businesses. This is followed by universities (about 22%), then by governments (about 11%). The increase in the EU's R&D spending seems to be almost totally driven by the business sector (making up about three-quarters of the increase), with a smaller increase from higher education (about one quarter). This is consistent with the trends in the USA, where there has also been a switch away from government and towards the business sector in R&D (Bloom, Williams and Van Reenen, 2019)[14]. Today, US federal funding of R&D as a fraction of GDP is only a third of its level in the mid-1960s. The move towards business R&D and away from government R&D may matter. If the government often supports more basic and higher-risk research than the private sector, this public R&D will tend to produce higher value innovations[15].

Figure 8-4: R&D expenditure in the EU by sector of performance (2000-2019)



Science, Research and Innovation Performance of the EU 2022

Source: Eurostat (2021). https://ec.europa.eu/eurostat/databrowser/view/tsc00001/default/table?lang=en

Note: All series are shown as share of GDP. 'Total' is all R&D expenditure, 'Business' refers to R&D expenditure conducted by business enterprises, 'Education' is the higher education sector, 'Non-profit' is the private non-profit sector and 'Government' is conducted by the state.

Stats.: link

14 The corresponding graph for the USA can be found in Appendix A.

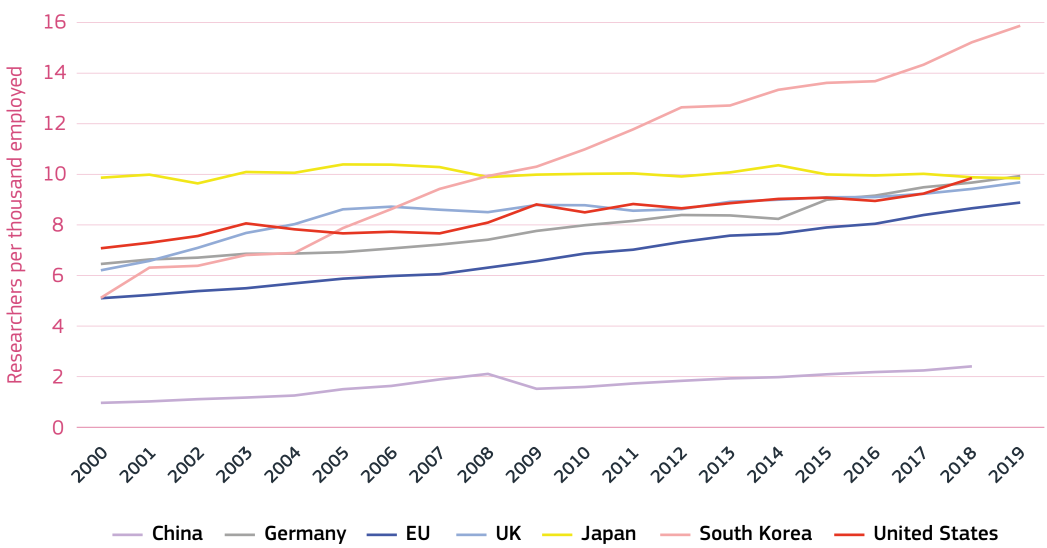
15 There is also some evidence that even within business R&D, the fraction of basic research has declined relative to applied research (e.g. Arora, Belenzon and Patacconi, 2018). Indeed, the decline in basic research in both public- and private-sector R&D spending may be one reason why the productivity of US R&D appears to have fallen over time, as documented by Bloom et al. (2020).

Although R&D is an attractive measure as it can be measured in a reasonably consistent way across time and countries, it does have well-known issues as a measure of innovation. R&D is an input and not an output of the innovation process: a lot of money could be spent too little avail. R&D also tends to be focused on formal activity in laboratories and misses out on much innovative effort in services, homes and garages. Productivity in Figures 1 and 2 are innovation output measures, but these are rather indirect and (as discussed above) could grow for many reasons such as diffusion or reductions in misallocation. Thus, TFP is inevitably coarse as a measure of technological progress and innovation.

An alternative measure is the relative size of the scientific workforce. This indicator has some attractive features as it abstracts away from the problem that R&D expenditure might be high only because the cost (rather than the volume) of R&D is high. On the other hand, R&D spending includes spending on capital (e.g. labs and equipment) as well as materials, whereas the scientific workers measure only includes labour.

Figure 5 shows that the number of researchers (per thousand employees) in the EU-27 has increased more or less continuously since 2000 (from 5.1% to 8.9%). The 2019 level in the EU is similar to that of the USA, UK and Japan. Consistent with the R&D spending numbers shown in Figure 3, South Korea has seen the biggest increase in the number of researchers per thousand employed over the period. China's levels are strikingly low compared with the other countries, although it has still experienced a doubling in their numbers from less than 1% to 2.4%. The general consistency between trends in R&D spending and number of researchers is unsurprising, as most R&D spending is on people, such as scientists.

Figure 8-5: Researchers per thousand employed in different countries (2000-2019)



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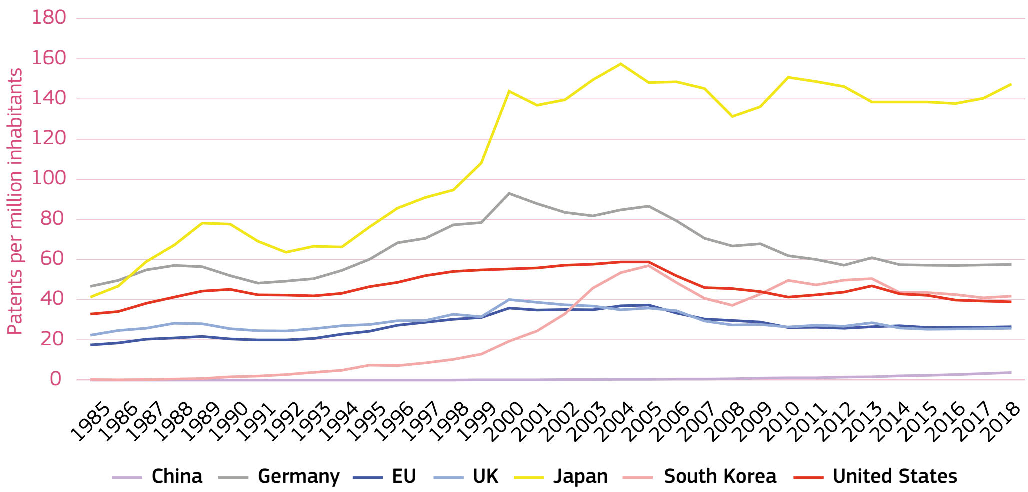
Source: OECD. https://data.oecd.org/rd/researchers.htm
Note: Data are shown per thousand employed. The line of China ends in 2018 due to limited data availability.
Stats.: link

A more direct measure of innovation is based on patents. With patent data, there are the well-known issues that some innovations may not be patented and thus will be missed in the statistics as well as the difference in patent definitions by different patent offices. In particular, a concern is that patents are of hugely heterogeneous values, with many duds and a few bonanzas. As a result, we focus on 'triadic' patents. These are patents that have been registered in at least three different patent offices: in the EU, in Japan and in the USA. These should be the relatively high-value patents.

Figure 6 shows patent registrations per million inhabitants since 1985. Over this period, patents per million inhabitants in the EU increased by about 41% (from 18.1% to 25.6%). The trend looks similar to those in the UK and the USA. The Asian countries show very different trends: Japan and South Korea have both seen massive increases in patents per million inhabitants (Japan's number has more than tripled, and South Korea's has increased from almost no patents per million inhabitants to more than 40). This occurred especially at the end of the 1990s and the beginning of the 2000s, mostly coinciding with increases in R&D spending, as shown in Figure 3.

Figure 8-6: Patents per million inhabitants in different countries (1985-2018)



Science, Research and Innovation Performance of the EU 2022

Source: OECD. Patent data: https://data.oecd.org/rd/triadic-patent-families.htm#indicator-chart, Population data: https://data.oecd.org/pop/population.htm

Note: Patents per million inhabitants are obtained by dividing total annual registered patents by million inhabitants in a country. We only consider triadic patents, which are registered at the European Patent Office (EPO), Japan Patent Office (JPO) and the United States Patent and Trademark Office (UPSTO). A patent's country of origin is determined by the residence of the inventor. The EU series ends in 2017 as patent data is not available for 2018.

Stats.: link

Summary

In summary, the EU is lagging behind the USA in most innovation statistics that we have considered. In terms of changes over time, advanced Asian economies, especially South Korea but also partly Japan and China have seen much more growth in their innovation metrics than the EU. It is important to note that there is large heterogeneity among EU Member States – whereas countries like Germany or Sweden show relatively strong R&D investment and patent numbers, others have relatively low spending and patent numbers.

3. What is the rationale for public intervention in innovation?

Are low innovation rates a problem? And if so, should governments intervene? We tackle this question in this section, broadly answering in the affirmative. The subsequent section then investigates whether governments can intervene successfully. Jones and Summers (2020) examine the arguments on why governments should support R&D in detail, so we only briefly summarise the arguments here (also see Mazzucato and Semieniuk, 2017; Bloom, Williams and Van Reenen, 2019; Bryan and Williams, 2021 for more detail)[16]. The bottom line is that both theory and (more importantly) evidence imply that there is under-provision of government support for innovation.

3.1 Rationale for public support of innovation: theory

The primary argument for public support of innovation is that there are large positive externalities from R&D. This is because there are benefits of the technological innovation created by the research that spill over to other agents who did not conduct the research. For example, although firms who invest in R&D expect to see some return – even if this is highly uncertain and a long way off – the profits obtained by the individual firm do not fully reflect the social benefits of the R&D. Spillover beneficiaries include other firms who might copy the innovation and/or build on the knowledge created by the inventor's R&D. Moreover, domestic and foreign consumers will get the innovation benefits potentially at a tiny fraction of the (full) costs. Flaubert's (1911) definition of inventors is often cited: 'All die in the poor house. Someone else profits from their discoveries; it is not fair.'

The externalities of research imply that there is a gap between the social and private benefits of R&D. The larger this gap, the bigger is the necessary government subsidy to promote innovation and reduce the difference between social and private returns.

Although knowledge spillovers are the main justification for government action, there are additional arguments. In particular, Arrow (1962) pointed to financial-market failures in innovation due to high risk, uncertainty, absence of collateral and asymmetric information (e.g. Hall and Lerner, 2010). A potential innovator must convince an external funder of the value of the innovation, especially if the investor is expected to take an equity stake, reflecting the uncertainty of the return. But revealing this information means that the funder might steal the idea from the inventor. All these financial frictions can lead to many good ideas being unrealised. In general, many other market frictions can lead to under-provision. For example, if labour unions are strong, they may demand higher wages if the firm innovates, and this 'hold-up tax' may discourage firms from investing in R&D in the first place (Grout, 1984; Menezes-Filho, Ulph and Van Reenen, 1998).

On the other hand, there may be other factors that lead to **too much** R&D. The most well-discussed mechanism is through the 'business stealing' effect of innovation due to product market rivalry. When a firm innovates, it not only expands the overall size of the market (or indeed creates new markets); it also takes some market share from rival firms due to higher quality and/or lower cost of products.

16 See also European Commission (2017) for an EU perspective on why public R&I support is important.

Although this creates a private incentive for the firm to innovate if there is only a small improvement in cost/quality, but a big shift in market share, this means that there will only be small social benefits. For example, 'me-too' drugs of minor therapeutic improvement can lead to large shifts in market share as doctors and patients want the best drug. In this case, the private returns may be larger than the social returns and there is somewhat of an R&D 'arms race'. We see such effects in Schumpeter's notion of creative destruction and in many industrial organisation models (Griffith and Van Reenen, 2021).

The fact that a decentralised market economy will not deliver the optimal amount of investment in innovation is well recognised. Indeed, there is a wide panoply of policies and institutions (see our discussion below on the evidence) that are designed to deal with this problem. Many of these policies are not always effective, and indeed they can themselves create more problems than they solve (i.e. the 'cure' can be worse than the 'disease'). A much-discussed example is the system of intellectual property (IP) rights. IP rights such as patents are designed to deal with the knowledge spillover problem by granting a temporary monopoly to an inventor of an original and commercially practical innovation. In return for making the knowledge public, a private incentive for R&D is restored to the inventor; when the patent runs out, all are free to use the invention. This seems in principle attractive, as there is no need for the government to directly intervene and 'pick winners', and the trade-off between dynamic innovation incentives (the monopoly period to incentivise investment) and static inefficiencies (the distortions from the high monopoly price) is embodied within the institution of IP rights.

Alas, in practice, the way the IP system works is far from its ideal. Many patents can be 'designed around' and may offer little effective protection. In many industries, innovation cannot be formally protected as it is often tacit, hard to codify and incremental. This suggests the under-investment problem will still occur in many if not all industries. Even more worryingly, in recent decades, especially in the USA, there is ample evidence that the patent system has been abused with (predominantly large) firms creating 'patent thickets' to block entry by rivals. This is characterised by trivial patents receiving protection (with massive legal expenditure being used to defend them) and much useful knowledge hidden in patent documents rather than being revealed (see Jaffe and Lerner, 2007, for a survey; Williams, 2017, for a more recent general discussion; Ouellette and Williams, 2020, for some specific ideas for reform; and Boldrin and Levine, 2013, for a call to fully abolish current patent systems).

3.2 Rationale for public support of innovation: evidence

We now turn to the evidence on whether the social benefits of R&D exceed the private returns. There is a wealth of evidence from case studies recording both dramatic failures of government subsidies for innovation (for example, the Anglo-French supersonic aircraft, Concorde; or see the more systematic review in Lerner, 2005) as well as successes (e.g. nuclear power, jet engines, GPS, radar and the internet, e.g. Janeway, 2012; Mazzucato, 2013). Such qualitative evidence is useful but by their nature, case studies are small, highly selective and hard to quantify. There is a literature of statistical studies, beginning with Griliches' (1958) hybrid corn analysis. Griliches (1958) found social returns to government investment to be many multiples of private returns but cautioned against generalisation.

The more modern econometric literature examines a wider range of firms, sectors and technologies. A popular approach here is to use patent citations. A patent application is legally required to cite the prior art and even if an applicant does not do this, the patent examiner will frequently add citations. Past citations are an explicit (or implicit) way in which previous ideas spill over to future ones. This dynamic pattern of ideas can be used to estimate the speed at which knowledge diffuses and decays. Many authors have shown how citations are geographically clustered (both by country and also within a country), with inventors more likely to cite original inventors they live geographically close to, even after controlling for the technological field (e.g. Trajtenberg 1990; Jaffe, Trajtenberg and Henderson 1993; Griffith, Lee and Van Reenen 2011).

A problem with patent citations as a measure of spillovers is that they are hard to translate into a numeraire to calculate out a euro value for the social vs private returns. To address this, another approach is to analyse the impact of R&D expenditures of firm A on the productivity of firms B and C ('neighbours'). This is a kind of 'peer effect' that is of great interest in economics and other social sciences. It is nevertheless very difficult to identify these effects econometrically (see Manski, 1993). An immediate issue is that there are a very large number of firms who might get R&D spillovers. For example, consider the productivity of Microsoft. Clearly, the company might draw on the past R&D efforts of other firms in the software industry in America. But how much does Oracle's R&D benefit Microsoft relative to say IBM's R&D? Do we simply add them up, even if their R&D investments are in different technological fields? And of course, there may be spillovers to Microsoft from non-software firms, say in hardware or telecommunications. Additionally, the R&D of European firms may also benefit Microsoft. In principle one could allow the productivity of Microsoft to depend on a separate variable for the R&D of every firm, but in practice there are not enough data and we suffer from 'the curse of dimensionality'.

One way to address this issue draws on the seminal paper by Jaffe (1986). The idea is that some firms are technologically closer to each other than others. The R&D of a firm that is closer will be more likely to have an impact on productivity than one that is more distant. There are many ways to define proximity, but a useful one has proven to be based on looking at the technology classes a firm is active in as revealed by its past patenting behaviour. A firm that has patented mainly in software will be very close to another that is solely in software. However, if this firm has 50% of its patents in software and 50% in pharmaceuticals, it will also benefit from firms that patent a lot in pharmaceuticals. Armed with such a distance metric between every pair of firms, the R&D of neighbours can be weighted to generate an 'R&D spillover pool', which is one variable instead of potentially thousands.

Bloom, Schankerman and Van Reenen (2013) generalise the Jaffe (1986) approach to consider a number of distant metrics in technology space, product market space, geography, etc. (see also Lychagin et al., 2016). Defining firms that are close in product market space enables them to identify the rivalry effect of business-stealing separately from the knowledge-spillover effect. For example, more R&D by a firm that is a close product market rival (but distant in technology) will **reduce** the market value of a firm via potential business stealing. By contrast, more R&D by a company that draws on similar technologies but operates in entirely different product markets will tend to **boost** market value and productivity. The paper also addresses the endogeneity issue. A strong and positive association between changes in a firm's productivity and growth in the R&D spillover pool may not be causal. A demand shock, for example, could drive up both the firm's own productivity and its neighbours' R&D. The authors exploit the differential exposure of firms to changes in R&D tax credits at the state and federal levels. These R&I policy changes increased R&D incentives differently across firms (see next section) and are unlikely to be related to changes in a firm's demand. Thus, the differential impact of the structure of the tax across firms generates instrumental variables for the spillover terms enabling the authors to identify the causal effects of R&D spillovers.

There is good evidence for substantial knowledge spillovers using the distance metric approach. For example, Bloom, Schankerman and Van Reenen (2013) and Lucking, Bloom, and Van Reenen (2020) use panel data on publicly listed firms in the USA and find evidence for both R&D knowledge spillovers and business stealing. Quantitatively, the knowledge spillover effect dominates, and they calculate that social returns are over three times as large as private returns. This implies that even with the current set of extensive innovation supporting policies, there is underinvestment in R&D subsidies in the USA.

4. R&I policies

There are a wide range of policies to boost innovation. We give a brief summary of the econometric evidence here, but interested readers are referred to Bloom et al. (2019) and Van Reenen (2021) for more details. We focus on studies that are relatively well-identified as aiming at causal effects, rather than more correlation-based studies. We do not focus on all policies. For example, there is literature on how regulation can have negative or positive effects on innovation. Some emphasise negative effects due to red tape whereas others argue for positive effects from, say environmental innovation (see Aghion, Bergeaud and Van Reenen, 2021, for a discussion). Moreover, there is literature on how policies can affect the direction of technical change, such as how carbon pricing may induce more clean, green innovation relative to dirty innovation (e.g. Aghion et al., 2016). These are important issues, but they are beyond the scope of this chapter.

4.1 Supporting innovation through the tax system

4.1.1 R&D tax credits

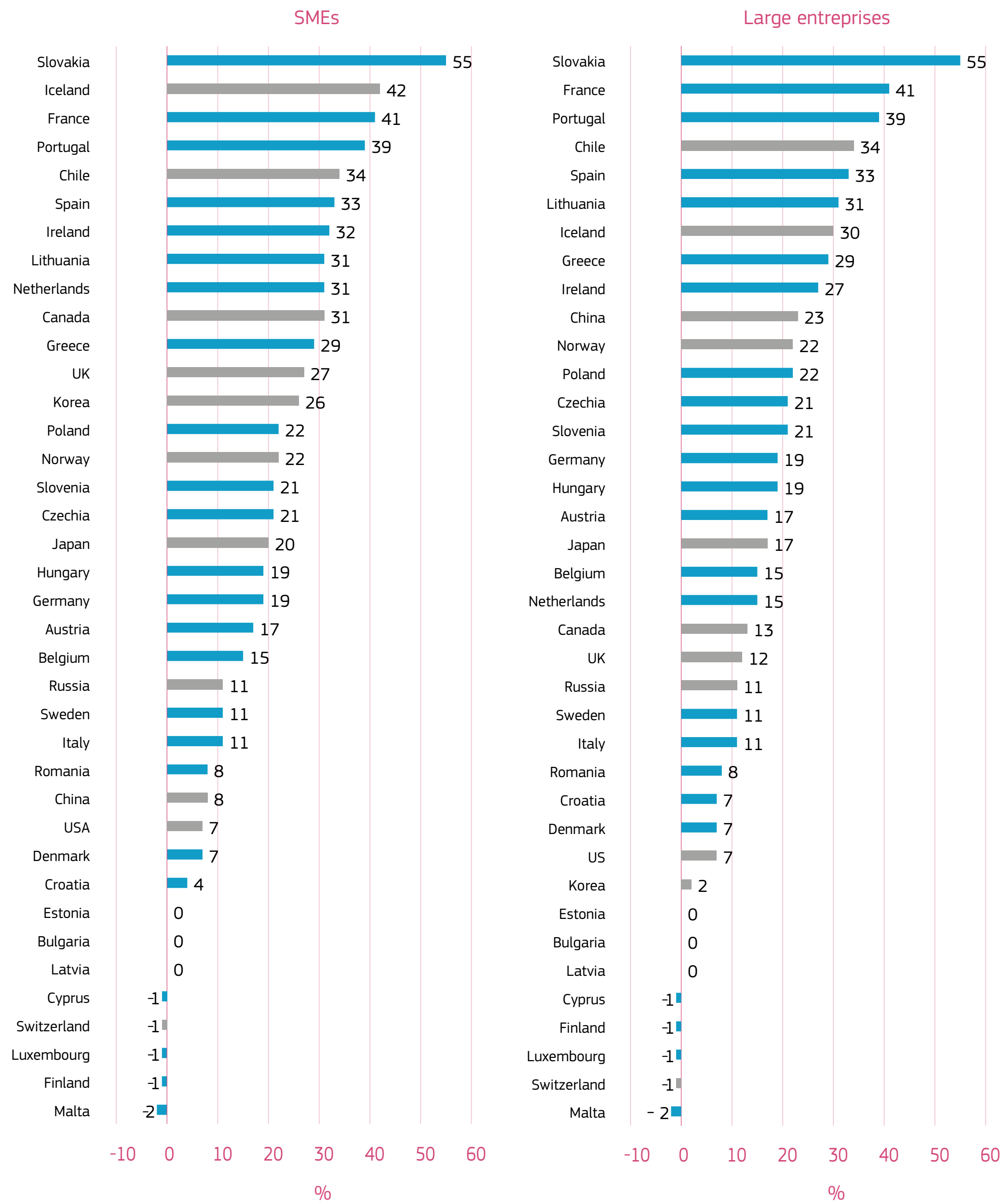
Given the gap between social and private returns on R&D documented in the previous section, the natural approach is to subsidise R&D through the tax code. Most R&D can be classified as current expenses (mainly people such as scientists, but also materials), although the returns on R&D are spread out over time (it is a form of intangible capital). As a result, the tax code implicitly treats it more generously than standard capital.

This is because R&D can be written off immediately against corporate tax bills ('100% deductibility'), whereas other investments in land or equipment can only be offset gradually over time. However, most countries offer additional incentives over and above this implicit incentive. These are generically called 'R&D tax credits' in the literature, although there are a variety of different ways the tax code is changed. A common strategy is to allow 'super-deductibility', where more than 100% can be written off (e.g. 175% for smaller firms in the UK after 2008).

Figure 7 shows the impact of the tax code on the effective subsidy rate for R&D in many OECD and some non-OECD countries. Panel A shows implied tax subsidy rates for SMEs and Panel B for large companies. The generosity varies a lot across the EU (the bars of EU Member States are coloured blue), from Slovakia, which has implied subsidies of over 50% (followed by France and Portugal on around 40%), to some with negative implied tax credits (e.g. Finland, Luxembourg and Malta). Several things stand out. First, fiscal incentives are generally more generous for SMEs than for large companies. Second, EU countries have more generous tax incentives than the USA, which is firmly in the bottom third of the table[17]. Third, tax credits seem to have increased in generosity since the mid-2000s. (e.g. Slovakia, Germany and Sweden were near zero in 2007; a corresponding graph can be found in the Appendix).

17 This is mainly because the tax credit is based on the incremental increase in a firm's R&D over a historically defined base level, rather than a subsidy based on the total amount of R&D spending.

Figure 8-7: Implied tax subsidy rates on R&D expenditure in different countries in 2020



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Source: OECD R&D Tax Incentives Database. https://stats.oecd.org/Index.aspx?DataSetCode=RDSUB

Note: Implied tax subsidy rates for SMEs (Panel A) and large enterprises (Panel B) in different countries in 2020 are shown. The bars for EU countries are blue; those for non-EU countries are grey. This is the 'profitable scenario'. For a detailed methodology behind calculations, see https://stats.oecd.org/Index.aspx?DataSetCode=RDSUB#. Countries with no notable bar (i.e. Latvia, Estonia and Bulgaria) have an implied tax subsidy rate of 0 %. Countries are ordered by level of tax subsidy rate (descending order). A corresponding graph showing the values for both firm types in 2007 as a comparison can be found in the Appendix.

Stats.: link

There is substantial literature examining the impact of R&D tax credits on R&D expenditure (for a survey, see Becker, 2015). Earlier studies tended to use data aggregated to the country level (e.g. Bloom, Griffith and Van Reenen, 2002, construct a cross-country panel dataset) or aggregated to the state level within countries (e.g. Wilson, 2009, uses a panel of US states). These studies relate changes in R&D spending to changes in the tax-price of R&D (i.e. filtering the tax rules through the Hall-Jorgenson tax-adjusted user cost formula in a similar way to that in Figure 7). The more recent literature exploits differential effects of tax rules across firms using firm-level panel data (see Hall, 1993, for a pioneering example). For example, Figure 7 showed that SMEs typically obtain more generous R&D tax treatment. Dechezlepretre et al. (2016) compare firms just below and just above the threshold before and after a surprise policy change in the UK using a regression discontinuity design to show large increases in R&D and patenting in response to the change in tax generosity. They also document substantial R&D spillovers using the same causal design.

Looking at the studies on R&D tax incentives as a whole, we believe that a reasonable conclusion is that the tax-price elasticity of R&D is at least unity and probably greater. In other words, a 1 % fall in the tax-price of R&D causes at least a 1 % increase in the volume of R&D in the long run. A concern about this conclusion is that firms may relabel existing expenditure as 'research and development' to take advantage of the more generous tax breaks. For example, there appeared to be substantial relabelling following a change in Chinese corporate tax rules according to Chen et al. (2021). To address this, some papers have looked directly at how non-R&D outcomes such as patenting, productivity or jobs respond to changes in tax credits. These more direct measures also seem to increase (with a lag) following tax changes, suggesting that relabelling is not driving the results (see Akcigit et al., 2018; Dechezlepretre et al., 2016; Bøler, Moxnes and Ulltveit-Moe, 2015).

4.2.1 Other tax policies

R&D tax credits are directly targeted at R&D. Other tax policies may have an impact even if they are not directly targeted. One popular alternative is 'patent boxes'. These are special tax regimes that apply a lower tax rate to revenues linked to patents relative to other commercial revenues. By the end of 2015, patent boxes (or similarly structured IP tax incentives) were used in 16 OECD countries (Guenther, 2017). These are indirect and encourage shifting about of patent revenue with no obvious direct incentive to do more R&D. Indeed, in practice their effect is mainly to encourage firms to shift their royalties into different tax jurisdictions (Griffith, Miller and O'Connell, 2011). This is particularly easy for multinationals, which are able to extensively manipulate where they book their taxable income from IP. Patent boxes do not have much effect on the real location or the quantity of R&D (see Gaessler, Hall and Harhoff, 2018), and appear to be simply a harmful form of tax competition.

General falls in corporate tax rates could have positive effects on innovation, especially if firms are credit-constrained. Atanassov and Liu (2020) present evidence in favour of this from UK publicly listed firms. Akcigit et al. (2018) use a variety of empirical strategies, including event studies and border designs, to argue that falls in effective individual tax rates and corporate rates have stimulated more patenting in the USA.

4.2 Government research grants

As discussed in the previous subsection, trying to incentivise R&D through the tax system is complex and may lead to a change in reporting rather than actual innovative activity. An alternative approach is to directly subsidise R&D

through grants. In principle, this is more efficient as the grants can be targeted directly towards the R&D that has the greatest knowledge spillovers (e.g. basic R&D such as that performed in universities rather than more applied R&D) and the least business stealing. Another advantage of grants is that they can be targeted directly towards the issues with high priority in the EU (e.g. climate change, health or digital transformation). A variety of government programmes seek to encourage innovation by providing grant funding to academic researchers and to private firms, for instance at the European level through Horizon Europe. These include the European Research Council and the Recovery and Resilience Facility support for Member States to implement reforms and investments that are in line with the EU's priorities.

There are also many potential disadvantages of direct government grants compared to a tax-based approach. First, the government agency has to select the high social-value programmes, and this is difficult given the great uncertainties and informational asymmetries around innovation. These exist in the private sector as well, of course, but it is likely that the R&D-performing firms have better information than the public funding body. Second, even for a well-informed agency, there is the risk of being politically captured and the public money flowing to well-connected firms, rather than the firms the benign planner would like to distribute resources to. Finally, there is the administrative costs of maintaining the bureaucracy to allocate and monitor the grants.

From an empirical perspective, identifying the causal impact of grant funding raises particular challenges. While the tax rules are usually widely applicable, a grant is specifically given for a reason and may target the most promising projects. A simple correlation between future success (e.g. R&D spending, patents or productivity) and R&D grant receipt will be biased upwards as the project would have enjoyed a good return even in the absence of the grant. On the other hand, the opposite might also be true, and the agency might give more money to firms and sectors who are performing poorly, generating a downward bias. The general problem is constructing a counterfactual for what would otherwise have happened in the absence of public R&D funds. A particular concern is that if EUR 1 of public R&D simply crowds out EUR 1 of private R&D that would otherwise have been invested in the same project, then public R&D could have no real effect on overall R&D allocations (or innovative outcomes). However, it is also possible that crowd-out is less than 100%, or even that public R&D 'crowds in' and attracts additional private R&D spending. For example, public R&D might complement private spending through intra-firm synergies, shared fixed costs (e.g. of R&D labs) and/or relieving financial constraints.

Although less extensive than the R&D tax literature, there is a growing body of work in this area. In terms of public grants to private firms, there are several papers that examine the Small Business Innovation Research (SBIR) scheme. SBIR is a US federal programme that is the largest SME innovation programme in the world. Howell (2017) examines outcomes for grant applicants from the Department of Energy (DOE), comparing marginal winners and losers. She estimates that early-stage SBIR grants roughly double the probability that a firm receives subsequent venture capital funding, and that receipt of an SBIR grant has positive impacts on firm revenue and patenting. Howell et al. (2021) also look at SBIR grants in the US Air Force using a regression discontinuity design. The authors show large causal effects of winning an SBIR grant on patenting, venture capital funding and the development of new military technologies[18]. Staying in the

18 Interestingly, they find that there are only positive impacts when the SBIR competitions are 'open': where the applicants can suggest new technologies. For the conventional SBIR competition where the Air Force tightly stipulates what technology it wants, the causal impacts of the programme are zero.

military context, Moretti, Steinwender and Van Reenen (2019) use shocks to defence spending (which are largely driven by geo-political events such as 9/11) as an instrument for public R&D spending. They also find crowd-in of private R&D and positive effects on TFP growth. Using a regression discontinuity design to analyse an Italian R&D grant programme, Bronzini and Iachini (2014) find that the programme's impact varies across firm size. Whereas they do not find a positive impact of subsidies (received by firms through grants) on investments for large firms, their results indicate that small firms increased R&D investments after receiving public support. They link this to higher financial frictions, which smaller firms tend to face.

There are also some studies focusing on the impact of academic grants[19]. Jacob and Lefgren (2011) show that National Institutes of Health (NIH) grants produce positive but small effects on research output, leading to about a 7 % increase in academic publications over 5 years. Azoulay et al. (2019) use changes in NIH budgets across research areas as an exogenous shock to look at the effect of academic research on commercialisable innovations. They find that NIH funding increases of USD 10 million lead to corporations filing just under three additional patents.

In summary, there seems an increasing corpus of work suggesting that R&D grants can stimulate more innovative activity, even if the empirical literature is still modest.

4.3 Universities

How important is higher education for innovation? Europe had the world's first modern secular university (Bologna), but in recent decades, the continent has fallen behind in research rankings compared to the USA. Currently, the EU has only seven universities in the Shanghai Rankings top 50, the list being dominated by the USA[20]. Areas with strong science-based universities such as Silicon Valley also seem to have substantial clusters of innovation. Valero and Van Reenen (2019) analyse 50 years of data from over a hundred countries, and document that the founding of a university increases local output per-capita and patenting in future years[21].

There are many ways in which universities could stimulate innovation. First, their founding and expansion increases the supply of individuals' science, technology, engineering and mathematics (STEM) qualifications. These STEM workers are likely to increase innovation. Second, the research efforts by academics create new ideas and these may be translated into commercial innovations through scientist entrepreneurial start-ups, university-corporate partnerships or informal links. In the previous subsection, we discussed the evidence that academic grants can stimulate innovation by academics and private firms in the life-sciences sector. Here, we look at graduate supply and academic incentives.

19 See also Jaffe (1989), Belenzon and Schankerman (2013) and Hausman (2018).
20 https://www.shanghairanking.com/rankings/arwu/2021 (last accessed on 03 September 2021).
21 See also Jaffe (1989), Acs, Audretsch and Feldman (1992), Belenzon and Schankerman (2013), Hausman (2018), Andrews (2020), Zucker, Brewer and Darby (1998) and Furman and MacGarvie (2007).

4.1.3 Graduate supply

Perhaps the best and most direct test of the role of universities in increasing STEM supply and innovation is the paper by Bianchi and Giorcelli (2019) on Italy. They exploit the fact that enrolment requirements for STEM majors changed in a particular year, which substantially boosted graduate numbers. Later, innovation increased, especially in medicine, chemistry and information technology, which are key STEM-related subjects. Another strong study is from Finland, where Toivanen and Väänänen (2016) find that individuals growing up near a technical university (which rapidly expanded in the 1960s and 1970s) had a significantly higher probability of becoming engineers. Norway also had a rapid increase in college start-ups in the 1970s. Carneiro, Liu and Salvanes (2018) compare areas where there was a particularly large increase in STEM-focused courses compared to non-STEM areas (synthetic cohorts). This seemed to lead to more R&D and a focus on STEM-related technological progress about 10 years after the colleges were founded[22].

4.2.3 Academic incentives

How can policies be designed that allow university discoveries to be made in commercialisable innovations? After the 1980 Bayh-Dole Act changed the ownership of inventions developed with public R&D (giving universities more ownership of the intellectual property), many US universities created 'technology transfer offices' to support this process. Lach and Schankerman (2008) find that larger ownership of patents by scientists generated more innovation.

In the case of Norway, Hvide and Jones (2018) argue that giving professors full innovation rights incentivised them to create more start-ups and file more patents. Financial returns for academics seemed to get more ideas out of universities and turn these into real products.

4.4 Immigration

Immigration is not conventionally thought of as an R&I policy. But it is striking that immigrants are heavily over-represented among inventors and entrepreneurs. For example, in the US immigrants account for 14 % of the workforce but 52 % of STEM doctorates, a quarter of all patents and a third of all US Nobel Prizes. Kerr and Kerr (2021) survey immigration and innovation in detail. Much research has found that immigrants (especially the more highly skilled) increase innovation. For example, Hunt and Gauthier-Loiselle (2010) report that increasing the share of immigrant college graduates by one percentage point boosts patenting per person by 9-18 %. Kerr and Lincoln (2010) find positive effects from changes in policies on H-1B visas. Bernstein et al. (2018) find large spillover effects of immigrants on native innovation from such changes. Moser and San (2019) show how changes in US immigration quotas in the early 1920s discouraged southern and eastern European scientists from migrating and reduced overall innovation (see also Doran and Yoon, 2018). Additionally, Moser, Voena and Waldinger (2014) show that the Nazi expulsions of Jewish scientists in the 1930s boosted innovation in US chemistry when they arrived[23].

22 For evidence of a causal impact of mathematics skills on labour market outcomes, see, for example, Joensen and Nielsen (2009).

23 Not all work finds such positive effects. Doran, Gelber and Isen (2015) use H1(B) lotteries and find smaller effects than Kerr and Lincoln (2010). Borjas and Doran (2012) look at publications by US mathematicians following the fall of the Soviet Union and argue for negative effects. But these findings may reflect special features of academic publishing, where the supply of journals is very slow to respond.

In our view, the weight of the literature suggests that immigration, especially skilled immigration, raises innovation. A liberal immigration policy is particularly attractive because the cost of educating immigrants has been borne by other countries rather than by the European taxpayer. Also, the increase in human capital can occur very quickly, which is different from other human capital supply side policies (such as improving education).

4.5 Increasing the quality of the inventor supply: 'lost Einsteins' and 'lost Marie Curies'

One under-appreciated way to increase the effective quantity of R&D is to reduce the barriers to talented people becoming inventors. Children born in low-income families, women and minorities are much less likely to become successful inventors. US children born into the top 1 % of the income distribution are an order of magnitude more likely to grow up to be inventors than are those born in the bottom half of the distribution (Bell et al., 2019a, b). Innate ability explains relatively little of this compared to the differential exposure rates to inventors in childhood. Bell et al. (2019a, b) argue that improved neighbourhoods, better school quality and greater exposure to inventor role models and mentoring could quadruple the innovation rate. Studies from other countries such as Finland find that discriminatory barriers are lower than in the USA, but they exist and serve to substantially lower innovation rates (Aghion et al., 2017)[24].

What kind of policies could be adopted to find the 'lost Einsteins' and 'lost Marie Curies' –[25]? Card and Giuliano (2016) review the effect of in-school tracking for minorities. They look at one of the largest US school districts, where schools with at least one gifted/high achiever (GHA) fourth (or fifth) grader had to create a separate GHA classroom. They found that students significantly improve their maths, reading and science when assigned to a GHA classroom, but these benefits were overwhelmingly concentrated among black and Hispanic participants. Cohodes (2020) examines the long-term effects of a similar programme in Boston Public Schools' Advanced Work Class (AWC) programme comparing those who scored just above and just below the admissions threshold. The programme increases college enrolment by 15 percentage points overall, again with gains primarily coming from black and Hispanic students. Breda et al. (2021) describe an intervention in French schools that exposed high-school girls to female scientists as role models. They found that this positively affected high-achieving grade 12 girls to choose STEM programmes in college. The most effective role model interventions are those that improved students' perceptions of STEM careers without overemphasising women's underrepresentation in science.

Although in its infancy, this evidence suggests that exposure policies can be effective. They are quite long-term and school-focused: there is a need for evidence whether they can also be effective in adults.

4.6 Competition and trade

It is well-known that the impact of competition on innovation is ambiguous in theory. Very high competition means little (or no) profit; consequently, Schumpeter (1942) argued that competition will discourage innovation. On the other hand, monopolists who benefit from high barriers to entry have little incentive to innovate and replace the stream of profits they already enjoy. Hence Arrow (1962) argued that entrants

24 See also Cook and Kongcharoen (2014) and Cook (2010) on gender and race and Murat (2018) for a general framework.

25 Gabriel, Ollard and Wilkinson (2018) have a useful survey of a wide range of 'innovation exposure' policies focusing on school-age programmes.

will have greater incentives to innovation (this is the 'replacement effect'). In Aghion et al. (2005), the relationship between innovation and competition is an inverted-U: when competition is low, the impact on innovation is at first positive (Arrow), and then becomes negative at higher levels of competition (Schumpeter).

Our reading of the empirical literature is that competition typically increases innovation (see Griffith and Van Reenen, 2021, for a recent survey). Some of the literature focuses on import shocks that increase competition, such as China's integration following its accession to the World Trade Organization. Shu and Steinwender (2018) find that in South America, Asia and Europe, trade competition tends to increase innovation (also see Blundell, Griffith and Van Reenen, 1999 and Bloom, Draca and Van Reenen, 2016). In North America, the evidence is more mixed, with Autor et al. (2020) finding negative effects of Chinese import competition on innovation in US manufacturing, and Xu and Gong (2017) arguing that R&D employees were mainly re-employed in services.

Trade openness can boost innovation by increasing market size, spreading fixed R&D costs over a larger market. Trade also leads to improved inputs and faster knowledge diffusion (e.g. Keller, 2004; Diamond, 1997). Aghion et al. (2018) use shocks to a firm's export markets to demonstrate large positive effects on innovation in French firms[26].

In our view, the literature suggests that greater competition and trade openness typically increase innovation. The financial costs of these policies are relatively low, given that there are additional positive impacts associated with policies that lower prices and increase choice. The downside is that such globalisation shocks may increase inequality between people and places.

26 See Melitz and Redding (2021) for a recent survey on trade and innovation.

5. Conclusions: summarising the evidence

Following Bloom, Van Reenen and Williams (2019), we summarise our judgements in Table 1, an R&I policy toolkit. Column 1 shows the policy; Column 2 summarises the quality of the empirical evidence; Column 3, the conclusiveness of the evidence; Column 4 shows the benefit-cost ratio in terms of a ranking where 3 crosses is the highest ranking (this is meant to represent a composite of the strength of the evidence as well as the magnitude of average effects); Column 5 shows whether the main effects would be short-term, medium term or long-term. Different policymakers (and citizens) will assign different weights to these alternative criteria.

In the short-run, research and development tax credits or direct public funding seem the most effective, whereas increasing the supply of human capital (for example, through expanding university STEM admissions) is more effective in the long-run. Skilled immigration has large effects, even in the short run. Competition and trade policies probably have benefits that are more modest for innovation but are cheap in financial terms and therefore also score highly.

One limitation of Table 1 is that it ignores interactions between policies. Moreover, it may be hard to build a political consensus to push for an ambitious programme of change. A way to tackle these issues is to bind them together in a programme aimed at a mission. The most pressing mission is climate change, and a key part of the battle is the stimulation of more green innovation.

Hence, one could consider how to bundle R&I policies together in such a way as to meet the climate challenge. Similarly, other missions include tackling health, defence and other environmental challenges.

The EU's main innovation programme, Horizon Europe, has a particular focus on policies that Table 1 summarises under 'Direct R&D grants'. Other parts of the budget, obviously, are directed towards other policy tools shown in the table. The broader European Research Area (ERA) for example fits into our 'Opening to Immigration' category[27]. One of the main goals, to create an open labour market for researchers, should make migration of researchers between EU countries easier. A further step would be to extend the ERA to additional non-EU member states, such that the EU could attract researchers and innovators from outside its borders. One relatively easy and quick way to increase incentives to innovate would be increases in tax credits by individual countries. As we showed in Section 4, these vary substantially across EU countries – there is room for increases in many countries. Additionally, there should be a focus on supply side policies such as greater educational support for children who show early promise in maths and science, but who are from low-income families. Moreover, there could be more mentoring and internship programmes that allow young people from under-represented groups to have greater exposure to the possibility of becoming inventors. Erasmus+ traineeships are a possible way to increase interactions between innovators and young people who could innovate in future[28].

27 For an overview on ERA, see https://op.europa.eu/en/web/eu-law-and-publications/publication-detail/-/publication/aae418f1-06b3-11eb-a511-01aa75ed71a1 (last accessed on 11 October 2021).

28 For more information on Erasmus+ traineeships, see https://erasmus-plus.ec.europa.eu/opportunities/individuals/students/traineeship-student (last accessed on 16 November 2021).

Increasing the scope of such programmes and focusing on students from under-represented backgrounds would lead to large long-run benefits.

To rebuild the economy after the COVID-19-crisis, a mix of short-term and long-term as well as demand and supply side policies is needed to stimulate innovation and thus make the European economy more sustainable and productive.

Figure 8-8: R&I Policy Toolkit

(1)	(2)	(3)	(4)	(5)
Policy	**Quality of evidence**	**Conclusiveness of evidence**	**Benefit-cost**	**Time frame**
R&D tax credits	High	High	+++	Short-term
Direct R&D grants	Medium	Medium	++	Medium-term
Universities: STEM supply	Medium	Medium	++	Long-term
Universities: incentives	Medium	Low	+	Medium-term
Opening up immigration	High	High	+++	Short-to-medium-term
Increasing inventor quality	Medium	Low	++	Long-term
Greater competition and trade openness	High	Medium	++	Medium-term

Source: Bloom, Van Reenen and Williams (2019)
Note: This is our highly subjective reading of the evidence. Column (2), 'Quality', is a mixture of the number of studies and the quality of the research design. Column (3) is whether the existing evidence delivers any firm policy conclusions. Column (4) is our assessment of the magnitude of the benefits minus the costs (assuming these are positive). Column (5) is whether the main benefits are likely to be seen (if there are any) in the short term (roughly, the next 3-4 years) or in a longer term.
Stats.: link

References

Acs, Z. J., Audretsch, D. B., & Feldman, M. P. (1992), 'Real Effects of Academic Research: Comment.', *American Economic Review* 82, pp. 363–67.

Aghion, P., Akcigit, U., Bergeaud, A., Blundell, R., & Hémous, D. (2019), 'Innovation and Top Income Inequality.', *The Review of Economic Studies* 86 (1), pp. 1-45.

Aghion, P., Akcigit, U., Hyytinen, A., & Toivanen, O. (2017), *The Social Origins of Inventors*, NBER Working Paper 24110.

Aghion, P., Bergeaud, A., & Van Reenen, J. (2021), *The Impact of Regulation on Innovation*, NBER Working Paper 28381.

Aghion, P., Bergeaud, A., Lequien, M., & Melitz, M. J. (2018), The Impact of Exports on *Innovation: Theory and Evidence*, NBER Working Paper 24600.

Aghion, P., Bloom, N., Blundell, R., Griffith, R., & Howitt, P. (2005), 'Competition and Innovation: An Inverted-U Relationship.', *The Quarterly Journal of Economics* 120 (2), pp. 701-728.

Aghion, P., Dechezleprêtre, A., Hemous, D., Martin, R., & Van Reenen, J. (2016), 'Carbon Taxes, Path Dependency and Directed Technical Change: Evidence from the Auto Industry', *Journal of Political Economy*, 124(1) pp. 1-51.

Akcigit, U., Grigsby, J., Nicholas, T., & Stantcheva, S. (2018), *Taxation and Innovation in the 20th Century*, NBER Working Paper 24982.

Andrews, M. (2020), 'How Do Institutions of Higher Education Affect Local Invention? Evidence from the Establishment of U.S. Colleges.', Mimeo, University of Maryland.

Arora, A., Belenzon, S., & Patacconi, A. (2018), 'The Decline of Science in Corporate R&D', *Strategic Management Journal* 39 (1), pp. 3–32.

Arrow, K. (1962), 'Economic Welfare and Allocation of Resources for Invention.' In National Bureau of Economic Research, *The Rate and Direction of Inventive Activity: Economic and Social Factors*, pp. 609–26. Princeton, NJ: Princeton University Press.

Atanassov, J., & Liu, X. (2020), 'Can Corporate Income Tax Cuts Stimulate Innovation?' *Journal of Financial and Quantitative Analysis*, 5(5) pp. 1415 – 1465.

Autor, D., Goldin, C., & Katz, L. F. (2020), 'The Race between Education and Technology Revisited.', *American Economic Review* 110, pp. 347–51.

Azoulay, P., Graff Zivin, J. S., Li, D., & Sampat, B. N. (2019), 'Public R&D Investments and Private Sector Patenting: Evidence from NIH Funding Rules.', *Review of Economic Studies* 86 (1), pp. 117–52.

Becker, B. (2015), 'Public R&D policies and private R&D investment: A survey of the empirical evidence.', *Journal of Economic Surveys*, 29(5) pp. 917–942.

Belenzon, S., & Schankerman, M. (2013), 'Spreading the Word: Geography, Policy and Knowledge Spillovers.', *Review of Economics and Statistics* 95 (3), pp. 884–903.

Bell, A., Chetty, R., Jaravel, X., Petkova, N., & Van Reenen, J. (2019a), 'Who Becomes an Inventor in America? The Importance of Exposure to Innovation.', *Quarterly Journal of Economics* 134 (2), pp. 647–713.

Bell, A., Chetty, R., Jaravel, X., Petkova, N., & Van Reenen, J. (2019b), 'Do Tax Cuts Produce More Einsteins? The Impacts of Financial Incentives vs. Exposure to Innovation on the Supply of Inventors.', *Journal of the European Economic Association* 17 (3), pp. 651–77.

Bergeaud, A., Cette, G., & Lecat, R. (2016), 'Productivity Trends in Advanced Countries between 1890 and 2012.', *Review of Income and Wealth* 62 (3), pp. 420-444.

Bernstein, S., Diamond, R., McQuade, T., & Pousada, B. (2018), The Contribution of High-*Skilled Immigrants to Innovation in the United States*, Mimeo, Stanford University.

Bianchi, N., & Giorcelli, M. (2019), *Scientific Education and Innovation: From Technical Diplomas to University STEM Degrees*, NBER Working Paper 25928. Cambridge, MA: National Bureau of Economic Research.

Bloom, N., Draca, M., & Van Reenen, J. (2016), 'Trade Induced Technical Change? The Impact of Chinese Imports on Innovation, IT and Productivity.', *The Review of Economic Studies* 83 (1), pp. 87-117.

Bloom, N., Griffith, R., & Van Reenen, J. (2002), 'Do R&D tax credits work? Evidence from a Panel of Countries 1979–1997.', Journal of Public Economics 85 (1), pp. 1-31.

Bloom, N., Jones, C. I., Van Reenen, J., & Webb, M. (2020), 'Are Ideas Becoming Harder to Find?', *American Economic Review* 110 (4), pp. 1104–44.

Bloom, N., Sadun, R., & Van Reenen, J. (2012), 'Americans Do I.T Better: US multinationals and the productivity miracle', *American Economic Review* 102 (1), pp. 167-201.

Bloom, N., Schankerman, M., & Van Reenen, J. (2013), 'Identifying Technology Spillovers and Product Market Rivalry.', *Econometrica* 81 (4), pp. 1347–93.

Bloom, N., Van Reenen, J., & Williams, H. (2019), 'A Toolkit of Policies to Promote Innovation.', *Journal of Economic Perspectives* 33 (3), pp. 163–84.

Blundell, R., Griffith, R., & Van Reenen, J. (1999), 'Market Share, Market Value and Innovation in a Panel of British Manufacturing Firms.', *The Review of Economic Studies* 66 (3), pp. 529-554.

Boldrin, M., & Levine, D. K. (2013), 'The Case against Patents.', *Journal of Economic Perspectives* 27 (1), pp. 3-22.

Bøler, E. A., Moxnes, A., & Ulltveit-Moe, K. H. (2015), 'R&D, International Sourcing, and the Joint Impact on Firm Performance.', *American Economic Review* 105, (12), pp. 3704-39.

Borjas, G. J., & Doran, K. B. (2012), 'The Collapse of the Soviet Union and the Productivity of American Mathematicians.', *Quarterly Journal of Economics* 127 (3), pp. 1143–1203.

Breda, T., Grenet, J., Monnet, M., & Van Effenterre, C. (2021), *Do Female Role Models Reduce the Gender Gap in Science? Evidence from French High Schools*, CNRS mimeo.

Bronzini, R., & Iachini, E. (2014), 'Are Incentives for R&D Effective? Evidence from a Regression Discontinuity Approach.', *American Economic Journal: Economic Policy*, 6 (4), pp. 100-134.

Bryan, K. A., & Williams, H. L. (2021), *Innovation: Market Failures and Public Policies*, NBER Working Paper 29173.

Card, D., & Giuliano, L. (2016), 'Can Tracking Raise the Test Scores of High-Ability Minority Students?', *American Economic Review* 106 (10), pp. 2783–816.

Carneiro, P. M., Liu, K., & Salvanes, K. G. (2018), *The Supply of Skill and Endogenous Technical Change: Evidence from a College Expansion Reform*, Discussion Paper Series in Economics 16/2018, Norwegian School of Economics, Department of Economics.

Celik, M. A. (2018), *Does the Cream Always Rise to the Top? The Misallocation of Talent in Innovation*, Mimeo, University of Toronto.

Chen, Z., Liu, Z., Suárez Serrato, J. C., & Xu, D. Y. (2021), 'Notching R&D Investment with Corporate Income Tax Cuts in China', *American Economic Review* 111(7), pp. 2065-2100.

Cohodes, S. R. (2020), 'The Long-Run Impacts of Specialized Programming for High-Achieving Students.', *American Economic Journal: Economic Policy* 12 (1), pp. 127–66.

Cook, L. D. (2014), 'Violence and Economic Activity: Evidence from African American Patents, 1870–1940.', *Journal of Economic Growth* 19, pp. 221–57.

Cook, L. D., & Kongcharoen, C. (2010), *The Idea Gap in Pink and Black*, NBER Working Paper No. 16331. Cambridge, MA: National Bureau of Economic Research.

Dechezleprêtre, A., Einiö, E., Martin, R., Nguyen, K. T., & Van Reenen, J. (2016), *Do Fiscal Incentives increase innovation? An RD Design for R&D*, CEP Discussion Paper 1413.

Doran, K., Gelber, A., & Isen, A. (2015), *The Effects of High-Skilled Immigration Policy on Firms: Evidence from H-1B Visa Lotteries*, NBER Working Paper No. 20668. Cambridge, MA: National Bureau of Economic Research.

Dorn, D., Hanson, G. H., Pisano, G., & Shu, P. (2020), 'Foreign Competition and Domestic Innovation: Evidence from US Patents', *American Economic Review*: Insights 2(3), pp. 357-74.

Draca, M., Sadun, R., & Van Reenen, J. (2007), 'ICT and Productivity' *Handbook of Information of Information and Communication Technologies*' R. Mansell, C. Avgerou, D. Quah and R. Silverstone (eds) Oxford Handbook on ICTs, Oxford University Press.

European Commission. (2017), 'The Economic Rationale For Public R&I Funding and its Impact.' EU Publications Office. https://ri-links2ua.eu/object/document/326/attach/KI0117050ENN_002.pdf.

Flaubert, G. (1911), *Le Dictionnaire des idées reçues* London: Dodo Press.

Furman, J. L., & MacGarvie, M. J. (2007), 'Academic Science and the Birth of Industrial Research Laboratories in the US Pharmaceutical Industry.' *Journal of Economic Behavior and Organization* 63, pp. 756–76.

Gabriel, M., Ollard, J., & Wilkinson, N. (2018), 'Opportunity Lost: How Inventive Potential Is Squandered and What to Do about It.' London: Nesta. https://media.nesta.org.uk/documents/Opportunity-Lost-December-2018.pdf.

Gaessler, F., Hall, B. H., & Harhoff, D. *Should There Be Lower Taxes on Patent Income?*, NBER Working Paper 24843.

Griffith, R., & Van Reenen, J. (2021), *Product Market Competition, Creative Destruction and Innovation*, LSE mimeo.

Griffith, R., Lee, S., & Van Reenen, J. (2011), 'Is Distance Dying at Last? Falling Home Bias in Fixed Effects Models of Patent Citations.', *Quantitative Economics* 2, pp. 211–49.

Griffith, R., Miller, H., & O'Connell, M. (2014), *Journal of Public Economics* 112(C), pp. 12-23.

Griffith, R., Redding, S., & Reenen, J. V. (2004), 'Mapping the Two Faces of R&D: Productivity Growth in a panel of OECD industries', *Review of Economics and Statistics*, 86(4), pp. 883-895.

Griliches, Z. (1958), 'Research Costs and Social Returns: Hybrid Corn and Related Innovations.', *Journal of Political Economy* 66, pp. 419.

Grout, Paul. (1984), 'Investment and Wages in the Absence of Binding Contracts: A Nash Bargaining Approach', *Econometrica*, 52(2), pp. 449-460.

Guenther, G. (2017), 'Patent Boxes: A Primer' Congressional Research Service https://sgp.fas.org/crs/misc/R44829.pdf.

Hall, B. H. (1993), 'R&D Tax Policy during the Eighties: Success or Failure?', *Tax Policy and the Economy* 7, pp. 1-35.

Hall, B. H., & Lerner, J. (2010), 'The Financing of R&D and Innovation.' In *Handbook of the Economics of Innovation*, vol. 1, edited by Bronwyn H. Hall and Nathan Rosenberg, 609–39. Amsterdam: North-Holland.

Hausman, N. (2018), *University Innovation and Local Economic Growth*. Mimeo, Hebrew University.

Howell, S. T. (2017), 'Financing Innovation: Evidence from R&D Grants.' *American Economic Review* 107 (4), pp. 1136–64.

Howell, S. T., Rathje, J., Van Reenen, J., & Wong, J. (2021), *OPENing up Military Innovation: An Evaluation of Reforms to the U.S. Air Force SBIR Program*, NBER Working Paper 28700.

Hunt, J., & Gauthier-Loiselle, M. (2010), 'How Much Does Immigration Boost Innovation?', American Economic *Journal: Macroeconomics* 2 (2), pp. 31–56.

Hvide, H. K., & Jones, B. F. (2018), 'University Innovation and Professor's Privilege.', *American Economic Review* 108 (7), pp. 1860–98.

Jacob, B. A., & Lefgren, L. (2011), 'The Impact of Research Grant Funding on Scientific Productivity.', *Journal of Public Economics* 95 (9–10), pp. 1168–77.

Jaffe, A. B. (1986), 'Technological Opportunity and Spillovers of R&D: Evidence from Firms' Patents, Profits and Market Value.', *American Economic Review* 76, pp. 984–1001.

Jaffe, A. B. 1989. 'Real Effects of Academic Research.', *American Economic Review* 79 (5), pp. 957–70.

Jaffe, A. B., & Lerner, J. (2007), *Innovation and its Discontents*. Princeton: Princeton University Press.

Jaffe, A. B., Trajtenberg, M., & Henderson, R. (1993), 'Geographic Localization of Knowledge Spillovers as Evidenced by Patent Citations.', *Quarterly Journal of Economics* 108 (3), pp. 577–98.

Janeway, W. H. (2012), D*oing Capitalism in the Innovation Economy: Markets, Speculation and the State*. Cambridge, UK: Cambridge University Press.

Joensen, J. S., & Nielsen, H. S. (2009), 'Is there a causal effect of high school math on labor market outcomes?', *Journal of Human Resources* 44 (1), pp. 171-198.

Jones, B. F., & Summers, L. H. (2020), *A Calculation of the Social Returns to Innovation*, NBER Working Paper No. 27863. Cambridge, MA: National Bureau of Economic Research.

Keller, W. (2004), 'International Technology Diffusion.', *Journal of Economic Literature* 42 (3), pp. 752-782.

Kerr, S. P., & Kerr, W. R. (2021), 'Whose Job Is It Anyway? Coethnic Hiring in New US Ventures.', *Journal of Human Capital* 15 (1), pp. 86-127.

Kerr, W. R., & Lincoln, W. F. (2010), 'The Supply Side of Innovation: H-1B Visa Reforms and U.S. Ethnic Invention.', Journal of Labor Economics 28 (3): 473–508.Lach, Saul, and Mark Schankerman. (2008), 'Incentives and Invention in Universities.', R*AND Journal of Economics* 39 (2), pp. 403–33.

Lerner, J. (2005), *The Boulevard of Broken Dreams*. Princeton, NJ: Princeton University Press.

Lucking, B., Bloom, N., & Van Reenen, J. (2020), 'Have R&D Spillovers Declined in the 21st Century?', *Fiscal Studies* 40 (4), pp. 561–90.

Lychagin, S., Pinkse, J., Slade, M. E., & Reenen, J. V. (2016), 'Spillovers in Space: Does Geography Matter?', *Journal of Industrial Economics* 64(2) , pp. 295-335.

Manski, C. F. (1993), 'Identification of Endogenous Social Effects: The Reflection Problem', *Review of Economic Studies*, 60, pp. 531-542.

Mazzucato, M. (2013), *The Entrepreneurial State: Debunking Public vs. Private Sector Myths*. London: Anthem Press.

Mazzucato, M., & Semieniuk, G (2017), 'Public financing of innovation: new questions.', *Oxford Review of Economic Policy* 33 (1), pp. 24-48.

Melitz, M. J., & Redding, S. J. (2021), *Trade and Innovation*. NBER Working Paper 28945.

Menezes-Filho, N., Ulph, D., & Van Reenen, J. (1998), 'R&D and Union Bargaining: Evidence from British Companies and Establishments', *Industrial and Labor Relations Review* 52(1), pp. 45-63.

Moretti, E., Steinwender, C., & Van Reenen, J. (2019), *The Intellectual Spoils of War? Defense R&D, Productivity and International Technology Spillovers*. NBER Working Paper 26483. Cambridge, MA: National Bureau of Economic Research.

Moser, P., & San, S. (2019), *Immigration, Science, and Invention: Evidence from the 1920s Quota Acts*. Mimeo, New York University.

Moser, P., Voena, A., & Waldinger, F. (2014), 'German Jewish Émigrés and US Invention.', *American Economic Review* 104 (10), pp. 3222–55.

Ouellette, L. L., & Williams, H. (2020), 'Reforming the Patent System' *The Hamilton Project: Policy Proposal* 2020-12.

Scur, D., Sadun, R., Van Reenen, J., Lemos, R., & Bloom, N. (2021), 'The World Management Survey at 18', *Oxford Review of Economic Policy* 37(2), pp. 231–258.

Shu, P., & Steinwender, C. (2019), 'The impact of trade liberalization on firm productivity and innovation.', *Innovation Policy and the Economy* 19 (1), pp. 39-68.

Toivanen, O., & Väänänen, L. (2016), 'Education and Invention.' *Review of Economics and Statistics* 98 (2), pp. 382–96.

Trajtenberg, M. (1990), 'A Penny for Your Quotes: Patent Citations and the Value of Innovations.', *RAND Journal of Economics* 21 (1), pp. 172–87.

Valero, A., & Van Reenen, J. (2019), 'The Economic Impact of Universities: Evidence from Across the Globe.', *Economics of Educatio*n 68, pp. 53–67.

Van Reenen, J. (2021), 'Human Capital Innovation Policy', POID Working Paper 5.

Williams, H. L. (2017), 'How Do Patents Affect Research Investments?', *Annual Reviews of Economics* 9, pp. 441-469.

Wilson, D. J. (2009), 'Beggar thy Neighbor? The In-State, Out-of-State, and Aggregate Effects of R&D Tax Credits.', *The Review of Economics and Statistics* 91 (2), pp. 431-436.

Xu, R., & Gong, K. (2017), 'Does Import Competition Induce R&D Reallocation? Evidence from the US.', IMF Working Paper 17/253.

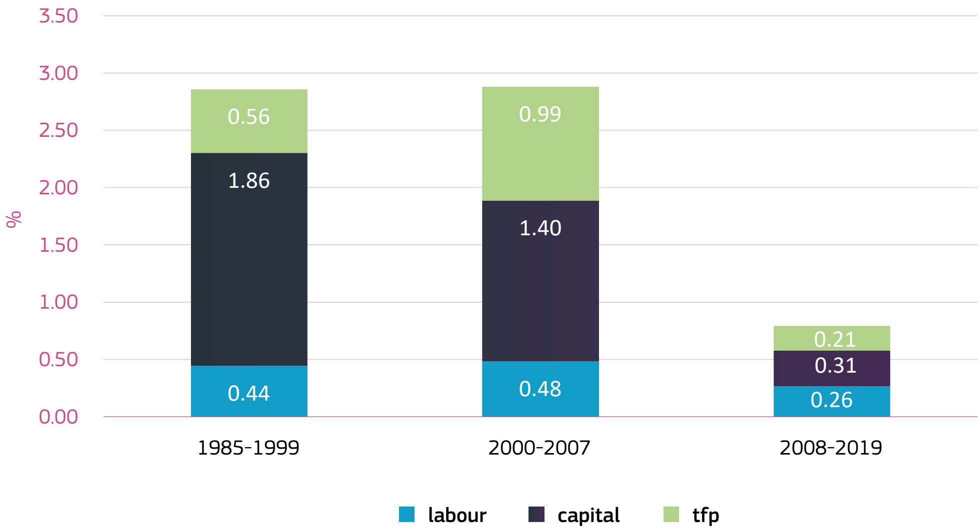
Yoon, C., & Doran, K. (2018), *Immigration and Invention: Evidence from the Quota Acts*. Mimeo, University of Notre Dame.

Zucker, L. G., Darby, M. R., & Brewer, M. B. (1998), 'Intellectual Capital and the Birth of US Biotechnology Enterprises.', *American Economic Review* 88, pp. 290–306.

Appendix A

Additional figures

Figure A-1: Contribution of labour, capital and TFP to GDP growth in the EU



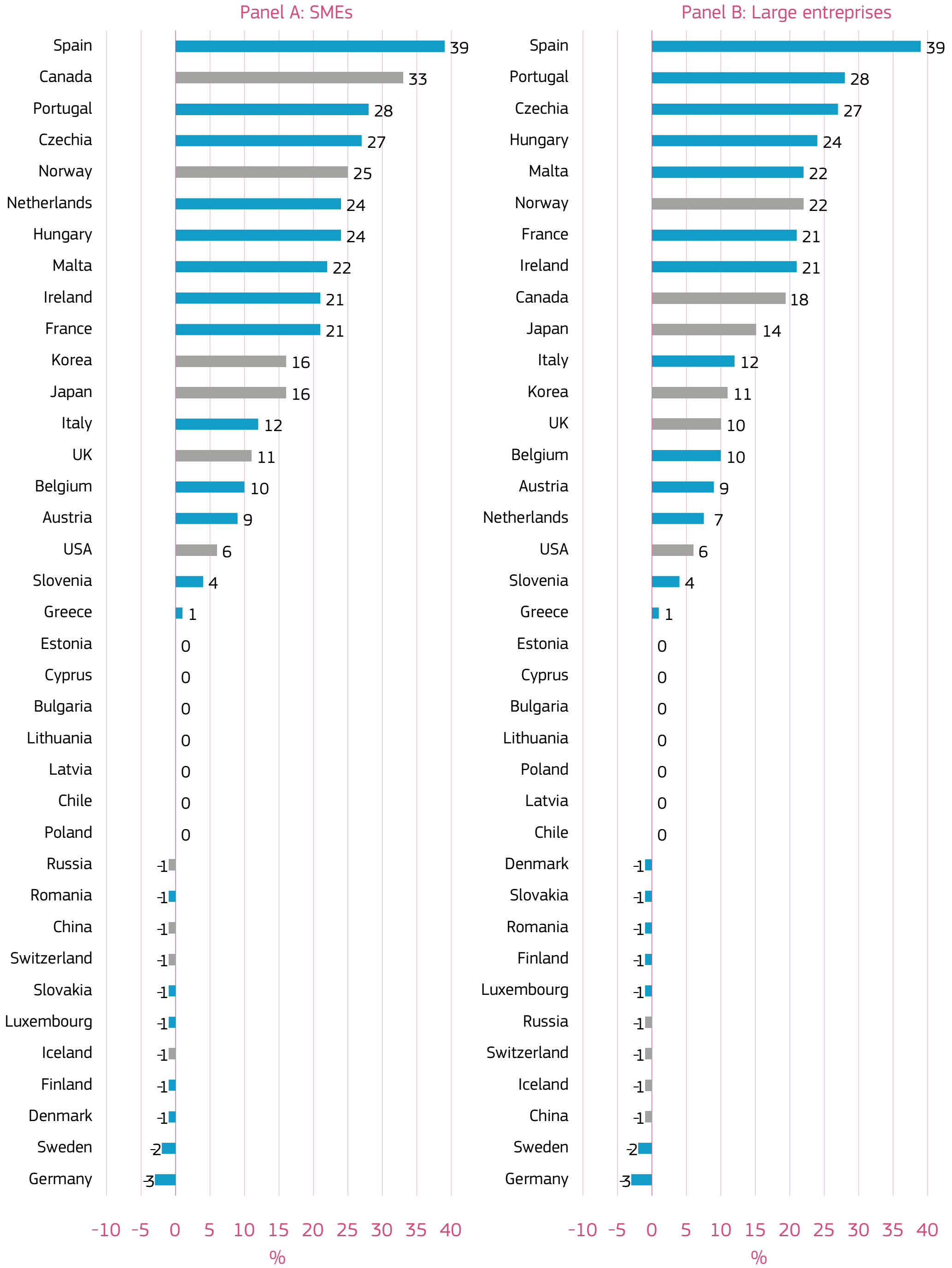
Science, Research and Innovation Performance of the EU 2022

Source: OECD productivity database. https://stats.oecd.org/index.aspx?queryid=66347#

Note: Each stacked bar represents the overall real GDP growth in the given time period as an average for a subset of EU countries (Belgium, Germany, Denmark, Spain, Finland, France, Greece, Ireland, Italy, Luxembourg, Portugal, and Sweden). The single components within a bar show the percentage point contribution of labour (measured as hours worked), capital (ICT and non-ICT capital) and TFP growth towards output growth.

Stats.: link

Figure A-2: Implied tax subsidy rates on R&D expenditure 2007, SMEs and large enterprises



Science, Research and Innovation Performance of the EU 2022

Source: OECD R&D Tax Incentives Database. https://stats.oecd.org/Index.aspx?DataSetCode=RDSUB

Implied tax subsidy rates are shown for SMEs (Panel A) and large enterprises (Panel B) in different countries in 2007. The bars of EU countries are blue, those of non-EU countries grey. This is the 'profitable scenario'. For a detailed methodology behind calculations, see HYPERLINK "https://stats.oecd.org/Index.aspx?DataSetCode=RDSUB" https://stats.oecd.org/Index.aspx?DataSetCode=RDSUB#. Countries with no notable bar have an implied tax subsidy rate of 0 %. Countries are ordered by level of tax subsidy rate (descending order).

Stats.: link

CHAPTER 9

INDUSTRIAL PERFORMANCE AND INVESTMENTS IN INTANGIBLE ASSETS DURING CRISES

Peter Bauer and Aurélien Genty
Joint Research Centre

Summary

We take the global financial crisis (GFC), as an example of a major crisis, to study the trends in intangible investment, the link between industrial performance and intangible assets, and the differences in financing intangible versus tangible assets during crises. We find an upward trend in in intangible investment intensities (investment-to-value added) that started well before the GFC and the crisis had little impact on it, in contrast to tangible investment intensities. We explore the potential role that intangible assets may play in weathering the negative effects of major crises using industry-level data. We find that pre-crisis R&D investment is robustly associated with economic resilience during the GFC, and higher productivity growth in the aftermath. Finally, we investigate how financial turmoil may affect the financing of intangible investment. We show that industries that are more dependent on external finance cut back their intangible investments during the crisis compared to industries that finance their investments mostly from internal sources. In contrast, tangible investments were not sensitive to the dependence on external finance. Our leading explanation is that tight credit conditions create a trade-off between tangible and intangible investment financing. Given the importance of intangible assets for productivity growth, our findings strengthen the case for ensuring uninterrupted financing of firms during crises.

1. Introduction

Intangible assets are a key driver of firm productivity in the modern economy, and ultimately of the competitiveness of economies, as shown by a couple of recent papers (Thum-Thysen et al., 2017; Bauer et al., 2020; Adarov and Stehrer, 2019; Cincera et al., 2020). Intangible assets support firms' digitalisation (software, databases), innovation (R&D, design, patents) and the business knowledge necessary for their functioning (market knowledge, organisational knowledge, training for employees). Furthermore, the impact of an intangible asset on firm performance is amplified by its complementarity to other intangible and tangible assets (Thum-Thysen et al., 2019).

We focus our analysis on the GFC as an example of major crises, to study the trends of intangible investment before, during and after such a major crisis and explore the potential role that intangible assets may play in weathering the negative effects of major crises. In this latter analysis, we analyse not only the association between intangible intensity and growth rates of different economic indicators (e.g. value added), we also use resilience metrics (e.g. strength of recovery) to assess the contribution of intangible assets to the resilience of economies against major shocks.

In parallel, we investigate how financial turmoil may affect the financing of these assets. Finally, we draw some general lessons that can also be applied to the COVID-19 crisis. The novelty of our approach relies on the use of industry-level data from the EU KLEMS (2019) database[1] to analyse industries' intangible investment and their performance in both the short term (output and employment) and the long run (productivity), depending on their intangible investment intensity.

When looking at investment intensity (as a share of value added), we find an upward trend for several kinds of intangible assets in almost all Member States, and in almost all industries. This trend started well before the GFC and overall, the crisis had little impact on it, in contrast to tangible investment intensity, which declined significantly during the GFC. We observe a similar phenomenon during the COVID-19 pandemic based on preliminary data available, despite the differences between the two crises. This suggests that a demand shock does not hit intangible investment as severely as it does tangible investment.

The subsequent detailed analysis sheds light on the dissimilar impact of different types of assets on industrial performance and the important role of finance. Despite the limitations of a comparison exercise between the GFC and other crises, we believe that a number of lessons can be drawn for the current COVID-19 crisis. This is not least because, for example, many economic activities after the outbreak continued to be held away from the workplace, which underscores the centrality of key intangible assets, such as organisational capital. Likewise, investments in training are also bound to be extremely relevant in times of protracted episodes of labour hoarding, where the aim is to avoid a deterioration in workers' skills. These aspects should be taken into account by both policymakers in order to efficiently support certain types of investment to foster faster recovery and stronger resilience as well as by firms in their future investment decisions.

1 For the details of the data, see Stehrer et al. (2019).

2. Investment intensities before, during and after the financial crisis

The pre-crisis period (2005-2007)

In the following, we analyse investments in intangible assets in the form of intensities calculated as an investment-to-value-added ratio based on EU KLEMS (2019) data. First, we focus on the intensities in the pre-crisis period, as we will use these variables in the next part to explain economic performance during and following the crisis.

The EU-15 countries are more intangible-asset intensive than the EU-13 Member States[2]. The main reason is the much higher investment intensity in software and especially R&D, while, e.g., investment intensities in organisational capital (both purchased and own-account) are quite similar. At the same time, **tangible-asset intensity is almost twice as high in the EU-13 Member States as in the EU-15**[3]. The intangible intensities of the USA are quite similar to the EU-15's, but with slightly more investment into **brand** and less investment into **design**.

Comparing industry investment intensities averaged (unweighted) over the EU-15 (Table 1), we find that, somewhat surprisingly, **manufacturing industries have a lower-than-average tangible intensity while a higher-than-average intangible intensity**. The result for intangibles is mainly explained by the high R&D intensity of manufacturing. This is consistent with the relevant literature (Thum-Thysen et al., 2019), which stresses the importance of complementarities between different assets, such as tangibles (e.g. machines) and intangibles. Digital transformation of firms, for example, requires not only joint investment in hardware and software but also in organisational capital and training.

The result for tangibles is explained by higher tangible intensity of such non-manufacturing industries as transportation, energy and telecommunication.

2 EU-15: Countries that were members of the EU before May 2004, the 'old Member States' (AT, BE, DK, FI, FR, DE, GR, IE, It, LU, NL, PT, ES, SE, UK). EU-13: Countries that joined the EU in May 2004 or later, the 'new Member States' (BG, HR, CY, CZ, EE, HU, LV, LT, MT, PL, RO, SK, SI).

3 This is not explained by our choice of a flow-type intensity instead of stock-type intensity. Tangible capital per value-added is highest among the EU-13 countries.

Table 9-1: Average investment intensities of EU-15 countries (2005-2007, percentage of value added)

	Industry	Tangible	Intangible*	Software +DB	R&D	Brand	Design	Purchased organisa-tional capital	Own-account organisation-al capital	Training
Manufacturing (C)	Food products	14.9%	9.9%	1.2%	1.4%	4.9%	0.9%	1.6%	0.8%	0.5%
	Textile	7.7%	6.7%	1.4%	1.6%	1.8%	0.7%	1.2%	0.9%	0.6%
	Wood and paper	15.0%	5.6%	1.5%	1.1%	1.0%	0.8%	1.1%	0.9%	0.5%
	Chemicals	15.2%	15.1%	1.8%	8.8%	2.0%	1.0%	1.4%	0.7%	0.4%
	Pharmaceutical	9.2%	25.0%	1.6%	18.6%	2.1%	1.2%	1.3%	0.5%	0.3%
	Rubber and plastics	13.9%	6.8%	1.3%	2.3%	1.0%	1.1%	1.2%	0.9%	0.5%
	Metals	15.4%	5.4%	1.2%	1.8%	0.5%	0.8%	1.0%	0.9%	0.5%
	Computer and electronics	6.9%	30.1%	5.3%	19.9%	1.7%	1.2%	1.7%	0.8%	0.4%
	Electrical equipment	7.8%	15.0%	2.7%	8.6%	1.0%	1.2%	1.4%	0.9%	0.5%
	Machinery	7.5%	12.1%	2.0%	6.4%	0.8%	1.5%	1.5%	0.9%	0.5%
	Transport equipment	11.6%	18.5%	2.2%	11.8%	1.4%	1.8%	1.3%	0.9%	0.5%
	Other manufacturing	7.2%	8.3%	1.7%	3.6%	1.2%	0.8%	1.0%	0.9%	0.5%
D	Energy	37.8%	5.4%	2.0%	0.9%	0.4%	1.0%	0.9%	0.4%	0.3%
E	Water, waste	42.6%	6.6%	1.4%	0.8%	0.6%	2.2%	1.4%	0.7%	0.4%
F	Construction	12.6%	6.4%	0.5%	0.1%	0.3%	4.6%	0.9%	0.6%	0.4%
Trade (G)	Trade of motor vehicles	9.8%	5.5%	1.0%	0.2%	2.4%	0.6%	1.1%	0.8%	0.5%
	Wholesale trade	7.2%	7.8%	2.0%	0.9%	2.1%	0.7%	2.0%	0.8%	0.4%
	Retail trade	9.7%	5.8%	1.5%	0.1%	2.0%	0.4%	1.7%	0.8%	0.5%
Transport (H)	Land transport	23.3%	2.8%	0.7%	0.1%	0.5%	0.7%	0.6%	0.7%	0.5%
	Water transport	56.3%	4.4%	0.7%	0.3%	0.9%	1.2%	2.9%	0.5%	0.4%
	Air transport	42.1%	5.8%	2.0%	0.0%	1.8%	0.6%	1.1%	0.6%	0.5%
	Warehousing	42.2%	5.3%	1.9%	0.1%	0.6%	1.1%	1.2%	0.7%	0.4%
	Postal activities	5.2%	4.2%	1.5%	0.6%	0.8%	0.6%	0.7%	0.8%	0.6%
I	Accomodation and food serv.	10.0%	2.6%	0.5%	0.0%	0.9%	0.4%	0.8%	0.5%	0.4%
Info-comm. (J)	Media	6.8%	22.5%	5.9%	1.5%	3.1%	1.1%	1.9%	0.6%	0.5%
	Telecommunication	22.3%	13.1%	6.3%	2.0%	2.1%	1.5%	1.2%	0.4%	0.3%
	IT services	5.5%	17.7%	10.2%	2.8%	0.8%	1.5%	2.0%	0.8%	0.6%
M-N	Professional and admin. serv.	14.4%	14.2%	2.2%	4.3%	1.5%	3.0%	3.2%	0.8%	0.7%
R	Recreation	20.3%	9.4%	1.6%	1.1%	1.1%	0.6%	1.1%	0.5%	0.4%
S	Other services	9.2%	5.1%	1.5%	0.9%	0.8%	0.6%	1.3%	0.6%	0.4%
	Average	17.0%	10.1%	2.2%	3.4%	1.4%	1.2%	1.4%	0.7%	0.5%

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Source: JRC calculation based on EU KLEMS 2019, BACH and ECB data

Note: Minimum value is green, median is yellow and maximum is red. All other cells are coloured proportionally.

* The aggregate intangible asset does not include own-account organisational capital and training, but does include other intellectual property products (not shown individually).

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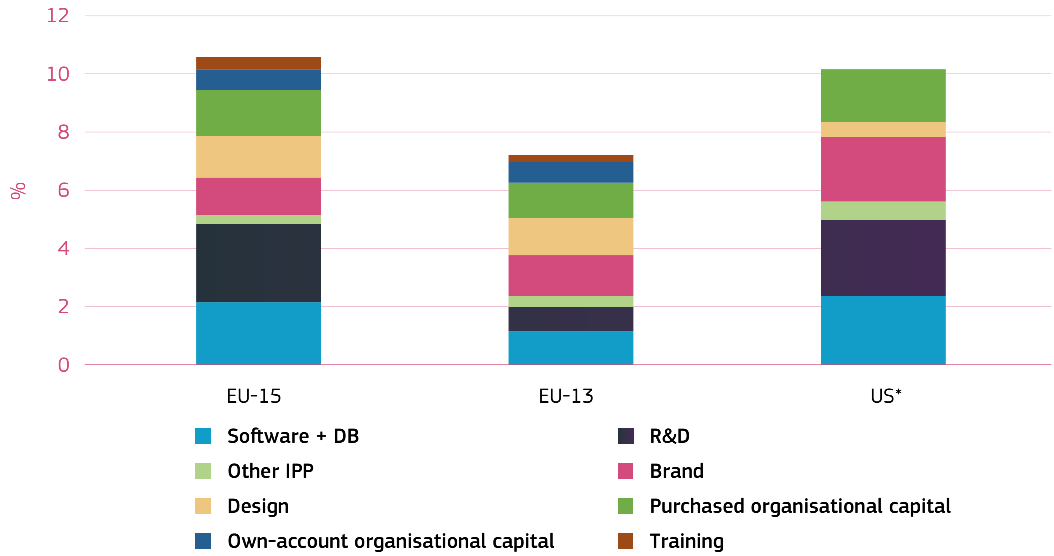
Figure 9-1: Average intangible investment intensity in the EU and the USA 2005-2007 (investment over value added, nominal terms)



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Source: JRC calculations based on EU KLEMS 2019

Note: * There is no data for own-account organisational capital and training for the US.

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Change of investment intensities during the GFC and subsequent recovery

Tangible intensity declined during the crisis both in the EU-15 and the EU-13 blocks[4]. (Figure 2). This decline clearly continued for new Member States during the late recovery (2014-2017) while it rebounded somewhat for the EU-15. Nevertheless, average tangible intensity is lower at the end of the sample period than before the crisis. **Intangible intensity in most assets increased** during the crisis and continued throughout the recovery both for the EU-15 and the EU-13 countries.

Exceptions include average investment intensity in software for the EU-13 Member States, own-account organisational capital for both country groups, and training for the EU-13 countries. For training, there was a general decline in investment intensity across industries even before the GFC[5], while for software and own-account organisational capital, intensity declined in some industries (e.g. manufacturing) and increased in others, the info-communication sector, for example.

4 This decline is also statistically significant based on the average change across industries. We will not repeat this, but almost all changes in investment intensities compared to pre-crisis levels were statistically significant (comparing country-industry pairs between the different time periods). The significance level is set at 10 % in all the analysis.

5 We should note that there are reasons to believe that training is the worst-measured asset in EU KLEMS, namely that the data are largely inconsistent with another intangible database, IntanInvest.

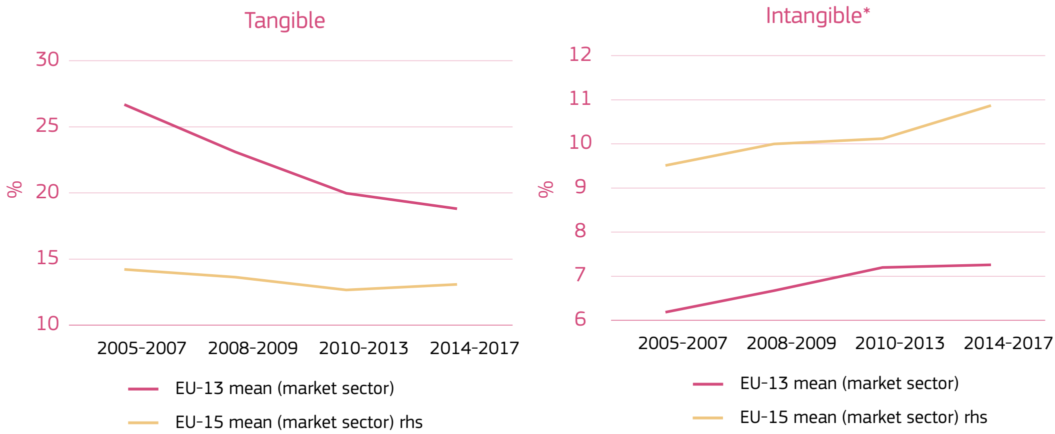
We should emphasise that we are analysing intensities here, and not the investments themselves. As value added decreased substantially during the financial crisis, the fact that intangible investment intensity did not decrease still means that intangible investment declined from 2008 to 2009, especially if we compare it to the pre-crisis trend. Thus, what we find here is that intangible investment declined more or less in proportion to value added, while the drop was bigger in case of tangible investment.

It is interesting to see how short-term developments around the GFC fit into a longer-term picture. We observe, since 1995, an upward trend in intangible intensity. **This trend was mainly unaffected by the financial crisis** (see Figure 3)[6]. This finding is consistent with previous results in the literature, where it is found that intangible investment is relatively insensitive to aggregate demand (Thum-Thysen et al., 2017 and 2019). It is remarkable that despite this overall increase in intangible intensity, the ranking of countries by this intensity is quite persistent (Figure 4).

Almost all intangible assets show an upward trend (except own-account organisational capital and training, see the Appendix for figures by individual assets), while the **biggest contributor to the aggregate trend is the increase in R&D intensity in case of EU-15 countries**. In the same vein as the old Member States, aggregate intangible intensity in **EU-13 countries** also shows a positive trend, but in this case, **mainly because of non-R&D intangibles**. In EU-13 countries, on average, R&D intensity did not show a positive trend before the crisis but started to grow just after the crisis. We analysed the trend of investment intensities at the detailed sectoral level (at the NACE 2-digit industry level) as well. We find that intangible intensity in almost all such detailed industries follows a positive trend in both country groups. In contrast to intangible assets, tangible investment intensity had a negative trend before the crisis for the EU-15 countries, while no negative trend was observed for the EU-13. Almost all 2-digit industries follow this negative trend in the EU-15. The crisis caused a drop in tangible intensity in both country groups. After the crisis, there was a partial rebound in the EU-15, while no rebound at all for the EU-13 countries.

6 Not only descriptive statistics but also statistical tests support this finding, using a country-industry-year panel regression with country and industry fixed effects. We used investment intensity as the dependent variable and included a linear trend and year dummies since 2008 as explanatory variables.

Figure 9-2: Tangible and intangible investment intensity of the EU-15 and EU-13 countries (percentageof nominal value added)



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Source: JRC calculations based on EU KLEMS 2019

* The aggregate intangible asset does not include own-account organisational capital and training, while it includes other intellectual property products.

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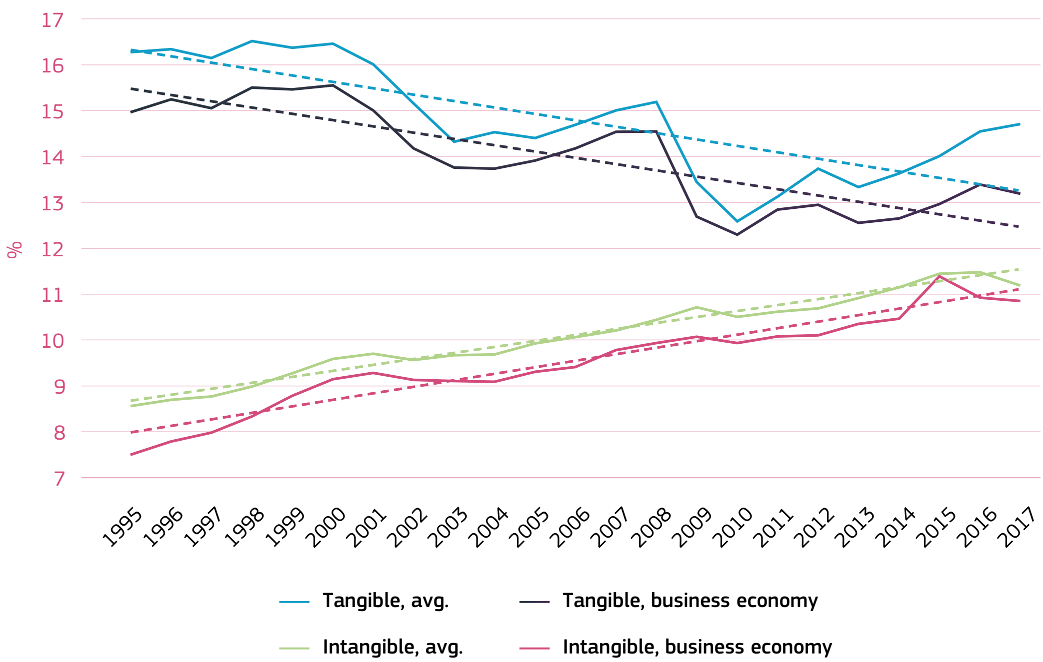
Figure 9-3: Tangible and intangible investment intensity trends for the EU-15 countries (unweighted averages across countries)



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Source: JRC calculation based on EU KLEMS 2019

Note: The aggregate intangible asset does not include own-account organisational capital and training. 'Avg.' means an unweighted average across countries and 2-digit industries, while 'business economy' means the unweighted average across countries of the aggregate business economy sector (which is a weighted average of industries).

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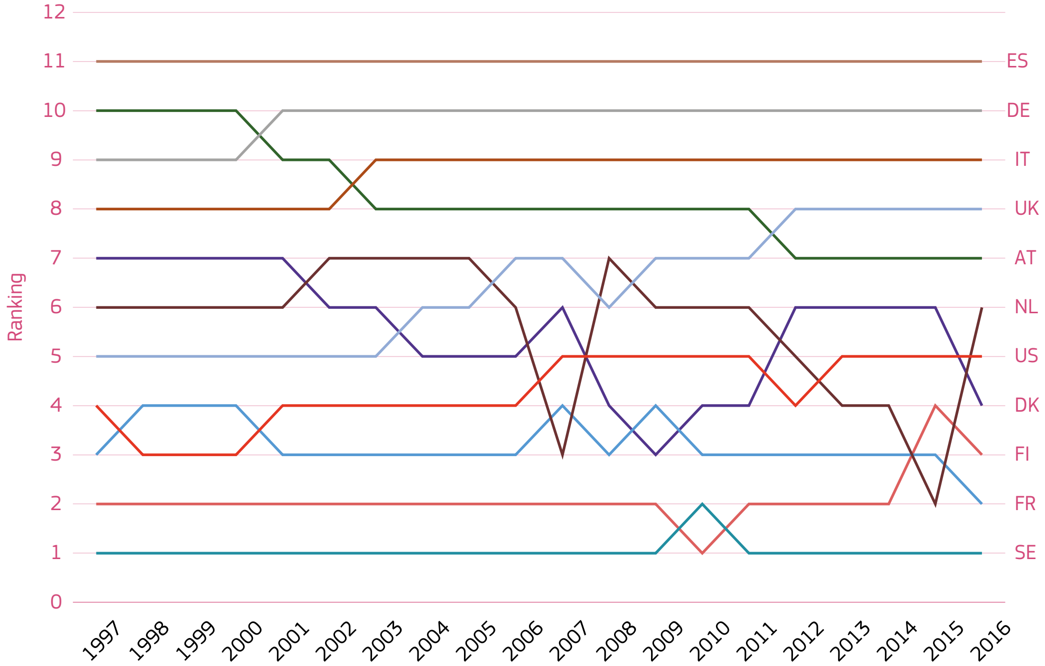
Figure 9-4: Ranking of EU-15 + USA countries over time according to intangible intensity in the business economy (lower numbers indicate higher intensity)



Source: JRC calculation based on EU KLEMS 2019

Note: The aggregate intangible asset does not include own-account organisational capital and training

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3. Growth in output, labour and productivity – results from a panel estimation

We analyse the role of tangible and intangible assets during the global financial crisis in output growth (measured by real value added), growth in labour (measured by the number of persons employed and hours worked) and productivity growth. We estimate the impact on both labour productivity growth (measured by real value added per hours worked) and total factor productivity (TFP) growth[7]. We also look at whether labour hoarding was more widespread in intangible-intensive industries, i.e. a decline in labour utilisation measured by the change in hours/employee.

First, we emphasise that for the analysis, the investment intensity of an industry is measured based on investments made during 2005-2007, i.e. before the crisis, to avoid potential endogeneity problems. As developments in industries during the crisis could depend on industry characteristics other than investment intensities (e.g. a higher drop in demand for high income-elasticity goods), we need to control for inherent industry differences. To this end, we estimated **country-industry panel regressions of the EU-15 countries and the USA**. We controlled for industry and country fixed effects, which means that any average differences between industries or countries were eliminated in terms of both the explanatory variables (investment intensities) and the dependent variables (output, labour and productivity growth). Thus, the intuition behind this setting is that we compare developments in the same industry between countries, or alternatively, we compare developments in the same country between industries.

We also controlled for tangible intensity wherever we estimated the effect of intangible intensity as these intensities are (weakly) correlated[8].

Thus, we estimate the following regression:

$$y_{cs}^{period} = \alpha TangibleInt_{cs}^{2005\text{-}2007} + \beta IntangibleInt_{cs}^{2005\text{-}2007} + \delta_c + \mu_s + u_{cs}$$

where c is country, s is industry and *period* is either 2005-2007, 2008-2009, 2010-2013 or 2014-2017. $TangibleInt$ and $IntangibleInt$ are average tangible investment intensity (as a share of value added) and intangible investment intensity (as a share of value added), respectively, for the pre-crisis period 2005-2007. Several intangible assets were used in the regression for intangible intensity (e.g. software, R&D, etc). y_{cs} is the average annual growth rate of the outcome variable over the specified period. The outcome variables[9] are our indicators of industry performance, such as real value added, employment (persons), hours worked, hours/employment, labour productivity (real value added per hour) and TFP. δ_c and μ_s are country and industry fixed effects, u_{cs} is the error term. We report the partial effect of intangible intensity on the outcome variable in the main text as the effect of a change from the bottom of the intensity distribution to the top, calculated as $\beta *(p75(IntangibleInt)-p25(IntangibleInt))$, where p75 and p25 are the 75th and 25th percentiles of the intensity distribution across country and industry.

7 TFP is taken from the EU KLEMS database. It is estimated by a standard growth accounting procedure, taking into account non-national account intangibles as capital inputs as well. We do not report the results for the version where TFP is calculated using only national account capital inputs. These results were qualitatively and quantitatively very similar to the former.

8 Where we report the result for tangibles, the aggregate intangible intensity was included as a control.

9 Outcome variables' in our case simply mean that these are our variable of interest, but they are not only output type variables (such as value added) but input type variables (such as employment) as well.

See Table 2 for the values of these percentiles for different assets. For example, in case of the overall intangible asset, we calculate the effect of a 8.9 percentage point change in the investment intensity. In addition to the point estimate, we also indicate graphically whether the association between investment intensity and the outcome variable is statistically significant or not at the 10 % level[10].

In the following, we will focus on results for the EU-15 countries, while results for the EU-13 countries are discussed only briefly afterwards as these were less conclusive.

Real value added growth

According to our estimates, pre-crisis growth was larger where tangible or intangible investment was higher[11]. Among specific types of intangibles, mainly R&D intensive industries grew faster, while own-account organisational-capital and vocational-training intensive industries were associated with lower growth. During the first phase of the crisis (2008-2009), **more tangible-intensive industries**, (keeping other industry and country characteristics constant) suffered more, while overall **intangible-intensive industries in general, and training-intensive industries in particular, were associated with higher growth**. On the long run (2014-2017), **R&D-intensive industries grew faster.**

Table 9-2: 25th and the 75th percentiles of the investment intensity distribution across countries and industries and difference between them (2005-2007).

	p25	p75	p75 - p25
Tangible	6,8 %	17,9 %	**11,0 %**
Intangible	4,9 %	13,7 %	**8,9 %**
Software + DB	0,8 %	2,3 %	**1,6 %**
R&D	0,2 %	3,8 %	**3,6 %**
Brand	0,5 %	1,7 %	**1,2 %**
Design	0,3 %	1,2 %	**0,9 %**
Purchased org. capital	0,6 %	1,9 %	**1,3 %**
Own-account org. capital	0,3 %	0,7 %	**0,4 %**
Training	0,2 %	0,7 %	**0,4 %**

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Note: 'DB' means database, and 'org. capital' means organisational capital.

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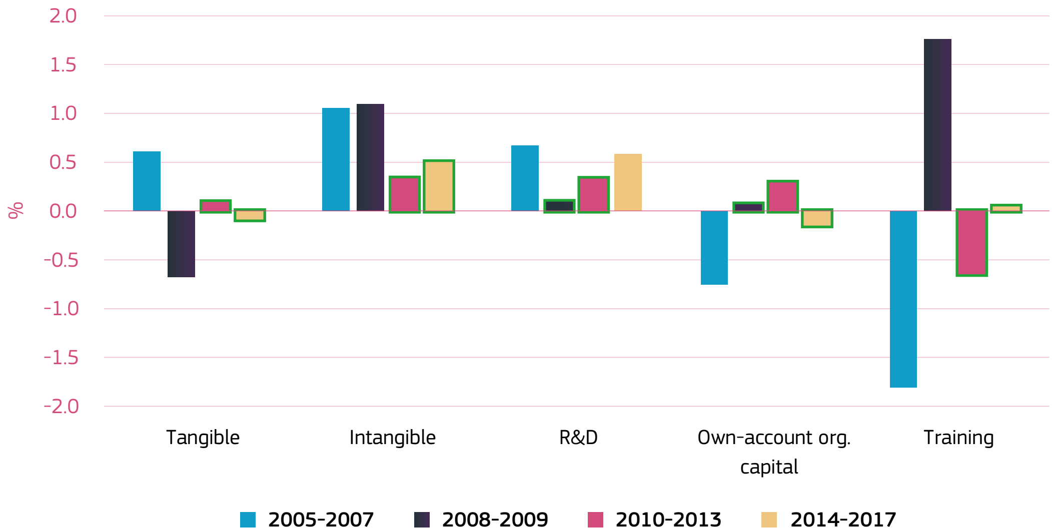
10 We do not report the estimated coefficients as our main results because investment intensities are quite heterogeneous for different assets, thus a 1 percentage point increase can either be considered large or small depending on the specific asset.

11 Results for the 2005-2007 period are only for illustration; they cannot be interpreted as causal effects because of (potential) simultaneity of the outcome variable and investment.

Figure 9-5: Percentage point effect on real value added growth of an increase in pre-crisis investment intensity equivalent to jumping from the bottom 25 % to the top 25 % of the intensity distribution (controlled for country and industry effects in a panel



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Source: JRC calculations based on EU KLEMS 2019
Note: The framed bars denote a non-significant coefficient in the panel estimation.
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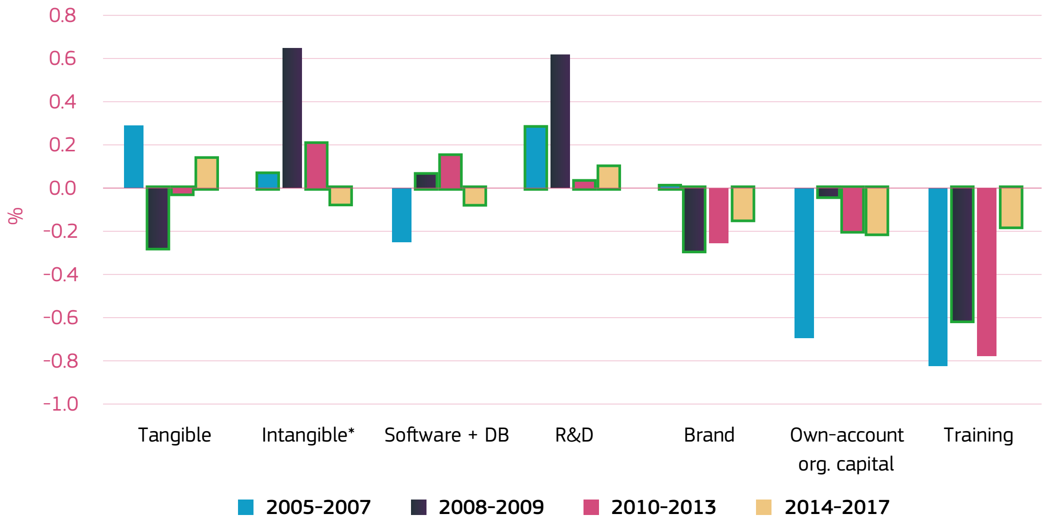
Employment growth

Employment grew faster in more tangible- and intangible-intensive industries before the crisis. From those, only the result for tangible intensive industries is statistically significant. During the first phase of the crisis (2008-2009), **employment growth was significantly positively correlated with overall intangible intensity and R&D intensity**. On the long run (2014-2017), there was no significant relationship between investment intensities and employment growth.

Figure 9-6: **Percentage point effect on employment growth of an increase of pre-crisis investment intensity equivalent to jumping from the bottom 25 % to the top 25 % of the intensity distribution (controlled for country and industry effects in a panel setting).**



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Source: JRC calculations based on EU KLEMS 2019
Note: The framed bars denote a non-significant coefficient in the panel estimation. DB= database
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Growth in hours worked

Before the crisis, tangible intensity and intangible intensity (in the case of a number of assets) were associated with faster growth in hours worked. However, we could not find any significant positive correlations. During the start of the crisis (2008-2009), **growth in hours was higher in R&D-intensive industries than in non-R&D-intensive industries**. Brand-intensive industries saw hours worked decline by more than less brand-intensive industries. On the long run (2014-2017), **organisational capital-intensive industries** (both purchased and own-account) **showed lower growth in hours.**

Productivity growth

Before the crisis, high overall intangible intensity was associated with higher productivity growth (keeping other industry and country characteristics constant). In contrast, productivity growth in tangible-intensive industries was lower relative to less tangible intensive industries but this effect is not statistically significant. During the crisis and partly during the recovery, measured productivity growth was strongly influenced by volatility in capacity utilisation, therefore we focus our analysis of labour productivity and TFP growth on the period from 2014 onwards.

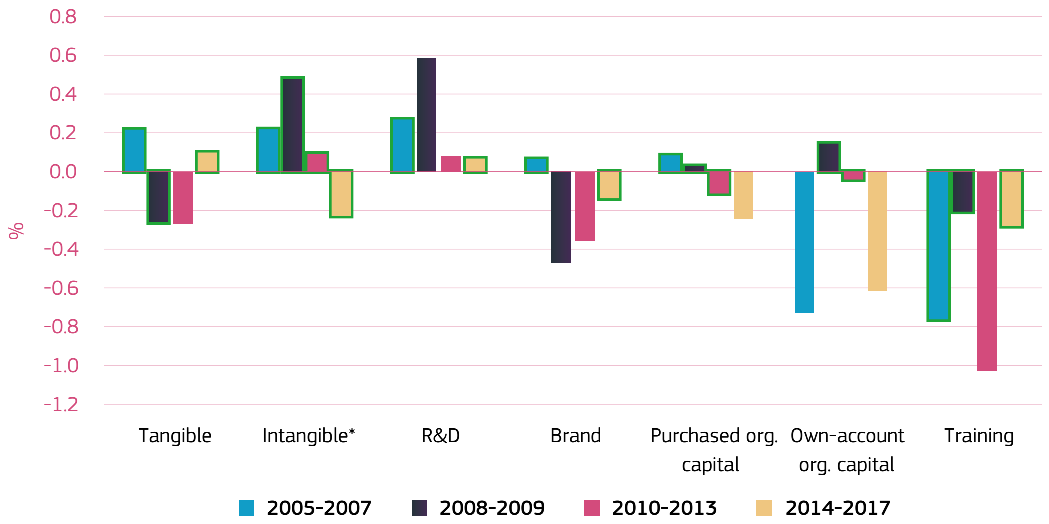
On the long run (2014-2017), **investment intensity** in a wide array of different assets (intangibles but also tangible) was also associated with **higher productivity growth**. Among these assets, **R&D and overall intangible**s bear a **statistically significant relationship** with both **labour productivity** and **TFP growth**. The result for R&D is in line with several papers showing the positive impact of R&D on productivity (see e.g. the seminal book of Griliches, 1998). Brand has a significantly positive effect on **labour productivity growth**, while **design** has a significantly positive effect on **TFP growth**. These results show the relevance of both innovative properties (R&D and design) and economic competencies (brand) for long-term productivity growth.

Overall, results for labour productivity growth and for TFP growth are very similar in terms of the importance of intangible assets as driving factors.

Results for selected resilience metrics

As our empirical approach is quite similar to the methodologies used in resilience analysis (see e.g. JRC, 2018), it seems natural to also adopt some of the usual 'resilience metrics' applied in the literature to analyse the role of intangibles in this respect. It is worth emphasising that our metrics are calculated using industry-level data. This is in contrast to the majority of the literature on resilience, which uses country-level aggregate data. We calculate

Figure 9-7: Percentage point effect on growth of hours worked of an increase of pre-crisis investment intensity equivalent to jumping from the bottom 25 % to the top 25 % of the intensity distribution (controlled for country and industry effects in a panel setting).



Source: JRC calculations based on EU KLEMS 2019
Note: The framed bars denote a non-significant coefficient in the panel estimation.
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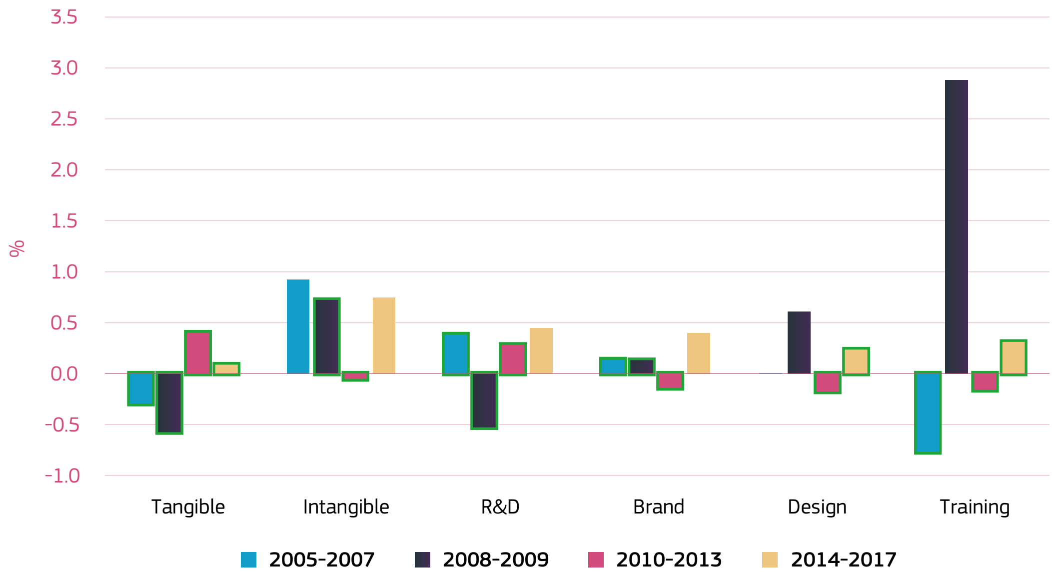
three different metrics taken from the related resilience literature: i) impact; ii) medium-term performance; and iii) speed of recovery. Impact is defined as the percentage difference in levels for a given variable between the worst year during the crisis (when the outcome variable was at a minimum[12] level) and the period just before the crisis. For example, for value added, impact is calculated as the cumulative drop in value added since 2007 until the given industry (in the given country) reached its minimum level. Medium-term performance is defined as the percentage difference in levels for a given variable between an end period long after the crisis for which data are available and the period just before the crisis. Obviously, the end period should be chosen to be before a recession starts again. In our case, 2017, the last available year in our database, was chosen as the end period. Recovery is measured as the percentage difference between the end period and the worst year during the crisis. The determination of the worst year is country and industry specific for both the impact and the recovery metrics. The recovery metric is identical to the difference of the medium-term and impact metrics by definition.

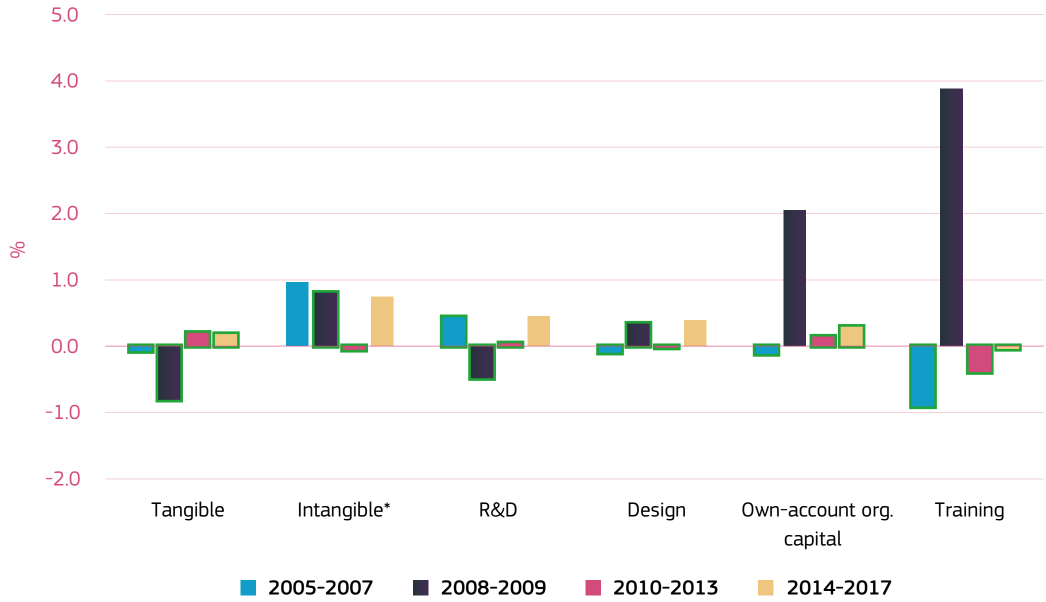
Figure 9-8: Percentage point effect on labour productivity growth of an increase of pre-crisis investment intensity equivalent to jumping from the bottom 25 % to the top 25 % of the intensity distribution (controlled for country and industry effects in a panel setting).



Source: JRC calculations based on EU KLEMS 2019
Note: The framed bars denote a non-significant coefficient in the panel estimation.
Stats.: link

12 For all our variables, we use the minimum level for the determination of the worst year. Of course, if we had used variables where the larger the variable, the worse the performance (e.g. unemployment), we would have calculated the maximum level.

Figure 9-9: Percentage point effect on TFP growth of an increase of pre-crisis investment intensity equivalent to jumping from the bottom 25 % to the top 25 % of the intensity distribution (controlled for country and industry effects in a panel setting).

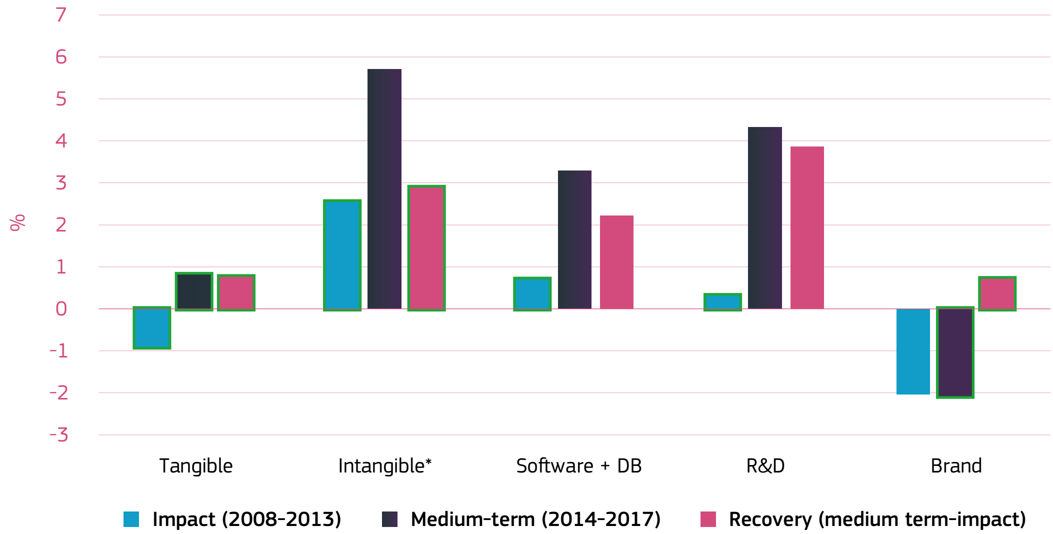


Source: JRC calculations based on EU KLEMS 2019
Note: The framed bars denote a non-significant coefficient in the panel estimation.
Stats.: link

After calculating the metrics, we did the same panel analysis as we did before for average growth rates (see the equation on page 6), but this time using these three metrics as dependent variables instead. The results are for the EU-15 + USA country group and reported as the effect of an increase in pre-crisis investment intensity from the bottom 25 % to the top 25 %.

We highlight only the most interesting results from this exercise. Overall intangible intensity is significantly positively associated with real value added, employment and hours in the medium-term. It is also significantly positively associated with employment and hours on impact. Positive association with the impact measure means a smaller decline. No statistically significant association with productivity is found (neither for labour productivity nor for TFP), although the estimated effects are positive. The effect of tangible intensity is never statistically significant. The effect of **R&D intensity is significantly positive** for **real value added (medium-term and recovery), for employment and hours (impact and medium-term), and for labour productivity** and **TFP (recovery)**. Other than R&D, the only assets that are significantly positively associated with TFP are own-account organisational capital and training (impact and medium term).

Figure 9-10: Percentage point effect on real value added of an increase of pre-crisis investment intensity equivalent to jumping from the bottom 25 % to the top 25 % of the intensity distribution (controlled for country and industry effects in a panel setting).



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Source: JRC calculations based on EU KLEMS 2019

Note: The framed bars denote a non-significant coefficient in the panel estimation.

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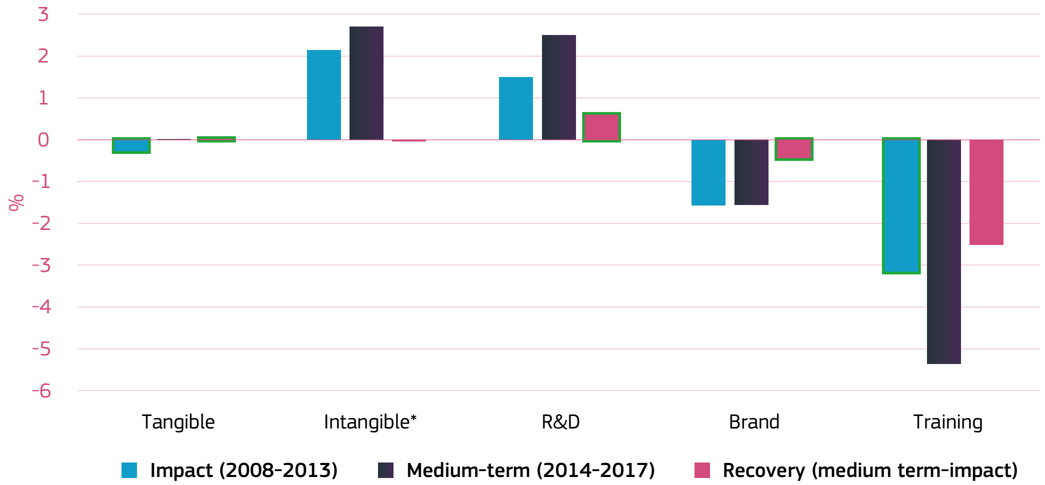
Figure 9-11: Percentage point effect on employment of an increase of pre-crisis investment intensity equivalent to jumping from the bottom 25 % to the top 25 % of the intensity distribution (controlled for country and industry effects in a panel setting).



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Source: JRC calculations based on EU KLEMS 2019

Note: The framed bars denote a non-significant coefficient in the panel estimation.

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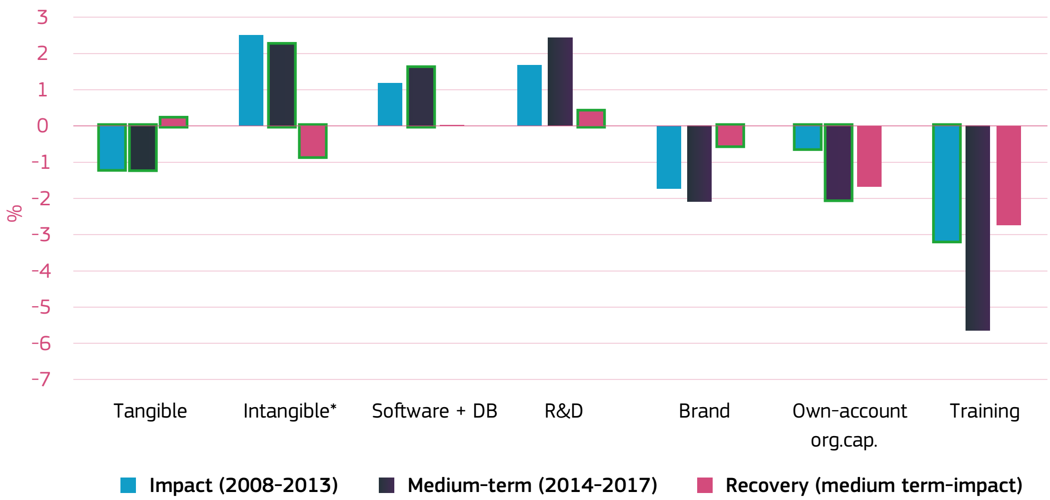
Figure 9-12: Percentage point effect on hours worked of an increase of pre-crisis investment intensity equivalent to jumping from the bottom 25 % to the top 25 % of the intensity distribution (controlled for country and industry effects in a panel setting).



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Source: JRC calculations based on EU KLEMS 2019

Note: The framed bars denote a non-significant coefficient in the panel estimation.

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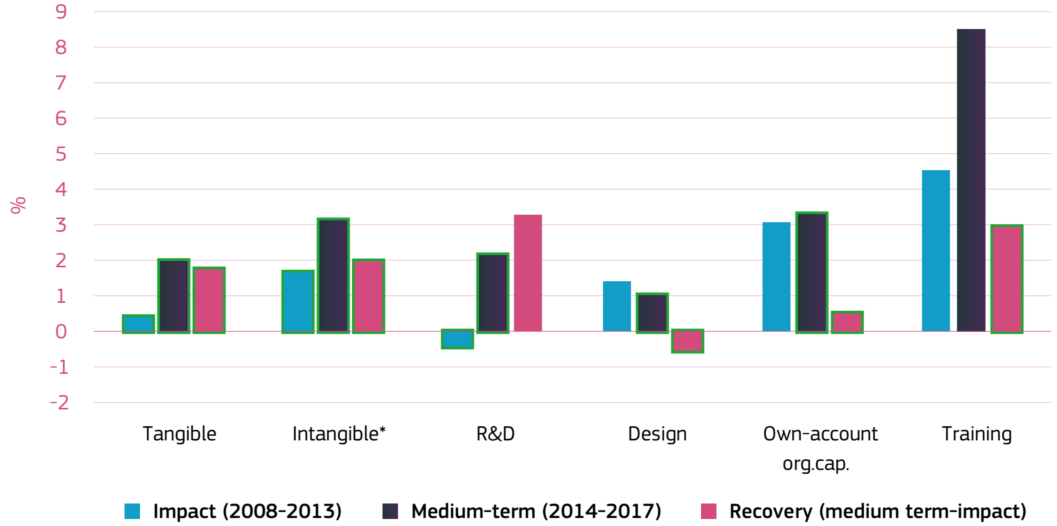
Figure 9-13: Percentage point effect on labour productivity of an increase of pre-crisis investment intensity equivalent to jumping from the bottom 25 % to the top 25 % of the intensity distribution (controlled for country and industry effects in a panel setting).



Science, Research and Innovation Performance of the EU 2022

Source: JRC calculations based on EU KLEMS 2019

Note: The framed bars denote a non-significant coefficient in the panel estimation.

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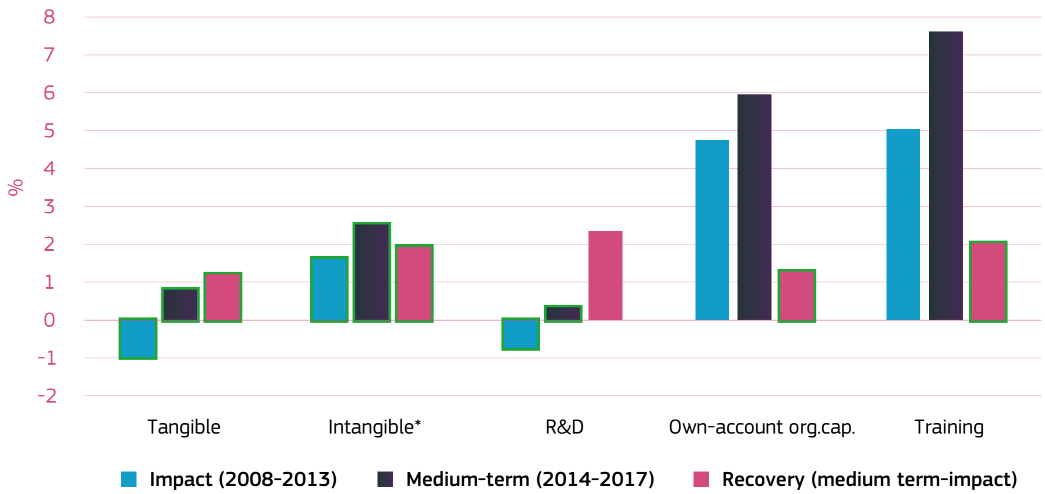
Figure 9-14: Percentage point effect on TFP of an increase of pre-crisis investment intensity equivalent to jumping from the bottom 25 % to the top 25 % of the intensity distribution (controlled for country and industry effects in a panel setting).



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Source: JRC calculations based on EU KLEMS 2019

Note: The framed bars denote a non-significant coefficient in the panel estimation.

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Results for the EU-13

The results for the role of intangibles as drivers of the different economic performance outcomes analysed for the EU-13 countries are generally inconclusive. Most of the results that we obtained for the EU-15 + USA country group become statistically insignificant if we add the EU-13 countries to the sample. Estimated separately, most of the results for the EU-13 are insignificant[13]. What we can highlight is that tangibles are most of the time associated significantly positively with the long-term values of outcome variables.

By contrast, among intangibles, only investments in software are associated significantly positively with long-term productivity growth. In case of the resilience metrics, we observe again that tangible investment seems much more important for the EU-13 countries compared to the EU-15 Member States. For example, tangibles are significantly positively associated with medium-term performance and recovery of labour productivity.

Why are results weaker for intangible investment in new Member States? Although this remains a question for future research, we can hypothesise a number of reasons.

First, it might be the case that for these countries, tangibles really are more important than intangibles, or that the countries lack some necessary ingredients (e.g. a critical mass of researchers) to successfully invest into intangibles. Furthermore, there may be a measurement issue in terms of the gap between the different locations of investment and the use of intangible assets. This problem is prone to be more binding in the case of the EU-13 countries, where a major part of economic output is produced by multinationals.

13 It is important to note that panel regressions run on the EU-13 sample have a small number of observations due to missing intangible investment data for many of these countries.

4. Intangible investment and finance

Uninterrupted financing of intangible investment is crucial as these investments are of a long-term nature and to a large extent, irreversible. For example, R&D investments are generally assumed to take longer to be productive (see, e.g., Aghion et al., 2010), while some of the investments (e.g. salaries paid to researchers) cannot be liquidated. Existing results in the literature show that intangible investment is less sensitive to long-term interest rates (Thum-Thysen et al., 2019) and less influenced by monetary policy (Döttling and Ratnovski, 2020). Potential reasons include that intangibles are usually financed more by internal sources or equity instead of debt, and that the higher depreciation rate of intangible assets weakens the link between interest rates and the user cost of capital. At the same time, the degree of financial development has a bigger impact on labour productivity growth in intangible-intensive industries, especially if they are more dependent on external finance (Demmou et al., 2019). The explanation is that as intangible investment faces stronger informational asymmetries and is harder to value, it is subject to more severe financial constraints. Financial frictions in intangible sectors have been a barrier to productivity growth, especially in financially less-developed countries. This finding is underpinned by firm-level evidence as well (Demmou et al., 2020). In a recent paper, Segol et al. (2021) using an EU-wide firm-level investment survey, document that insufficient loan amounts, high lending rates and more stringent collateral requirements have a detrimental effect on intangible investment intensity.

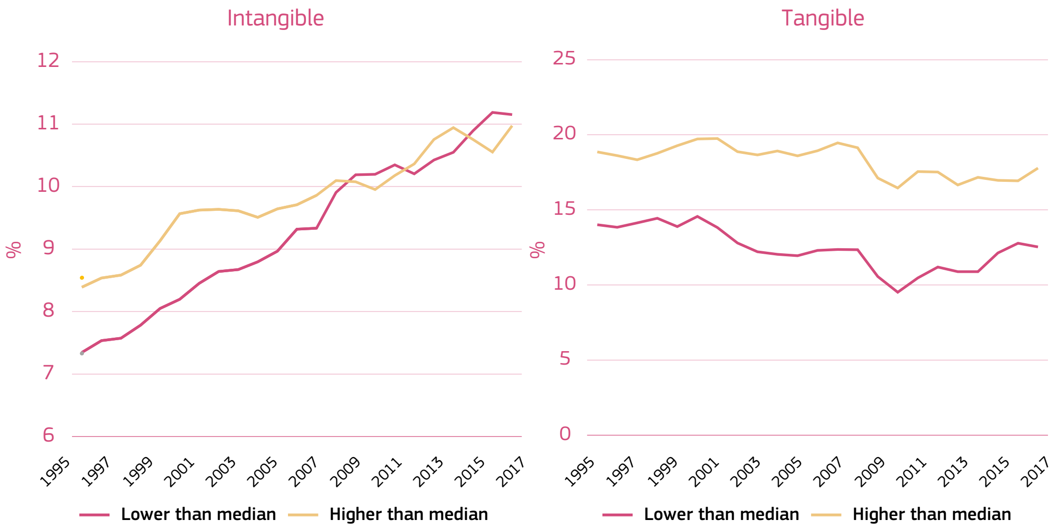
All this evidence reviewed above suggests that intangible investment is exposed to financial shocks. Based on that, the GFC should have had a major negative impact on intangible investment. What is puzzling is that we do not see a significant drop in intangible intensity on average during that period (see 'Investment intensities before, during and after the financial crisis'). This is in contrast with the large decline in tangible intensity.

A possible solution to this apparent contradiction is that the disruption in finance for intangible investment might not be even across sectors but it could be more severe in industries and in countries where investment is financed from external instead of internal sources. This is especially true if it is intangible investment that is financed externally (by credit or by equity). However, the external financing of tangible investment might also have a detrimental effect on intangible investment indirectly, as we will explain later. We already cited the papers of Demmou et al. (2019) and (2020), which show the importance of external financial dependence (EFD) for intangible investment. Focusing only on R&D, Peia and Romelli (2022), on a large sample of European firms, find that financially more constrained firms invested less during periods of tight credit supply. This effect is amplified in sectors with high dependence on external finance. Similarly, Aghion et al. (2012) show, using pre-GFC data, that the R&D investment share in total investment is countercyclical, but more procyclical if credit constraints are binding, and that this effect is magnified for highly external-finance dependent sectors.

Thus, these findings are mostly in line with our hypothesis about the relevance of EFD for the behaviour of intangible investment during crises.

To investigate this issue, we established a link between a country-industry measure of EFD and intangible investment. Following Rajan and Zingales (1998), EFD is defined as the share of investments (including both tangible and intan-

Figure 9-15: Average investment intensities of industries with lower and higher than median values of external financial dependence for intangibles (left panel) and tangibles (right panel)



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Source: JRC calculation based on EU KLEMS 2019, BACH and ECB data

Note: We include all country-industry cells where we have data for EFD. The linear trend lines are fitted on the pre-crisis period of 1995-2007.

Stats.: link

gible investment) that is not covered by cash flow. Thus, the higher the value of EFD, the higher the dependence on external finance. In our case, it is calculated by country and by 2-digit-level NACE industry. Examples of high EFD industries are air transport (in Spain and in Italy), construction (in Austria) and chemicals (in Denmark), while EFD is low in telecommunications (in Germany) and in food production (in Spain and in France) (see the Appendix for details of the calculation of EFD, and its tabulated values).

Before turning to the econometric estimation, we show an illustration of how differently investment intensity developed during the financial crisis depending on whether an industry's dependence on external finance is high or low (Figure 15). High EFD industries decreased their intangible intensity in 2008 and 2009 compared to the pre-crisis trend while the opposite happened with low EFD industries: intangible intensity increased, even compared to the pre-crisis trend. For tangibles, we do not see a characteristic difference in the behaviour of investment intensities by EFD during 2008-2009.

Now we turn to the formal econometric analysis. We use a country-industry-year panel with investment intensity (for different assets) as the dependent variable and EFD interacted with year dummies as explanatory variables. We include a rich set of fixed effects in the regression.

Thus, our regression equation is the following:

$$InvInt_{cst} = \beta^{2008} EFD_{cs} * \delta_t^{2008} + \beta^{2009} EFD_{cs} * \delta_t^{2009} + \dots$$

$$+ \beta^{2017} EFD_{cs} * \delta_t^{2017} + \lambda_{cst} + \mu_{cst} + \varrho_{st} + u_{cst}$$

where c is country, s is industry, t is year, InvInt is the investment intensity in a specific asset in year t (tangible, aggregate intangible, R&D, etc.). EFD is the EFD of industry s in country c calculated over the period 2000-2004. δ_t is the year dummy, which is 1 when t is in the specific year (2008, 2009, ..., 2017) and otherwise is 0. λ_{cs}, μ_{ct} and ρ_{st} are country-industry, country-year and industry-year fixed effects. u_{cst} is the error term. The estimated β is the partial effect of a unit increase of EFD on investment intensity in the specific year compared to the average of the pre-crisis period.

According to the results (see Table 1), industries with higher dependence on external finance (keeping other industry and country characteristics constant) experienced a bigger drop in intangible intensity during the crisis compared to pre-crisis.

This link between EFD and the change in investment intensity holds for the overall intangible intensity, R&D intensity and investment intensity of software, though the exact years when the effect is significantly negative depends on the specific asset. According to our estimates, for example, a 100 percentage-point higher EFD (which is not an extremely high difference in our dataset) caused a 0.24 percentage-point lower intangible intensity in 2008, a non-trivial effect. The estimated impact on tangible intensity is mostly positive, in some years statistically significantly positive.

In the following, we take into account the heterogeneous nature of financial shocks across countries during the GFC. Because of this heterogeneity in timing and size between countries, capturing the effect of the GFC with year dummies can only give a preliminary and imprecise estimate. Thus, instead of year dummies, a country-level indicator of financial stress (CLIFS) provided by the European Central Bank will be used as a measure of the timing and size of the financial crisis by countries.

Monthly observations of the original CLIFS indicator were averaged over a year to get an annual indicator. The following equation is estimated:

$$InvInt_{cst} = \beta EFD_{cs} * CLIFS_{ct} + \lambda_{cs} + \mu_{ct} + \varrho_{st} + u_{cst}$$

Where $InvInt$ is the investment intensity of an asset (we estimate the equation asset-by-asset), c is country, s is the 2-digit sector, t is time (year), EFD is external financial dependence (at the country-sector level) and $CLIFS$ is the country level indicator of financial stress (with variation across countries and years). β is the differential impact of the GFC on more externally financed industries compared to less externally finances industries, our main target of interest. We also include all the possible fixed effects (country-sector, country-time, sector-time, λ,μ,ϱ), and u is the error term. Our expectation is that β is negative, which means that at the same level of financial stress, more dependence on external finance decreases investment intensity. Phrasing this differently, higher stress decreases investment intensity while keeping EFD constant.

Table 9-3: 25th and the 75th percentiles of the investment intensity distribution across countries and industries and difference between them (2005-2007).

		2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Tangible	Coef.	0,0013754	-0,0010458	-0,0010791	**0,0052562**	0,0022034	0,0008434	**0,0061021**	0,0027343	0,0015757	0,0026875
	P>t	0,603	0,693	0,683	0,047	0,405	0,75	0,021	0,302	0,552	0,321
Intangible	Coef.	**-0,0024103**	**-0,0023037**	**-0,0033721**	**-0,0025208**	-0,0005426	-0,0009861	0,0000253	-0,0002203	-0,001859	-0,0012366
	P>t	0,033	0,042	0,003	0,026	0,631	0,383	0,982	0,845	0,1	0,285
R&D	Coef.	-0,0010631	-0,0005592	-0,0014581	0,0003018	0,0004401	0,0002073	0,0010197	0,0005684	0,0001112	0,0002793
	P>t	0,091	0,373	0,02	0,631	0,484	0,741	0,105	0,366	0,86	0,664
Software	Coef.	-0,0005781	**-0,0008454**	**-0,000738**	**-0,0012557**	0,0003287	0,0000794	0,0000742	0,0000571	-0,000412	-0,0001581
	P>t	0,133	0,028	0,056	0,001	0,393	0,837	0,847	0,882	0,285	0,688
Brand	Coef.	-0,0002274	**-0,0003347**	**-0,0004322**	**-0,000516**	**-0,0005966**	**-0,0005448**	**-0,0005866**	**-0,0004385**	**-0,0003083**	**-0,0004709**
	P>t	0,201	0,06	0,015	0,004	0,001	0,002	0,001	0,014	0,083	0,008
Design	Coef.	-0,00011	0,000042	-0,0000793	-0,0001375	-0,0001767	**-0,0001803**	-0,0003564	0,000258	0,0002849	0,0002749
	P>t	0,562	0,824	0,676	0,468	0,351	0,342	0,06	0,174	0,133	0,147
Purchased org. cap.	Coef.	-0,000156	-0,000098	-0,0001335	-0,0002016	-0,0000914	-0,0000244	-0,0000789	-0,0000793	-0,0001065	-0,0001248
	P>t	0,281	0,498	0,356	0,164	0,528	0,866	0,586	0,584	0,462	0,389
Training	Coef.	0,0000115	-3,83E-06	6,38E-06	7,23E-06	-0,0000208	-0,0000379	**-0,0000453**	-0,0000212	**-0,000055**	**-0,000045**
	P>t	0,645	0,878	0,798	0,771	0,403	0,128	0,069	0,395	0,027	0,07

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Note: Estimated on the 2005-2017 sample, countries: Austria, Germany, Denmark, France, Spain and Italy, 2-digit NACE industries. Country-industry, country-time, industry-time fixed effects are included. We omitted the results for own-account organisational capital because data were available for only two countries in the sample. 'Coef.' in the table means the estimated coefficient for the specific asset.

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The results for different assets are the following, estimated for the countries that we have both EFD and intangible data (Austria, Germany, Denmark, Spain, France, Italy):

Table 9-4: **Estimated coefficient of the interaction of EFD and CLIFS for different assets**

	Coefficient	Standard error	t-value	p-value	Number of observations
Intangible	**-0.010**	0.004	-2.400	0.016	1858
R&D	**-0.006**	0.002	-2.450	0.014	1858
Software + DB	**-0.004**	0.001	-2.970	0.003	1858
Brand	0.000	0.001	-0.570	0.571	2158
Design	0.000	0.001	0.350	0.725	2158
Purchased org. cap.	0.000	0.001	-0.520	0.605	2158
Training	**0.000**	0.000	2.090	0.037	1898
Tangible	-0.005	0.010	-0.530	0.600	1858

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Source: JRC calculation based on EU KLEMS 2019, BACH and ECB data

Note: 'DB' and 'org.cap.' mean 'database' and 'organisational capital', respectively.

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According to the results, in the case of overall intangibles, R&D and software, the estimated impact is statistically significantly negative, while for tangibles it is not significant (although it is negative). For training, it is statistically significantly positive, but the estimated coefficient is very small[14].

In sum, this latter analysis also shows very similar results as the one based on year dummies, namely that there is a different response of tangible vs intangible investment to financial shocks. The finding that intangible investment is sensitive to external financial conditions is consistent with the results of the reviewed literature in the beginning of this section. As intangible assets cannot be pledged as collateral and are subject to substantial information asymmetries, intangibles are typically financed from liquidity as opposed to tangible assets, which tend to be financed from credit (see Altomonte et al., 2021, for causal evidence on France, and Ferrando and Preuss, 2018, for a representative sample of EU-28 firms).

When external finance dries up, firms tend to move part of the internal cash flow to finance tangible investment. Thus we find a significant negative effect on intangibles and a small or no effect on tangibles (Altomonte et al., 2022, provide indirect evidence for this mechanism using cross-country firm-level data).

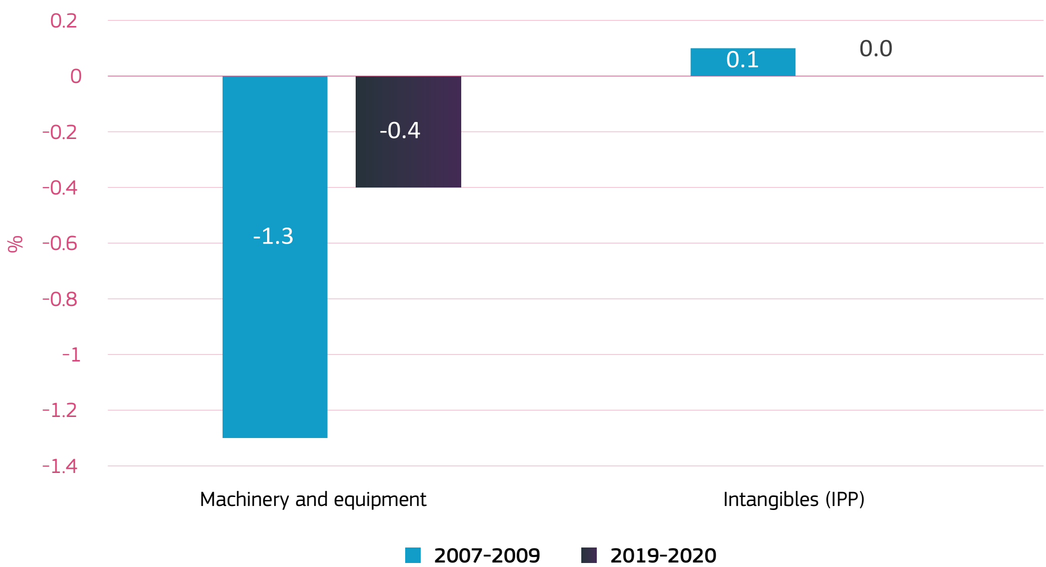
Thus we find that intangible investment is vulnerable to financial shocks. At the same time, we know that intangibles are important drivers of productivity, and we showed earlier in this chapter that intangibles may contribute to resilience against crises. Considering the importance of intangible investments, and their vulnerability at the same time, it is logical to suggest that supporting the financing of intangible investment during times of financial distress might contribute to further productivity growth and resilience of the economy.

14 Furthermore, there are reasons to think that training is the least robustly measured intangible asset in the EU KLEMS database, based on comparisons with the IntanInvest database, another data source on intangible investment.

5. Development of intangible investment in the COVID-19 crisis

The COVID-19 pandemic induced a major supply and demand shock on the global economy in 2020. Despite substantial differences from the global financial crisis in the cause of the crisis, in its pace of development and in the strength and speed of the policy response, the huge drop in GDP in almost all EU countries caused a significant decline in investment activity of firms. Lessons from the GFC suggest that a large decline in demand causes a less severe drop in intangible investment than for tangible investment, while financial stress affects intangible investment more than tangibles in financially exposed industries. In the COVID-19 crisis, a credit crunch similar to the GFC was avoided and firms were supported by ample liquidity due to the swift policy reaction. This suggests that financial conditions played a minor role in this crisis. On the other hand, the decrease in demand was much larger than before. All these indicate a larger drop in tangible investment than in intangible investment, similarly to the GFC, while we do not expect a differential impact on intangibles depending on the financial exposure of a given industry. We have limited data so far to check these hypotheses. From national accounts, intangibles include a limited number of assets, collectively called IPP (intellectual property products: software and databases, R&D, other intellectual property products). This preliminary data confirms our first hypothesis: while intangible investment decreased, this was much more muted than the drop in tangible investment. Furthermore, thanks to the policy response, even the decline in tangibles was smaller compared to the drop in GDP than during the GFC.

Figure 9-16: Change in overall and intangible investment intensity (investment/GDP) in the EU (percentage points)



Source: Eurostat (national accounts)
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6. Conclusion

A number of papers already showed the relevance of intangible capital as a factor of production and driver of productivity. In this chapter, we focused on the economic performance in terms of output, employment and productivity of countries and industries in Europe around the period of the global financial crisis. We linked this performance to the difference in intangible investment intensity. We found that intangible intensity, in general, contributed to better performance and resilience of economies. We also analysed trends of intangible investment before, during and after the financial crisis. We found an upward trend of intangible investment intensity in nearly all countries and industries, which started well before the crisis and continued almost uninterruptedly through the recession periods. Finally, we investigated the sensitivity of intangible investment to the availability of external finance. According to our results, intangible investment was more sensitive to financial conditions than tangible investment.

Despite significant differences between the reasons for and the unfolding of the GFC and the current COVID-19 crisis, our results emphasise the significance of intangible investments in making economies more resilient. Furthermore, we find a link between external financing and intangible investments, which indicates the financial vulnerability of these investments. Among intangible assets, we find this link for R&D and software investments.

Our leading explanation for the sensitivity of intangible investment to the tightening of external financial conditions is based on the trade-off between tangible and intangible investment induced by financial stress. During expansion periods, liquidity of firms is mostly used for financing intangible investment while credit is used for financing tangible investment. Financial stress makes financing tangible investment from credit more difficult. Firms thus tend to use part of their liquidity to finance tangibles, creating a trade-off between tangible and intangible investment (Altomonte et al., 2022).

These findings strengthen the case for supporting uninterrupted financing of firms during crises. At the same time, targeted support of finance for intangible investment might pose a challenge, given that intangibles cannot be pledged as collateral. However, there are several possibilities to overcome this difficulty. First, financing is not necessarily bank lending; it can be equity finance or grants. These instruments are already widely used in financing R&D investments. Furthermore, bank lending can be facilitated by using loan guarantees (see Demmou and Franco, 2021, for experiences with loan guarantees during the COVID-19 crisis). Finally, there are examples in some Asian countries where intangibles are accepted as collateral (see Manigart et al., 2020).

In the COVID-19 crisis, demand played a larger role than financing conditions. Preliminary data on the COVID-19 crisis supports the conclusion that intangibles are less sensitive to a drop in demand, which materialises in the much larger decline in tangible investment compared to intangible investment.

References

Aghion, P., Angeletos, G. M., Banerjee, A., & Manova, K. (2010), Volatility and growth: Credit constraints and the composition of investment, *Journal of Monetary Economics*, Elsevier, vol. 57(3), pp. 246-265, April.

Aghion, P., Askenazy, P., Berman, N., Cette, G., & Eymard, L. (2012), Credit Constraints and the Cyclicality of R&D Investment: Evidence from France, *Journal of the European Economic Association* 10, 5, pp. 1001–1024.

Altomonte, C., Favoino, D., Morlacco, M., & Sonno, T. (2021), *Markups, Intangible Capital and Heterogeneous Financial Frictions*. Centre for Economic Performance, London School of Economics and Political Science, Discussion Paper 2021/1.

Altomonte, C., Bauer, P., Gilardi, A. M., Soriolo, C. (2022), *Intangible assets, industry performance and finance during crises*, Manuscript.

Balta, N. and Nikolov, P. (2013), Financial dependence and industrial growth in the euro area during the crisis. Part II/ Chapter 3 in: Product Market Review (2013), *Financing the real economy*, European Economy 8/2013.

Bauer, P., Fedotenkov, I., Genty, A., Hallak, I., Harasztosi, P., Martínez-Turégano D., Nguyen D., Preziosi, N., Rincon-Aznar, A., Sanchez-Martinez, M. (2020), *Productivity in Europe – Trends and drivers in a service-based economy*, EUR 30076 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-10610-4, doi:10.2760/469079, JRC119785.

Cincera, M., Delanote, J., Mohnen, P., Santos, A., Weiss, C. (2020), *Intangible investments and productivity performance*. GEE Papers 0145, Gabinete de Estratégia e Estudos, Ministério da Economia, March 2020.

Demmou, L., Stefanescu, I., Arquié, A. (2019), *Productivity growth and finance: The role of intangible assets – A sector level analysis*, OECD Economics Department Working Papers 1547.

Demmou, L., Franco, G., Stefanescu, I. (2020), *Productivity and finance: the intangible assets channel – a firm level analysis*, OECD Economics Department Working Papers 1596.

Demmou, L. and Franco, G. (2021), *From hibernation to reallocation: Loan guarantees and their implications for post-COVID-19 productivity*, OECD Economics Department Working Papers 1687.

Döttling, R. and Ratnovski, L. (2020), *Monetary policy and intangible investment*, ECB Working Paper Series 2444, July 2020.

Ferrando, A. and Preuss, C. (2018), What finance for what investment? Survey-based evidence for European companies. *Economia Politica*: Journal of Analytical and Institutional Economics, Springer; Fondazione Edison, 35(3), pp. 1015-1053, December.

Griliches, Z. (1998), *R&D and Productivity: The Econometric Evidence*, The University of Chicago Press, Chicago.

JRC (2018), *The resilience of EU Member States to the financial and economic crisis: What are the characteristics of resilient behaviour?*, EUR 29221 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-85746-1.

Manigart S., Vanacker T., Knockaert M., Verbouw J. (2020), *Financing intangibles: Is there a market failure?*, Mimeo.

Peia, O., and Romelli, D. (2022), Did financial frictions stifle R&D investment in Europe during the great recession? *Journal of International Money and Finance*, Volume 120, February.

Rajan, R. G. and Zingales, L. (1998), Financial Dependence and Growth. *The American Economic Review*, 88(3), pp. 559-586.

Segol, M., Kolev, A., Maurin, L. (2021), *The impact of bank loan terms on intangible investment in Europe*, EIB Working Papers, No. 2021/05, ISBN 978-92-861-5036-4, European Investment Bank (EIB), Luxembourg, http://dx.doi.org/10.2867/974979.

Stehrer, R., A. Bykova, K. Jäger, O. Reiter and M. Schwarzhappel (2019), *Industry level growth and productivity data with special focus on intangible assets*, wiiw Statistical Report 8.

Thum-Thysen, A., Voigt, P., Bilbao-Osorio, B., Maier, C., Ognyanova, D. (2017), Unlocking Investment in Intangible Assets, *European Economy Discussion Paper* 047.

Thum-Thysen, A., Voigt, P., Bilbao-Osorio, B., Maier, C., Ognyanova, D. (2019), Investment dynamics in Europe: Distinct drivers and barriers for investing in intangible versus tangible assets? *Structural Change and Economic Dynamics*, Volume 51, December, pp. 77-88.

Appendix: Calculation of EFD

The idea behind our measure of EFD goes back to the seminal paper of Rajan and Zingales (1998), and the calculation is based on the approach of Balta and Nikolov (2013). We use the BACH database from the Banque de France containing balance sheet data for a number of countries. We have six countries where the data could be used for our purpose: Austria, Germany, Denmark, Spain, France, Italy. We calculate the share of investments that is not covered by cash flow by country and 2-digit level industry (we calculate shares for services as well as for manufacturing). Cash flow is approximated by gross operating surplus, while investment is calculated as the change in tangible and intangible fixed assets plus depreciation of these assets[15]. The higher the share of investments not covered by cash flow, the stronger the need for external finance for these investments. We average this share over the 2000-2004 period, substantially far away from the GFC during a period of abundant liquidity. Thus we hope that this measure reflects the country-industry specific demand for external finance. For the EFD values see Table 5.

15 Balta and Nikolov (2013) used a somewhat different version of this calculation: they used net operating profit as cash flow and considered only tangible fixed assets for investment. We find the gross numbers a more adequate proxy of cash flow if we want to explain gross investment (i.e. investment that includes replacement investment). As for the type of investment, our main goal is to explain intangible investment. Thus, it is natural for us to include intangible fixed assets as well even if balance-sheet data and macroeconomic statistical data may differ substantially in the case of intangible investment. A further reason is that depreciation cannot be separated between tangible and intangible assets in the dataset.

Table 9-5 EFD for different countries and industries (percentage share of investment not covered by cash flow averaged over 2000-2004)

Code	AT	DE	DK	ES	FR	IT
C10-C12	-67%	-88%	-864%	-319%	-395%	-1%
C13-C15	-98%	-240%	-864%	-144%	-213%	-102%
C16-C18	-46%	-91%	-664%	-90%	-59%	-60%
C20	-123%	-146%	108%	-109%	-77%	-78%
C21	-69%	-98%		-181%	-186%	-134%
C22_C23	-91%	-109%	-378%	-122%	-97%	-60%
C24_C25	-98%	-88%	-399%	-105%	-83%	-61%
C26	-132%	7%	-864%	-145%	-10%	-72%
C27	-180%	-126%	-864%	-165%	-109%	-100%
C28	-176%	-123%	-184%	-253%	-151%	-126%
C29_C30	-357%	-23%	-864%	34%	-73%	35%
C31-C33	-194%	-134%	-700%	-107%	-119%	-90%
D	-45%	-219%		-83%	-57%	-77%
E	-70%	-70%		-7%	-66%	-14%
F	108%	-101%	-864%	-64%	-98%	-114%
G45	-122%	-151%	-864%	-117%	-130%	-65%
G46	108%	-219%	-864%	-154%	-209%	-111%
G47	-139%	-101%	-864%	-49%	-99%	18%
H49	-12%	56%	-175%	-42%	-4%	64%
H50	-237%	-105%		-477%	-74%	29%
H51	-54%			108%		108%
H52	-59%	-58%	-864%	-3%	108%	-52%
H53	-517%			9%		-129%
I	45%	-58%	-763%	-52%	-46%	-12%
J58-J60	-60%	-152%	-850%	-153%	-57%	-49%
J61	-40%	-531%		-123%		-86%
J62_J63	-67%	-77%	-769%	-182%	-58%	-90%
M_N	-56%	-169%	-784%	-24%	-48%	-17%
R	-148%	108%		-24%	-83%	99%
S	-50%	6%		-83%	-37%	1%

Science, Research and Innovation Performance of the EU 2022

Note: The table shows winsorised values at the 5th and 95th percentile of the distribution.

Stat. link: link

CHAPTER 10

RESEARCH AND INNOVATION POLICIES FOR THE GREEN TRANSITION

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Summary

This chapter provides a selective review of policies that can help to foster a transition towards green technologies. R&I are crucial to tackling sustainability challenges, and public policies are needed to direct technological change towards more environmentally friendly products and processes. Supply-side policies, such as R&D funding, and demand-side policies, such as carbon pricing and clean technology standards, are complementary. While there is urgency to invest in deployment of green technologies today, investing in R&D remains a central pillar for the medium- and longer-term potential of the green transition. A critical takeaway is that there is no silver-bullet policy. Governments should adopt and implement a coordinated mix of policies to achieve carbon-emission reductions that are as large as possible at the lowest possible cost. Despite all the criticisms, carbon pricing remains an essential part of this policy mix.

1. Introduction

Humans are confronted with many environmental and natural resources issues. One of the most prominent in scale and complexity is climate change: higher atmospheric greenhouse gas concentrations result in more frequent floods, droughts, heatwaves, hurricanes and sea-level rise. Humans will undoubtedly adapt to many of those changes. However, beyond certain thresholds, opportunities for adaptation will be limited. Reducing emissions is, therefore, the only way to ensure humanity remains within a 'safe operating space' (Rockström et al., 2009). For a long time, studying environmental issues consisted in describing humans' impact on the natural environment. Now that its magnitude has been ascertained, societies have decided to act, and a central question is: what can be done about it?

This chapter provides a selective review of policies that can help to foster a transition towards green technologies. Several important aspects are not covered due to lack of space but would deserve further attention, such as innovation ecosystems that could bring forward innovations at higher speed than before, financial architecture, international collaborations and the trade-offs between leap-frogging and catching-up strategies. This chapter, however, provides an overview of policies that support the supply of clean technologies, such as R&D funding, as well as those supporting demand, such as carbon pricing and clean technology standards. Demand-side policies typically aim at levelling the playing field between clean and dirty technologies, thereby fostering demand for clean products and processes.

First, Section 2 examines the role of technology in environmental issues and reaffirms the crucial part of R&I. Since reducing emissions, first and foremost, means that the economy must change the technologies it runs on, I discuss the need for public policies to direct technological change. Sections 3 and 4 review supply-side and demand-side policies, respectively, and what they mean for innovation. Section 5 examines how strong the case is for increasing spending on R&D as opposed to deployment. Finally, Section 6 highlights the necessity (and complementarity) of implementing both supply- and demand-side policies with increasing ambition over time.

2. Technology and the environment: a double-edged sword

2.1 New solutions, new problems?

R&I have the potential to lower humans' impact on natural systems. Ironically though, technology is also the reason why we have many environmental problems today. Three hundred years ago, humans had few cheap ways of converting energy into processes and goods. Starting with the Industrial Revolution in the 1850s, technological change brought us the combustion engine, modern chemistry and electricity, and with them, staggering improvements in living conditions. Technology has made our lives safer, easier and more comfortable. However, these technologies also release pollutants into the air and water and lead to the over-extraction of natural resources. As both consumption per capita and population have massively increased over the past decades, the magnitude of environmental impacts can no longer be ignored.

Technological change offers the prospect of substituting dirty technologies with cleaner ones. For example, in the 1990s, ozone-depleting substances such as CFCs were successfully phased out and replaced with ozone-safe molecules called HFCs. Electric vehicles can lower both local air pollution and CO_2 emissions (provided that the electricity they use is non-fossil). But green technologies sometimes get bad press: as they solve a problem, some argue they may create new ones that are just as thorny to deal with. HFCs, for example, are potent greenhouse gases, and therefore, even though they make the ozone layer safer, they worsen climate change. Similarly, electric vehicles may be great news for air pollution. Still, their batteries require the extraction and use of rare precious metals (often from countries with poor working conditions and even child labour (Sanderson, 2019)) and pose a challenge in how to dispose of them safely and efficiently (Harper et al., 2019).

2.2 About techno-pessimism

Whether we can (and should) rely on technology to solve environmental problems is an old debate. In the 1970s, and in particular with the publication of the book The Limits to Growth, intellectuals started discussing what 'sustainability' meant and whether economic development could realistically continue on its current path (Meadows et al., 2012). Scholars highlighted the negative environmental impacts of human activities and their reliance on finite non-renewable natural resources such as fossil fuels and precious metals. The arguments focused on whether these trends were sustainable and whether humanity could engineer a way out. The debate drew a line between two paradigms called 'weak' and 'strong' sustainability (Neumayer, 2003). In weak sustainability, technological change and input substitution (substituting dirty with clean inputs) are the primary mechanisms through which humans react and adapt to nature's constraints to support economic growth. In contrast, strong sustainability sees such mechanisms as exceptions and binding scarcity as the rule.

Debates about the role of technology are still alive and well. Should technological change be at the front and centre of the green transition? Are clean technologies an absolute requirement of success? Or will new technologies bring about new problems, and is the role of technology overstated? Typically, the limitations of clean technologies are used to argue either for inaction or for an approach focusing instead on cultural changes and 'degrowth.' The first camp, those in favour of inaction, claim that the cost of abating pollution is too high and that a net-zero transition would dangerously disrupt our economies. The strength of such arguments continues to weaken as the costs of clean technologies maintain their steady decline.

The other camp thinks that technology is more part of the problem than the solution because adopting new technologies still leaves our economy on a 'growth-addicted' path. They argue that the root causes of environmental degradation are not the technologies we use but rather over-consumption, population growth, poverty, industrial agriculture (Heinberg, 2017; Sugla, 2020). They emphasise that social norms and economic and political institutions have locked people into unsustainable lifestyles and that, even with cheap renewables, our economies will overshoot ecological limits and perpetuate social injustice. They insist, therefore, on rejecting 'the convenience of technological optimism' (Boucher et al., 2017) and instead focus on the social causes of the problems.

The most practical course of action, in their view, relies on a cultural shift that changes consumption patterns rather than finding cleaner means of production. Concretely, people should consume less energy, fewer goods (especially those with high ecological footprints), drive less and take fewer flights (and to closer destinations). We should also eat less beef or move altogether to vegetarian diets; embrace sobriety and minimalism – and contraception, since population growth is usually seen as a core driver of environmental impacts.

2.3 The need for directed technological change

There is no necessity to think of consumption and production in opposition. Shifts in cultural norms and technology change are not mutually exclusive. Both will be welcome and needed, and, in fact, innovations can be an important driver of both. For example, many employees worked from home during the COVID-19 pandemic, saving much energy that would have otherwise been spent on commuting and on heating and lighting office buildings. Without advancements in information and communication technologies, most employees would not have been able to work from home.

Arguably, blind faith in technology will not solve any issue on its own. Solutions to problems typically do not fall from the sky, or from market economies when markets are blinded to the problems. The response to the environmental crisis does not consist in waiting for cleaner technologies to come about but instead in designing government interventions that will tackle the various market failures at different points of the technological change pipeline. The story about how solar became cheap, for example, highlights how multiple policies from different jurisdictions at different points in time took turns in supporting the supply of and demand for photovoltaic technologies, which eventually led to impressive cost reductions (Nemet, 2019).

Notably, the policy response is not just about accelerating innovation in the general sense. What matters is the direction of technological change: clean technologies must improve, not just in absolute terms, but relative to dirtier ones. Scholars usually conceptualise the core issue at stake as a race between clean and dirty technologies (Acemoglu et al., 2012). Just like in Aesop's fable 'The Tortoise and the Hare', the two contenders are not on an equal footing: cleaner technologies remain more expensive than their dirtier substitutes. However, as we know from the fable, this does not preclude the initially less advanced sector from winning the race. And, indeed, an appropriate mix of policies can ensure that technological change is directed towards clean sectors.

2.4 Towards a diverse mix of policies

Economists have identified several market failures that contribute to clean technologies being under-provided (Jaffe et al., 2005; Popp et al., 2010). First is the environmental market failure: pollutants are emitted as a side effect of economic activities and impose a cost on society overall, for example, due to their negative impacts on the climate, human health and ecosystems. This is what economists call negative externalities. Typically, economic agents decide how much to produce and consume while ignoring that these economic activities incur broader social costs. The policy prescription here is straightforward: internalise the externality, that is, tax pollution. Importantly, as long as pollution is not priced in, it will be relatively cheaper to use polluting technologies. Demand-side policies such as carbon pricing ensure that clean technologies compete on an equal footing with dirtier ones and, therefore, support the demand for clean technologies.

A second market failure relates to the public-good characteristics of knowledge. When knowledge is created, it can often be acquired and used by others for free: economists call this positive externalities or spillovers. As a result, the private marginal returns from generating knowledge are smaller than the social ones, which leads to knowledge and new technologies being under-provided, even when intellectual property regimes are in place (e.g. patents). Again, the policy prescription here is straightforward: governments should support knowledge creation and technology development, for example, by funding R&D activities. Furthermore, technologies that generate higher knowledge spillovers should receive higher amounts of funding, and this seems to be the case for greener technologies. Indeed, Dechezleprêtre, Martin and Mohnen (2014) show that patents on clean technologies receive more follow-on citations than those on dirty technologies, suggesting that they generate more knowledge spillover.

Beyond knowledge spillovers, scholars have also shown that path dependency in R&D provides a further rationale for supporting R&D funding in clean sectors. Aghion et al. (2016) argue that firms that have a lot of prior experience with dirty technologies will find it more profitable to keep innovating in dirty technologies. This makes it harder to incentivise firms to start innovating in clean technologies. R&D subsidies are the best tools to help to break such path dependency as they provide the needed incentives to begin accumulating knowledge and expertise in clean technologies.

Although pricing pollution and subsidising R&D activities are the two most important policy recommendations, other market failures require governments' attention on the supply and demand sides of green technologies. On the supply side, new technologies typically exhibit strong learning-by-doing effects (a type of dynamic increasing returns) and increasing returns to scale in production. Hence, policies that subsidise the adoption of a particular technology (e.g. feed-in tariffs) can be justified to foster higher levels of adoption, which ensure that the increasing returns are realised.

There are also other market failures on the demand side that justify the use of policies other than carbon pricing. In the context of energy efficiency, several issues may lead to an under-investment and under-adoption of energy-savings products (Gerarden et al., 2017). For example, consumers may have high discount rates or may lack information about the technologies, such as their costs. There can also be agency problems when tenants would benefit from upgrades that landlords must pay for. In these cases, the use of standards, such as mandating a minimum energy-efficiency performance, can be Pareto-improving.

Another example where a technology standard is justified is the case of electric-vehicle charging stations. The benefits of purchasing electric cars increase as the network of compatible charging stations expands. However, in the absence of government regulations, manufacturers may develop chargers specific to their own brands, leading to a fragmented network. The government's role here is to mandate a technology standard for the charging plugs so that all vehicle owners can use them (Li, 2019).

2.5 Policy trade-offs

The variety of market failures in green technological change establishes the need for a mix of policies that go from carbon pricing and R&D subsidies to technology standards and adoption subsidies. There is broad consensus that carbon pricing is complementary to other policies targeting the upstream part of the innovation pipeline, but there has been more discussion (in the scholarship and in public debates) about the types of environmental policy instruments that we should use to deal with demand-side issues.

Some political scientists argue that although elegant and simple in theory, carbon pricing is grossly inadequate to tackle climate change (Mildenberger et al., 2020). They suggest we abandon the idea of pricing carbon and, instead, intervene with a mix of standards, adoption subsidies, procurement policies and regulations that would create a demand-pull for clean technologies. For example, policymakers can mandate clean electricity, clean cars or clean cement. In practice, many jurisdictions have already done so, e.g., with the renewable portfolio standard in the USA. The main argument in favour of standards is that they are much more politically palatable while still leading to increased adoption of low-carbon alternatives, like a carbon price would, in theory, do. A key difference is that the standards force adoption regardless of the costs of clean technologies. For that reason, they lead to higher compliance costs in the short term and are not considered as cost-effective.

Importantly, environmental policies with higher compliance costs in the short term imply that there may be fewer public resources to spend on supply-side measures such as R&D subsidies on clean technologies, which eventually are critical to lower long-term compliance costs. The overall policy objective should be about emission reductions at the lowest compliance cost possible both in the short and longer term. Supply- and demand-side policies are both essential to that objective, but given that government budgets are limited, there is a risk that costly demand-side measures get implemented at the expense of further support for supply-side policies. This opens a vital policy debate about the proportions in which we should do both, which I examine more closely in Section 5.

3. Supply-side policies

3.1 Clean-energy R&D spending

This section discusses how much public and private actors spend on energy R&D. According to Cunliff (2020), the energy and automotive industries invest about 0.5 % and 3.2 % of revenues in R&D, respectively. These numbers are much smaller than in other industries such as pharmaceuticals. Several factors may explain why private-sector investments in energy innovation are low. First, clean and dirty electrons look the same to consumers, and, as a result, price discrimination on the type of electricity is not effective, and clean technologies must compete on prices. The industry is also heavily regulated with strong policy pressures to keep prices low.

On the supply side, the industry's typical high capital intensity and long payback periods require patient investing with very deep pockets, which private-sector firms may not be able to provide easily. As a result, the public sector has a complementary role to play by having higher tolerance to risk and payback time, which is also critical when supporting the development of early-stage and more radical innovations. On the other hand, the private sector is better positioned to improve mature technologies and to develop nearly mature ones into marketable products. Firms have strong incentives to invest in these sorts of incremental innovations as they can easily materialise into short-term financial returns.

As highlighted above, R&D spending on clean energy in the private sector has not been high. Unfortunately, the COVID-19 pandemic may have worsened the situation. A key finding from an IEA survey run in May 2020 is that many firms believe that their R&D budget will likely be reduced, or at least has become more uncertain due to the COVID-19 crisis (IEA, 2020). Thankfully, public R&D funding seems to be less impacted, and some recovery packages have distinctive green flavours. In addition, in 2015, 24 countries came together under the Mission Innovation initiative to pledge a doubling of their annual clean energy RD&D budget by 2020. These countries represented more than 90 % of global public investments in clean energy at the time, and a doubling of their budget would have increased funding from USD 14.5 billion in 2015 to USD 28.9 billion (Myslikova et al., 2020).

Five years later, only a few countries had met the pledge: the Netherlands (+185 %, to EUR 285 million), the United Kingdom (+175 %, to GBP 550 million), South Korea (+100 %, to KRW 1.1 billion), as well as Chile, Japan and Norway (Mission Innovation, 2021a). If not doubling, at least, almost all countries increased their budget. The EU, for example, went from about EUR 1 billion in 2015 to EUR 1.8 billion in 2020; Germany from EUR 450 to EUR 780 million; and France from EUR 44 to EUR 49 million. The USA, which invests the largest amount, increased by 42 %, adding another USD 6.8 billion to the US Department of Energy (DOE)'s USD 14.8 billion energy budget. By 2019, China had added USD 2 billion to its clean energy R&D budget, which in 2015 was about USD 3.8 billion. Some emerging economies such as India or Brazil also substantially increased their budget.

In recent meetings, the Mission Innovation members did not reassert a pledge to keep increasing their clean energy budget after 2020. Instead, the initiative now focuses on more intangible aspects such as knowledge exchange across members and public-private partnerships (Mission Innovation, 2021b). Those aspects are, indeed, essential complements to R&D funding.

Still, it will be crucial that countries demonstrate their commitment to, at least, maintaining the current levels of clean R&D spending over the coming decades. Indeed, constraints will also come from human capital: training a new generation of young researchers will take several years, and clear signals that R&D support is there to stay will be instrumental in convincing talents to choose clean energy careers. There is evidence for such high adjustment costs in the case of the US National Institutes of Health (NIH) doubling of their budget between 1998 and 2003 (Freeman et al., 2009).

3.2 Beyond R&D spending: improving the involvement of the private sector

Beyond R&D spending, improving and supporting the involvement of the private sector should be a key policy objective of the green transition, especially given the low levels of private R&D spending in the energy industry. The recent success story of vaccine development during the COVID-19 pandemic has prompted renewed interest in how effectively the public and private sectors can cooperate. Other examples include the US space race and the Sematech public-private partnerships, highlighted in Myslikova et al. (2020). More insights into how to emulate these success stories would be useful.

Knowledge exchanges between public and private actors should be supported and fostered throughout the innovation pipeline. An excellent example in this area is the German network of Fraunhofer Institutes: 67 applied research institutes that bring together scientific and engineering expertise in different technological fields and are partly funded by industry (Dechezleprêtre, Martin and Bassi, 2019).

Other initiatives focus on demonstration and deployment rather than R&D. This is the case of Breakthrough Energy Ventures-Europe, a pilot fund investing in European companies working on low-carbon solutions that amounts to a total budget of EUR 100 million, half from the European Commission and half from Breakthrough Energy Venture, a group of about 50 private firms and individuals spearheaded by Bill Gates. Such public-private partnerships are ideal for building on the respective strengths of the public and private sectors. As highlighted before, energy R&D needs patient investors; the public sector here is therefore welcome. Conversely, the private sector is better positioned to identify promising companies because it holds more expertise and information about technologies and markets.

Finally, the Mission Innovation initiative could also play a role in spurring improvements in reporting systems and harmonising energy RD&D data. Tracking clean energy R&D spending in the private sector is not easy, and the initiative could ask its member countries to require firms to report investments made in clean energy R&D, as well as to clarify how R&D within state-owned firms is reported in official numbers (Myslikova et al., 2020).

3.3 Clean energy innovation policies in the EU and the USA

3.3.1 USA

The USA has historically been the leading contributor to clean energy R&D funding. Figure 1 illustrates the key initiatives for energy innovation policy, which, in the US, are managed within the DOE. The Office of Science supports early-stage and fundamental energy research, in particular via the National Laboratories. The applied research activities are structured around 20 programme areas such as energy efficiency, renewable energy, electricity, fossil energy and nuclear energy. These programmes include a wide range of tools aimed at supporting technologies at different levels of maturity: grants and tax incentives for supporting the upstream part of the pipeline (i.e. R&D) and loan guarantees to support demonstration projects. To help finance deployment and infrastructure, the DOE also leverages other types of credit enhancement and bond financing (Cunliff, 2020).

In parallel to the programme areas, the DOE has created a separate semi-autonomous agency, called ARPA-E, that focuses on high-risk high-impact early-stage technologies. ARPA-E stands outside of any of the other technology-specific programmes and targets topics that are generally cross-cutting. It is an attempt to reapply the success story of the Defense Advanced Research Projects Agency (DARPA). As in DARPA, the programme managers are critical elements: those managers are technical experts recruited from industry or academia for a period of 4 years (Bonvillian et al., 2011). The distinctive features of the agency seem to be bearing fruit: projects funded by ARPA-E are five times more likely to produce a patent or scientific publication than projects funded by programme areas. Since 2007, when ARPA-E was created, 850 projects have been funded with a total of USD 2.3 billion, and 161 projects attracted USD 32 billion in follow-on private investment (Cunliff, 2020).

Although the US DOE budget for energy innovation has increased over the last few years, it remains lower than the all-time high reached in 1978. In 2020, the US DOE budget was USD 8 billion, that is 0.04 % of US GDP. In 1978, the budget was, in fact, higher with USD 10.5 billion (in 2020 USD), corresponding to 0.14 % of GDP at the time (Cunliff, 2020). Given today's US GDP, this would be equivalent to a budget of USD 32 billion today, 4 times higher than the actual amount invested in 2020. The last three decades have not placed energy at the very top of the priority list. In the 1970s, oil crises and energy security concerns made investing in energy a bipartisan move. Since then, spending has been decreasing both in overall levels and in percentage terms; other areas, for example, health, have not suffered the same fate.

In the 2000s, the budget increased slightly, presumably because energy prices were rising, and some worried that the USA was falling behind in clean technologies (Cunliff, 2020). A significant one-time increase also came with the post-financial crisis recovery packages in 2009, particularly the USD 2.3 billion dedicated to creating ARPA-E. Since 2015, the DOE energy R&D spending has slowly increased from below USD 6 billion to USD 8 billion in 2020. With a total increase of more than USD 2 billion requested for the 2022 budget, the US energy-innovation budget may finally overtake the historical high of 1978 (Cunliff and Nguyen, 2021). However, we are still far from the historic high of 0.14 % of GDP, and, as highlighted before, this is also far from the doubling pledge made as part of Mission Innovation.

3.3.2 EU

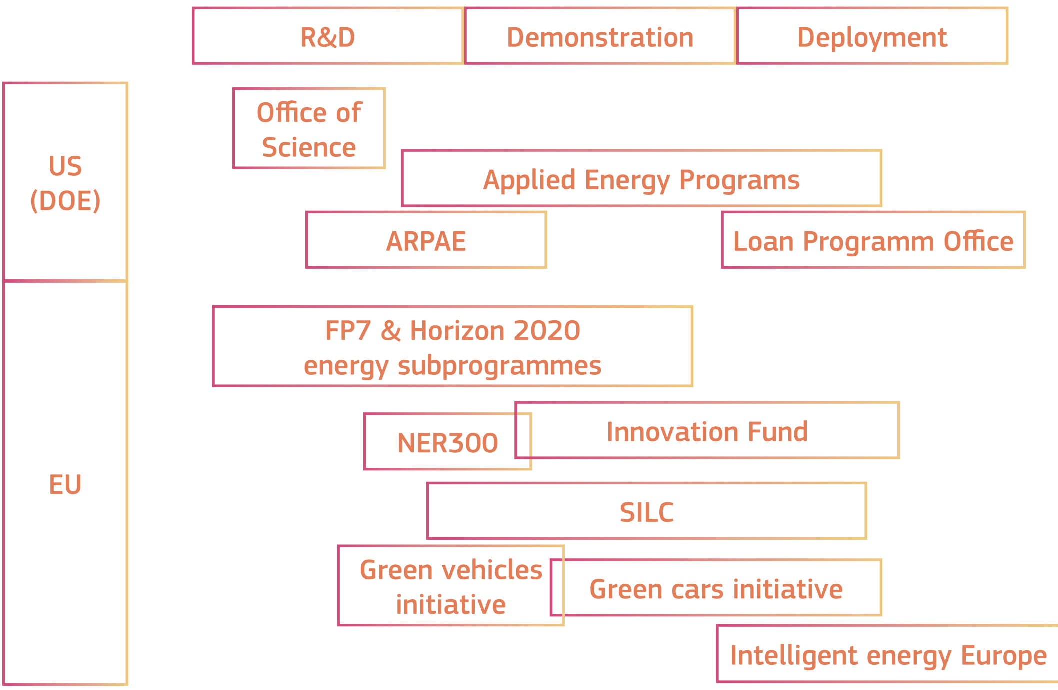
The European energy innovation policy landscape is scattered across several initiatives. The main channel for RD&D funding is via the Framework Programmes (FP) for Research and Technological Development. The FP introduced a specific energy subprogramme for the first time in 2007, with an allocated budget of EUR 2.35 billion. In 2014, the programmes were reformed (and rebranded under the name of 'Horizon') to adopt a more mission-oriented approach that organises funding, in part, around key societal challenges (Mazzucato, 2018). In this context, Horizon 2020 almost tripled the amount of funding to clean energy with EUR 5.9 billion for the 'Secure, Clean and Efficient Energy' challenge. This came in addition to another EUR 6.3 billion for 'Smart, Green and Integrated Transport' and EUR 3 billion for 'Climate action, Environment, Resource Efficiency and Raw Materials' (European Commission, 2021).

The move to a mission-oriented approach takes direct inspiration from the US DARPA and ARPA-E agencies and is an attempt to reapply lessons learned from past innovation success stories. Ex-post evaluations will be useful to understand to what extent the Horizon programmes successfully supported technological change and to assess what new lessons can be learned. Ex-ante, one may already highlight some potential pitfalls. First is the possibility that other considerations than innovation objectives influence the design and management of the programmes. A review of the selection process and how selection criteria are applied in practice would be informative. Second, a strategy of aiming for high-risk, high-reward projects requires a certain tolerance for failure, which may be challenging to implement at the European level. A central question is who takes responsibility for the risk and, incidentally, who can afford to lose political capital over failure.

Although mission-oriented R&D programmes in the EU have emerged only recently, several initiatives, such as the European Technology (and Innovation) Platforms, were already in place in the early 2000s to improve knowledge exchange in industries that were identified as strategic (e.g., wind and solar). However, these initiatives did not come with money attached and focused on more intangible aspects such as coordinating stakeholders (Consult, 2008).

Other smaller programmes exist beyond Horizon to support clean technologies, particularly at the demonstration stage. For example, NER300

Figure 10-1: Key energy innovation policies in the US and in the EU



Source: author's elaboration.
Stats.: https://ec.europa.eu/assets/rtd/srip/2022/figure-10-1.xlsx

and its successor, the Innovation Fund, recycle the revenues from the sales of new allowances in the EU Emission Trading Scheme (ETS) to fund projects on low-carbon technologies that stand between R&D and commercialisation. Initially endowed with a EUR 2 billion budget, the next phase has a larger budget of EUR 20 billion. In addition, the Sustainable Industry Low Carbon (SILC) was a small initiative between 2011 and 2020 that provided funding for the development, demonstration and dissemination of low carbon technologies in industrial sectors. Its successor, SILC II, has been included within Horizon 2020. NER300 and SILC also initially funded projects closer to the development stage, such as pilot plants, but the successor programmes are now more focused on demonstration.

Another programme worthy of mention is the EU Green Cars Initiative, which started in 2008 with a EUR 5 billion budget for public-private partnership for R&D projects focusing on electrification in the automotive industry. At the time, this initiative was part of the EU's wider Economic Recovery Plan. In 2013, the initiative was prolonged, rebranded as the European Green Vehicles Initiative, and funded as part of Horizon. Finally, Intelligent Energy-Europe was a EUR 45-million programme that, until 2013, funded soft-skills projects on energy such as capacity building, knowledge and skill exchange, policy input and awareness raising and information provision.

4. Demand-side policies (and their impact on innovation)

4.1 The arguments in favour of carbon pricing

The arguments in favour of pricing carbon rely on two fundamental aspects: static efficiency and cost-effectiveness. Static efficiency ensures that we reduce carbon emissions to the point where it makes us better off. In other words, at the margins, we should be indifferent between paying for an extra unit of pollution abatement or being exposed to one more unit of pollution. In the context of climate change, economic theory dictates that the carbon price be set to the level of the social cost of carbon, a number that has proven elusive in many regards and has lost relevance for some policymakers (Atkinson et al., 2018).

Indeed, the net-zero targets announced by various governments imply that the policy objective is to abate a particular **quantity** of carbon rather than the amount that would follow from setting a particular **price** on carbon. The focus on targets is evidence that the policy debate has moved beyond caring about efficiency, but this does not mean that carbon pricing is no longer relevant. Indeed, the level of the carbon price can be chosen based on technological options in order to remain consistent with specific targets. For example, discussions about the EU ETS have focused on limiting price variations, for example, by setting a floor price that would make it never profitable to generate electricity using coal or that would make green hydrogen competitive without subsidies. Kaufman et al. (2020) estimate that for the USA to be credibly on a net-zero path, the carbon prices need to be between USD 36 and USD 64 per tCO_2 by 2025 and between USD 77-124 per tCO_2 by 2030.

The second key theoretical motivation for carbon pricing is cost-effectiveness. Carbon pricing ensures that emission reductions are realised at the least cost because it is technology-neutral and it incentivises all economic actors to look for ways to reduce pollution. This mechanism leads to the cheapest technologies being adopted and ensures the lowest possible compliance cost in the short term.

4.2 The induced innovation effect of carbon pricing

Carbon pricing also incentivises economic actors to innovate and develop cheaper clean technologies. Doing so, firms can lower the cost of abating carbon: this is what economists call 'dynamic efficiency'. Importantly, this ensures that compliance costs are as low as possible in the longer term. Carbon pricing is able to induce innovation because it creates a market for clean technologies, thereby creating expectations of demand, which, for investors, means there will be profit-making opportunities in clean sectors. Without expectations of future profitability, investors would not be willing to invest money, time and effort into developing new technologies. As such, demand-side policies such as carbon pricing are critical to the dynamics of green innovation.

Carbon pricing, however, may not stimulate innovation as much as we would like. It may be more effective at fostering incremental innovation on technologies close to market rather than radical innovations further away from commercialisation. It remains a demand-side measure that is most effective at promoting the adoption of alternatives that are commercially available. Carbon pricing will provide incentives for firms to innovate, but those incentives will be stronger for technologies that are not characterised by high levels of uncertainty, for example, when reducing costs at the margins on technologies that are already proven. This may explain why we see path dependency in innovation outcomes. As highlighted before, supply-side support such as R&D subsidies is vital in such cases.

4.3 Political economy hurdles

Many industrialised countries are trying to set up carbon pricing mechanisms, either via carbon taxes or ETSs. Governments, however, have been very limited in their political ability to set high prices or to increase the number of firms and industries covered by ETSs. This is mainly due to concerns about competitiveness. In the USA, constrained by the low bi-partisan support for carbon pricing, the Biden administration is moving ahead focusing instead on sectoral standards and green public procurement.

Much of the debate around the pros and cons of carbon pricing focuses on the massive political economic hurdles that it faces. It is unpopular, and some also argue that it is an easy target for polluting lobbies to demonise, which tends to polarise the debate and leads to a policy standstill (Mildenberger et al., 2020). The only politically feasible prices may be too low to induce the changes needed in the necessary timescales (Hepburn et al., 2020). Therefore, other instruments such as regulations or standards, even if not the first best according to economic theory, must be used.

Arguably, the level of the carbon price is critical not just to spur adoption of more expensive clean technologies but also to induce innovation. The stronger and more stringent the policy, the clearer the signal sent to investors and innovators. Some have argued that there is little empirical evidence for the induced innovation effect of carbon pricing, but few countries have enacted high carbon prices. We should not be surprised if low carbon prices provide weak incentives to invest in clean energy R&D. Calel et al. (2016), in fact, showed that innovation did increase with the EU ETS but only after a substantial price increase that took place in the second phase.

4.4 Standards as imperfect alternatives

High carbon prices are unlikely to be politically feasible to implement, at least as long as clean technologies remain expensive. Standards and regulations may be more appealing because the costs are less visible. However, one way or another, citizens still pay the bill for carbon abatement. And the distributional aspects could be worse than those of carbon pricing (Metcalf, 2019; Rausch et al., 2014).

Greenstone et al. (2020) estimate that the costs of renewable portfolio standards in the USA were generally above USD 100 per tCO_2. The Legislative Analyst's Office of the State of California highlighted that the state's rooftop solar policies may have cost between USD 150 and USD 200 per tCO_2 (Petek, 2020). Gillingham et al. (2018) also reviewed many similar studies, and the overall conclusion is that many environmental policies to reduce carbon emissions end up being multiple times more expensive than what would usually be expected of a carbon tax.

As standards, subsidies and regulations accumulate and overlap, the shadow price of some emissions can also become much higher than others. This is the inherent inefficiency of the regulatory approach: the cheapest technologies are not necessarily used, leading to higher compliance costs than if the whole economy had one carbon price. The fundamental argument in favour of carbon pricing, as opposed to standards, is its ability to reduce compliance costs in the short and longer-term. Concretely, it means that we can reduce emissions more for the same costs. Resources are scarce, and carbon pricing can direct those resources to the cheapest emission reductions.

Designing and implementing specific guidelines for each sector is also a difficult task. To decide what and how things are produced and consumed, policymakers must know a lot about technologies, such as their emissions, costs and future potential. The private sector typically knows much more about these things, and regulators, who are subjected to lobbying, may find themselves at a disadvantage when negotiating and drafting regulations. The odds of policy mistakes, such as a regulatory design incurring unfortunate unintended consequences and administrative errors or malpractice, are also much higher.

Furthermore, the process of designing regulations can take many years. If we are pressed for time, as is the case, there is an important argument to be made in favour of carbon pricing, which is faster and easier to implement since it does not require a central authority with much knowledge. A price on carbon changes the whole system at once by shifting choices and behaviours in many different sectors without needing to know much. The level of ambition is also very transparently demonstrated by the level of the price itself. Within a regulatory approach, it is less obvious what defines ambitions, and there is a higher risk that lobbying restrains their magnitude (Majkut, 2020). Finally, regulations are not likely to be more popular with industry than carbon pricing because many firms favour straightforward and predictable climate policies rather than a regulatory piecemeal approach.

4.5 Carbon pricing, systemic changes and path dependency

Framing the problem as a market failure leaves some with a definite taste of over-simplicity, a belief that simply pricing in externalities will not suffice, and a view that a more systemic approach is needed (Rosenbloom et al., 2020). When it comes to reaching and impacting all parts of a system at once, carbon pricing is, in fact, a great policy tool. However, an argument can be made that changing prices at the margin may not help as much as we would think if many of changes needed are structural in nature and if there is path dependency.

This is most evident with urban planning, for example, with large cities designed around the use of automobiles. Infrastructure was developed in blissful ignorance of pollution impacts. This infrastructure is still with us and constrains many of our marginal choices. Similarly, it may be argued that our history of cheap but polluting energy has locked cultural norms around comfort and attire that are not helping to decarbonise heating systems. Since our economies have developed without paying much attention to environmental impacts, we may have locked ourselves into carbon-intensive paths.

The assumption that there is stickiness in the way our economy works and in the way agents and firms make their choices implies that changing prices at the margin may not suffice. Structural aspects may respond weakly or slowly to marginal price changes, and in these cases, standards and public spending on green infrastructure can be more effective (Hepburn et al., 2020).

5. Supply vs demand: investing in R&D or deployment?

5.1 Too late for R&D?

Policy advocacy for R&D spending has never been an easy task. Taking a technology from the lab to commercial deployment requires time, financial and human capital investments. The process can also be a long and twisted road paved with slow-paced activities and uncertain returns. Typically, many incremental successes are made along the way, but they rarely make the headlines, despite their importance to improving our understanding of technologies and reducing their uncertainties and costs.

As a result, R&D investments look to some as money not well spent, especially given the opportunity costs. For example, McLaren et al. (2020) argue that focusing on developing technological solutions delays concrete immediate actions and advocate instead for spending more on deploying behavioural responses and technologies that are already available.

A sense of emergency has also emerged in recent policy discussions about climate change, with calls for massive emission reductions to happen in the next 10 years. Investing in R&D does not chime well with such calls because it does not translate into emission reductions in the short term. The framing of emergency may lead some to believe that it is 'too late' and that we cannot take the time to invest in R&D.

5.2 RD&D support remains critical

Citizens may even doubt that we need more R&D as they regularly hear that we 'have' the necessary technologies. For example, in 2014, the IPCC report concluded that carbon-free economies were feasible. There has, indeed, been very impressive progress in renewable energies, but this is not sufficient. We know which technologies we will need but the issue is that many are not ready yet.

The IEA modelled what it would take to reduce emissions to meet a net-zero target by 2050 (IEA, 2020). According to their model, 17 % of the emission reduction relies on technologies that are still in the lab or prototypes. Another 17 % depends on technologies that are only at a demonstration stage. Another 41 % of reduction relies on technologies that are today in early adoption. Finally, only 25 % of reduction can depend on mature technologies such as wind and solar electricity.

Key technologies have yet to receive adequate support, for example, grid-scale storage, which will be needed as more of our electricity is generated by renewable energy. Hydrogen is also a central technology to reduce emissions in hard-to-abate sectors such as long-distance shipping, steel and cement. Finally, carbon capture and storage has seen much progress over the last decade and is included in most pathways to net-zero. Yet it is still not commercially ready.

Many technologies have been shown to work in the lab or at a pilot scale. But they must be demonstrated at full scale. In other words, they must be shown to work at the scale at which they would eventually be commercialised. Demonstration is crucial to convince investors that the technology performs as intended and that the costs are as expected. Only then can a technology be widely adopted. This process can take many years, even decades, and can suffer from persistent uncertainties and rollbacks. Scientists and engineers may have ideas about how to make the technology cheaper or more resilient to field conditions, but there is also no guarantee that things will work out.

Further R&D investments are therefore crucial to ensure that we can indeed reduce emissions in 20 or 30 years from now (Harrabin, 2020). If everything goes well, high-income countries will then aim at 100% clean electricity rather than 80%, and the focus will also shift to hard-to-abate sectors such as cement, aviation and shipping. The pace of progress is inherently linked to public policies, and given the lag times in innovation processes, the policies decided and implemented today will determine the speed and success of green technologies tomorrow. How much we invest in R&D this decade will therefore determine whether we can fully decarbonise in the medium and longer term.

5.3 Are we spending too much on energy R&D?

Another crucial question is whether spending on R&D and spending on demand-side policies such as adoption subsidies are appropriately balanced. Are we spending too much on one and not enough on the other? An argument in favour of demand-pull policies is that they allow cost decreases thanks to learning by doing, learning by using and economies of scale. Hence, investments in both supply-side and demand-side policies may be warranted. But, in the end, the optimal balance will depend on the magnitude of the spillovers at play.

Fischer et al. (2017) develop a model to look at the optimal ratio of deployment vs R&D spending and find that spendings disproportionately favour the former. They argue that, for a technology such as wind, the ratio should not be more than one. Only when assuming extreme learning by doing spillovers, the ratio may rise as high as 10. Next, they compare their theory-derived optimal ratios with empirical estimates. In 2010, the six largest EU countries spent EUR 315 million in R&D on solar and wind. Meanwhile, several key regulations were in place to spur the adoption of solar and wind, which bore an implicit cost of EUR 48 billion for the same year (Zachmann et al., 2015). The ratio between the two types of spending was, therefore, about 150. It seems reasonable to qualify this as unbalanced.

In the context of solar, we have evidence that R&D money was money particularly well spent. When looking at the dramatic drop in photovoltaic costs, we may wonder how much of it can we really attribute to R&D (as opposed to non-R&D phases of technological change). Kavlak et al. (2018) argued that this may be as much as 60% and suggest that R&D was a strong contributor to this technology due to the intense competition between different designs (e.g. crystalline silicon and thin films). Admittedly, economies of scale have also played an important role, especially in recent years, and account for about 20% of cost declines.

A few other studies make a similar case for other energy-related technologies. For example, Dowd (2017) attempted to quantify the benefits generated by investments made by the DOE's clean energy R&D programmes. He estimates that those investments offered a return of USD 32 on every dollar invested. These studies already make a strong policy case for increasing overall investments in R&D, but a further rationale is that those investments generally do not spill over abroad as much as demand-pull policies, argument which policy makers may find effective in swaying public opinion (Dechezleprêtre and Glachant, 2014).

6. Demand-side and supply-side measures need each other

6.1 For domestic policy-making

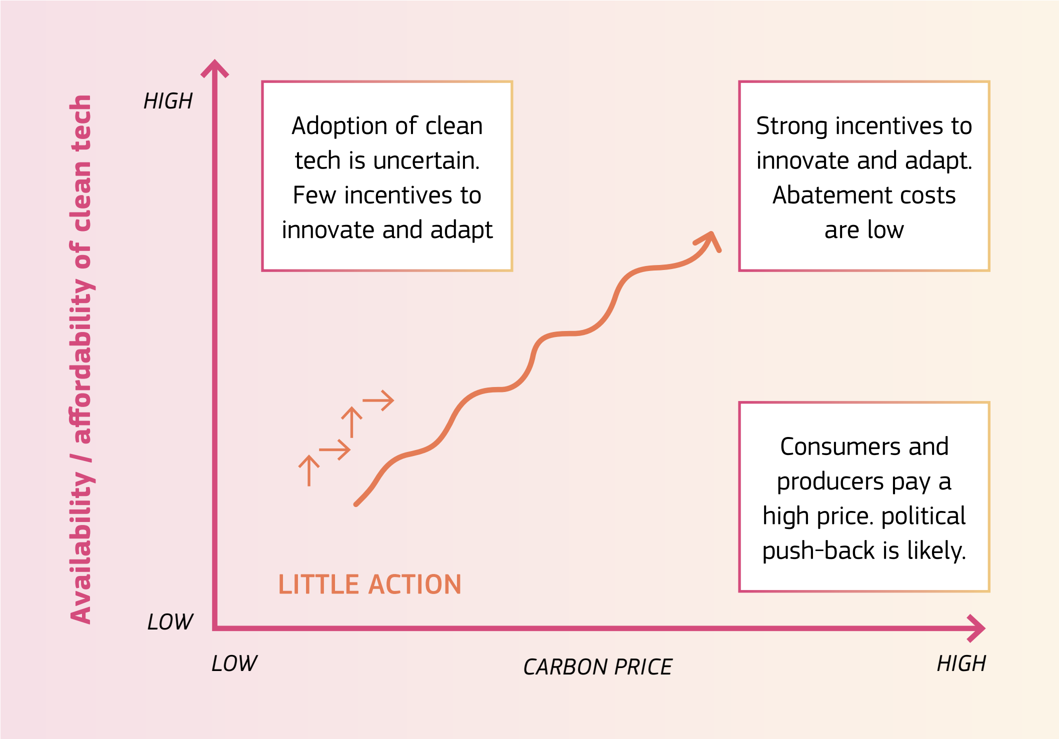
An important argument in favour of putting science and innovation front and centre of the green transition is that green innovations make the benefit-cost equations of domestic environmental policies more attractive and less politically polarising. Often, governments do not sufficiently intervene to tackle environmental issues because they fear that would make them unpopular with the general public or because special interests have lobbied them effectively. As the costs of renewable energies and battery technologies have gone down, we have seen many countries announcing plans to increase adoption. For example, Texas, a mostly republican state with an ever-present oil and gas industry, has seen its share of wind power increase steadily over the years. The abundance of wind resources and the lower cost of wind turbines meant business opportunities, which spoke louder than climate sceptics' words (Subramanian, 2017). Cheaper clean technologies, therefore, represent a formidable opportunity to make environmental policy more ambitious.

On the other hand, a carbon price would level the playing field for clean technologies, creating expectations of future business opportunities in clean sectors and fostering innovation and further cost reductions. In short, carbon pricing and innovation need each other to take our economies onto carbon-neutral paths. Figure 2 illustrates this point. At one extreme, in the bottom-left part of the graph, let us imagine a world with no commercially available clean technologies and a low carbon price. Clean alternatives are too early-stage and uncertain, and the carbon price is too low to provide strong incentives for firms to invest in these alternatives. Consumers, therefore, continue to buy carbon-intensive products while paying a small carbon fee. In these conditions, we may expect little carbon abatement to happen in the present and in the future.

The bottom right of the graph is a world with a high carbon tax but few commercially available clean technologies. In this case, the carbon price makes carbon-intensive production and consumption expensive. In the long term, this should induce innovation in green technologies, but in the short term, consumers and producers pay a high price for a limited amount of carbon reduction. Indeed, as Heal et al. (2019) highlight, alternative technologies must be commercially available for a carbon price to work.

In the opposite scenario, at the top-left corner, the carbon price is low but clean technologies are cheap. In this case, the adoption of clean technologies is uncertain because it will depend on whether clean technologies become more affordable than their carbon substitute. A small carbon price, however, should, in this case, be sufficient to phase out carbon-intensive technologies.

Figure 10-2: Combining carbon pricing and innovation policy to accelerate the transition to net-zero



Source: author's elaboration.
Stats.: https://ec.europa.eu/assets/rtd/srip/2022/figure-10-2.xlsx

Finally, a world with cheap clean technologies and a high carbon price, at the top right, would have strong incentives for innovation and adoption while abatement costs remain low. This is the best possible state of the world, which governments should strive to foster. Arguably, today, we are closer to the lower-left corner than the top right. But by combining both supply-side and politically acceptable demand-side policies, including carbon pricing, we may step by step take a path to the top-right corner. As clean technologies get cheaper, the burden imposed by carbon pricing will reduce and higher carbon prices will progressively become politically acceptable.

6.2 For global cooperation

As argued above, improvements in greener technologies lower the costs of environmental policies and make them more politically acceptable. A similar logic applies at the international level: cheaper clean technologies will make global cooperation easier. This should be seen as a core argument for making science and innovation the top priority. Many environmental problems are global in nature. Climate change can be tackled only if CO_2 emissions are reduced at the global level. The UNFCCC was set up to provide a framework for countries to discuss and negotiate how to do so. The inherent weakness of such international negotiations is that no third party can enforce the agreements. No world government exists, and countries remain sovereign.

The literature on the economics of IEAs has considered at large how to construct agreements that would be self-enforcing (Barrett, 2005). A self-enforced agreement makes it costly for a country to defect on its pledge. For example, the Montreal Protocol to protect the ozone layer included trade restrictions and possible trade sanctions in the case that a signatory did not reduce its CFC emissions by as much as it had committed itself to do. However, no sanctions were ever needed because the chemical industry was quickly able to offer viable CFC substitutes.

Unfortunately, self-enforced agreements are rare. But theory predicts that we are most likely to negotiate them if the costs of mitigating the environmental issue at stake are low (Barrett, 1994). This does not necessarily mean we must have all the ins and outs of green technologies figured out, but that, at least, some technologies must exist on paper or in the lab, and a path to commercialisation is seen within reasonable uncertainties. That is the story behind the success of phasing out ozone-depleting substances. In 1987, high-income countries negotiated an agreement that scholars have qualified to be self-enforced. With this agreement, countries committed their domestic industries to reducing CFC emissions. The reduction targets set in Montreal were far from a full phase-out which environmental NGOs at the time requested. But they were a concrete step that countries deemed technologically feasible.

What happened next is possibly the best example of induced green innovation at the global level. Firms scaled up their efforts to ensure they would meet the targets. Evidence of such efforts is the large increase in the number of patents and scientific articles in the aftermaths of the treaty's signature (Dugoua, 2021). The treaty was soon renegotiated to make targets more ambitious and include more substances in the list of molecules to phase out. Today, the ozone layer is recovering.

Improving the science and engineering of green technologies will be a key enabler of global cooperation on sustainability. Even if scientists and engineers do not provide us with all the ready-made solutions that we would like to have at our disposal, they can nonetheless provide us with a beginning of a solution that may be enough to convince parties to lock our institutions into the right incentives.

7. Conclusions

An array of policy solutions is available to policymakers to direct technological change away from dirty and towards clean technologies. Supply-side policies such as R&D funding are better positioned to impact and direct the earlier stages of technological change. Policies such as carbon pricing, standards or adoption policies create a demand-pull for clean technologies, which influences all stages of technological change. This chapter has highlighted some critical trade-offs to consider. In particular, lowering compliance costs in the longer term requires investing in R&D to reduce the costs of clean technologies. Lowering compliance costs in the short term would be easier with market-based instruments such as carbon prices, but they are unpopular, and governments often opt for standards and adoption subsidies that are typically more expensive.

A critical takeaway is that there is no silver-bullet policy. Governments should adopt and implement a coordinated mix of policies to achieve as much carbon-emission reduction as possible at the lowest possible cost. Despite all the criticisms, carbon pricing remains an essential part of this policy mix. Governments should aim at implementing politically acceptable carbon prices on all carbon emissions in the economy. In the short term, the carbon price levels are likely to be too low to induce as much emission reduction as we'd like. As a result, other policy instruments such as standards or adoption subsidies may be needed to ensure polluting technologies are phased out. Over the medium and long term, however, as the costs of clean technologies decrease, governments should find it more politically manageable to increase carbon prices.

References

Acemoglu, D., Aghion, P., Bursztyn, L., Hemous, D. (2012), 'The Environment and Directed Technical Change.' *American Economic Review*, 102 (1), pp. 131–166.

Aghion, P., Dechezleprêtre, A., Hemous, D., Martin, R., Van Reenen, J. (2016), 'Carbon Taxes, Path Dependency, and Directed Technical Change: Evidence from the Auto Industry.', *Journal of Political Economy* 124 (1), pp. 1–51.

Atkinson, G., Braathen N. A., Groom B., and Mourato S. (2018), 'Chapter 14: The Social Cost of Carbon.' In *Cost-Benefit Analysis and the Environment: Further Developments and Policy Use*, edited by OECD, pp. 335–372. OECD Publishing, Paris.

Barrett, S. (1994), 'Self-enforcing International Environmental Agreements.' *Oxford economic papers*, pp. 878–894.

Barrett, S. (2005), 'Chapter 28 The theory of international environmental agreements.' In *Handbook of Environmental Economics*, edited by Karl-Göran Mäler and Jeffrey R Vincent, 3, pp. 1457–1516. Elsevier, January.

Bonvillian, W. B., Van Atta, R. (2011), 'ARPA-E and DARPA: Applying the DARPA Model to Energy Innovation.' T*he Journal of Technology Transfer* 36 (5), pp. 469– 513.

Boucher, M. J., and Loring P. (2017), OPINION: Climate change is more than a tech problem, so we need more than a tech solution. https://ensia.com/voices/climate-change-social-fix/?utm_source=pocket_mylist. Accessed: 2021-10-6.

Calel, R., Dechezleprêtre, A. (2016), 'Environmental Policy and Directed Technological Change: Evidence from the European Carbon Market.' *The Review of Economics and Statistics* 98, no. 1 (March), pp. 173–191.

Consult, Idea. (2008), *Evaluation of the European Technology Platforms (ETPs)*. IDEA Consult nv.

Cunliff, C. (2020), Energy Innovation in the FY 2021 Budget: *Congress Should Lead* [inen]. Technical report. Information Technology and Innovation Foundation.

Cunliff, C., Nguyen, L. (2021), *Energizing Innovation: Raising the Ambition for Federal Energy RD&D in Fiscal Year 2022*. Technical report. Information Technology and Innovation Foundation.

Dechezleprêtre, A., Glachant, M. (2014), 'Does Foreign Environmental Policy Influence Domestic Innovation? Evidence from the Wind Industry.' *Environmental & Resource Economics* 58, no. 3 (July), pp. 391–413.

Dechezleprêtre, A., Martin, R., Bassi, S. (2019), Climate change policy, innovation and growth, In *Handbook on Green Growth*, Edward Elgar Publishing.

Dechezleprêtre, A., Martin, R., Mohnen, M. (2014), *Knowledge spillovers from clean and dirty technologies*. CEP Discussion Paper 1300.

Dowd, J. (2017), *Aggregate Economic Return on Investment in the US DOE Office of Energy Efficiency and Renewable Energy*. US Department of Energy 2.

Dugoua, E. (2021), *Induced innovation and international environmental agreements: evidence from the Ozone regime*, Grantham Research Institute on Climate Change and the Environment Working Papers (363), Grantham Research Institute on Climate Change and the Environment, London School of Economics and Political Science, London, UK.

European Commission. (2021), Horizon 2020 structure and budget. https://ec.europa.eu/research/participants/docs/h2020-funding-guide/grants/applying-for-funding/find-a-call/h2020-structure-and-budget_en.htm Accessed: 2021-10-7, July.

Fischer, C., Preonas, L., Newell, R. G. (2017), 'Environmental and Technology Policy Options in the Electricity Sector: Are We Deploying Too Many?' *Journal of the Association of Environmental and Resource Economists* 4, no. 4(4), pp. 959-984.

Freeman, R., Van Reenen, J. (2009), 'What If Congress Doubled R&D Spending on the Physical Sciences?' *Innovation Policy and the Econom*y 9 (January), pp. 1–38.

Gerarden, T. D., Newell, R. G., Stavins, R. N. (2017), 'Assessing the energy-efficiency gap.' *Journal of economic literature* 55 (4), pp. 1486–1525.

Gillingham, K., Stock, J. H. (2018), 'The cost of reducing greenhouse gas emissions.' *The journal of economic perspectives: a journal of the American Economic Association* 32(4), pp. 53–72.

Greenstone, M., Nath, I. (2020), *Do renewable portfolio standards deliver cost-effective carbon abatement*? Becker-Friedman Institute Working Paper.

Harper, G., Sommerville, R., Kendrick, E., Driscoll, L., Slater, P., Stolkin, R., Anderson, P. et al. (2019), 'Recycling lithium-ion batteries from electric vehicles' [in en]. *Nature* 575(7781), pp. 75-86.

Harrabin, R. (2020), 'Climate change: Clean tech 'won't solve warming in time'.' *BBC* (February).

Heal, G. M., Schlenker, W. (2019), Coase, Hotelling and Pigou: The Incidence of a Carbon Tax and Co 2 Emissions, *NBER Working Paper*, w26086.

Heinberg, Richard. (2017), Why Climate Change Isn't Our Biggest Environmental Problem, and Why Technology Won't Save Us. https://www.resilience.org/stories/2017-08-17/climate-change-isnt-biggest-environmental-problem-technology-wont-save-us/?utm_source=pocket_mylist Accessed: 2021-10-6, August.

Hepburn, C., Stern, N., Stiglitz, J. E. (2020), 'Carbon pricing special issue in the European economic review' [in en]. *European economic review* 127, pp. 103440.

International Energy Agency. (2020), Energy Technology Perspectives 2020 - *Special Report on Clean Energy Innovation*.

Jaffe, A. B., Newell, R. G., Stavins, R. N. (2005), 'A Tale of Two Market Failures: Technology and Environmental Policy.' *Ecological economics: the journal of the International Society for Ecological Economics* 54 (2), pp. 164–174.

Kaufman, N., Barron, A. R., Krawczyk, W., Marsters, P., McJeon, H. (2020), 'A near-term to net zero alternative to the social cost of carbon for setting carbon prices' [in en]. *Nature climate change* 10(11), pp. 1010-1014.

Kavlak, G., McNerney, J., Trancik, J. E. (2018), 'Evaluating the causes of cost reduction in photovoltaic modules.' *Energy policy* 123, pp. 700–710.

Li, J. (2019), 'Compatibility and Investment in the U.S. Electric Vehicle Market.'

Majkut, J. (2020), The Immediate Case for a Carbon Price [in en]. https://www.niskanencenter.org/the-immediate-case-for-a-carbon-price/ Accessed: 2021-10-7, October.

Mazzucato, M. (2018), *Mission-Oriented Research and Innovation in the European Union: A Problem-Solving Approach to Fuel Innovation-Led Growth*. Technical report. European Commission.

McLaren, D., Markusson, N. (2020), 'The co-evolution of technological promises, modelling, policies and climate change targets' [in en]. *Nature climate change* 10(5), pp. 392-397.

Meadows, D., Randers, J. (2012), *The limits to growth: the 30-year update*. Routledge.

Metcalf, G. E. (2019), 'The distributional impacts of U.S. energy policy.' *Energy policy* 129, pp. 926–929.

Mildenberger, Matto, and Leah C Stokes. (2020), The Trouble with Carbon Pricing. https://bostonreview.net/articles/leah-c-stokes-matto-mildenberger-tk/ Accessed: 2021-10-6.

Mission Innovation. (2021a), *Country Highlights 6th MI Ministerial 2021*. Technical report.

Mission Innovation. (2021b), *Mission Innovation 2.0 Vision*. Technical report.

Myslikova, Z., Gallagher, K. S. (2020), 'Mission Innovation is mission critical' [in en]. *Nature Energy* 5, 10, pp. 732-734.

Nemet, G F. (2019), *How Solar Energy Became Cheap: A Model for Low-Carbon Innovation*.

Neumayer, E. (2003), *Weak Versus Strong Sustainability: Exploring the Limits of Two Op-posing Paradigms* [in en]. Edward Elgar Publishing, January.

Petek, G. (2020), Assessing California's climate policies—electricity generation. https://autl.assembly.ca.gov/sites/autl.assembly.ca.gov/files/CalifLAO- ElectricityEmissions.pdf. Accessed: 2021-10-7.

Popp, D., Newell, R. G., Jaffe, A. B. (2010), 'Chapter 21 - Energy, the Environ-ment, and Technological Change.' In *Handbook of the Economics of Innovation*, edited by Bronwyn H Hall and Nathan Rosenberg, 2, pp. 873–937. North-Holland, January.

Rausch, S., Mowers, M. (2014), 'Distributional and efficiency impacts of clean and renewable energy standards for electricity.' *Resource and Energy Economics* 36(2), pp. 556-585.

Rockström, J., Steffen, W., Noone, K., Persson, Å., Chapin, F. S., Lambin, E. F., Foley, J. A. et al. (2009), 'A Safe Operating Space for Humanity.' *Nature* 461 (7263), pp. 472-475.

Rosenbloom, D., Markard, J., Geels, F. W., & Fuenfschilling, L. (2020), 'Opinion: Why carbon pricing is not sufficient to mitigate climate change–and how 'sustainability transition policy' can help' [in en]. *Proceedings of the National Academy of Sciences of the United States of America* 117(16), pp. 8664-8668.

Sanderson, H. (2019), 'Congo, child labour and your electric car.' *Financial Times* (July).

Subramanian, M. (2017), In West Texas Where Wind Power Means Jobs, Climate Talk Is Beside the Point. https://insideclimatenews.org/news/26122017/wind-energy-jobs-booming-texas-clean-renewable-power-climate-change/
Accessed: 2021-10-7, December.

Sugla, R. (2020), Opinion: We need massive societal change if we're going to survive and thrive on Earth. https://ensia.com/voices/opinion-we-need-massive-societal-change-if-were-going-to-survive-and-thrive-on-earth/?utm_source=pocket_mylist
Accessed:2021-10-6.

Zachmann, G., Serwaah-Panin, A., Peruzzi, M. (2015), When and how to support renewables?—Letting the data speak, In *Green energy and efficiency*, pp. 291-332. Springer, Cham.

CHAPTER 11

ARTIFICIAL INTELLIGENCE FOR SOCIAL GOOD: THE WAY FORWARD

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Summary

The chapter explores both opportunities and challenges linked to the implementation of artificial intelligence (AI) methods to address the sustainable development goals (SDGs). AI has the potential to improve our ability to measure and identify weaknesses, priorities and areas of improvement related to the SDGs, while accelerating their achievement. To realise such potential, five types of barriers need to be addressed (institutional, technical, ethical, financial and environmental) to effectively leverage the power of data-driven AI methods and accelerate their positive impact on the SDGs.

'It was the best of times, it was the worst of times, it was the age of wisdom, it was the age of foolishness, it was the epoch of belief, it was the epoch of incredulity, it was the season of Light, it was the season of Darkness, it was the spring of hope, it was the winter of despair, we had everything before us, we had nothing before us, we were all going direct to Heaven, we were all going direct the other way – in short, the period was so far like the present period, that some of its noisiest authorities insisted on its being received, for good or for evil, in the superlative degree of comparison only.'

Charles Dickens, *A Tale of Two Cities*

1. Introduction

As in Dickens' words, it is indeed the best of times and the worst of times. We live in a time of prosperity, but we also face tremendous global challenges that threaten our existence as a species – from poverty and hunger to climate change and the destruction of entire ecosystems. Effectively tackling these challenges requires an ambitious and coordinated commitment from most nations in the world. Hence, since the mid-1990s, starting with the Copenhagen Declaration on Social Development in 1995 and the six International Development Goals that followed in 1996, the United Nations (UN) has periodically established far-reaching goals for the world, aimed at addressing the most pressing issues of our times at a global scale and in a coordinated manner.

In 2015, when the Millennium Development Goals approached their target date, the UN defined a new set of global goals and the 2030 Agenda for Sustainable Development, which was adopted by all EU Member States in 2015. The resulting global goals are known as the 17 SDGs, a call to action by all countries (developed and developing) with the aim of eradicating the world's poverty and other deprivations, together with improving health and education, fostering economic growth, reducing inequality, preserving our environment and combating climate change.

In parallel to the establishment of such an ambitious agenda for the world, a global movement gained traction on the role that data and AI could play in this context from two perspectives: first, to help us better measure the level of achievement of the SDGs and identify weaknesses, priorities and areas for improvement; and second, to enable and accelerate the achievement of the SDGs. In November 2014, the UN published the report 'A World that Counts: mobilizing the data revolution for sustainable development'[1], authored by

1 https://www.undatarevolution.org/wp-content/uploads/2014/11/A-World-That-Counts.pdf

the Independent Expert Advisory Group on a Data Revolution for Sustainable Development as requested by the UN Secretary-General. The report outlines both the opportunities and the risks that the 'data revolution' presents for sustainable development, and proposes five key recommendations for actions, including investing resources in capacity development, sharing technology and innovations for the common good, developing a global consensus on principles and standards and creating the Global Partnership for Sustainable Development Data[2], which was created in 2015 'to help stakeholders across countries and sectors fully harness the data revolution for sustainable development, using this new knowledge to improve lives and protect the planet'. The UN subsequently organised three editions of the World Data Forum, in 2017, 2018 and 2020 in South Africa, Dubai and Switzerland, respectively. The 2018 Forum wrapped up with the launch of the Dubai Declaration, which aims to increase financing for better data and statistics for sustainable development.

Moving from a global context to the European arena, the European Commission established six priorities for the 2019-2024 period[3], which include the twin green and digital transitions, captured by the 'European Green Deal' and 'Europe fit for the digital age' priorities, respectively. The European Commission considers these two transitions to be deeply interrelated, as it is evident that digital technologies are playing and will continue to play a crucial role in enabling Europe to move to a clean and circular economy, restore biodiversity and reduce pollution. Thus, data and AI are considered to be not only key pillars of the digital transition, but also of the green transition.

The European Commission recognises that data – and more importantly, the ability to use it, analyse it (prominently by means of data-driven AI methods) and draw insights from it – are essential for sustainable growth and innovation. The European vision for AI entails developing and using trustworthy AI systems, that is, systems that are safe, ethical, transparent, unbiased and under human control. Such a vision is articulated in several strategic documents, including an ethical framework to achieve trustworthy AI[4], a set of policy and investment recommendations to boost Europe's competitiveness in AI[5], a new European regulation on data governance to facilitate data sharing across the Member States – placing citizens at its centre and contributing to the creation of a European single data market[6], and a new European regulation of AI systems based on a classification of their risk, which can range from unacceptable (and thus banned) to minimal risk[7].

A key question posed by many scientists, policy makers, practitioners, activists and citizens today is whether these data and AI revolutions that we are immersed in will contribute to achieving **sustainable development**, i.e. development that not only meets the needs of the present but ensures the ability of future generations to meet their own needs.

In this chapter, I provide an overview of both the tremendous opportunities that data-driven AI methods offer to help us address the 17 SDGs and the challenges and limitations posed by AI that might hinder the realisation of such potential.

2 https://www.data4sdgs.org/
3 https://ec.europa.eu/info/strategy/priorities-2019-2024_en
4 https://digital-strategy.ec.europa.eu/en/library/ethics-guidelines-trustworthy-ai
5 https://www.europarl.europa.eu/italy/resource/static/files/import/intelligenza_artificiale_30_aprile/ai-hleg_policy-and-investment-recommendations.pdf
6 https://data.europa.eu/en/highlights/data-governance-act-open-data-directive
7 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52021PC0206

2. AI and the 17 SDGs

AI is the discipline within computer science or engineering that has the objective of the development of computationally – i.e. non-biological – intelligent systems, taking human intelligence as a reference. In the same way that human intelligence is complex and diverse, there are many areas of knowledge within AI that aim to emulate specific aspects of human intelligence, such as computer vision, speech recognition, natural language processing, planning, reasoning, knowledge representation, learning theory and decision-making.

Historically, there have been four views in the literature as to how to achieve AI or what AI means: (1) AI means **acting humanly**, i.e. acting like a person – the Turing test is a classic example of such view of AI; (2) AI means **thinking humanly**, i.e. thinking like a person, which is the object of study of cognitive science; (3) AI means **thinking rationally**, i.e. modelling thinking as a logical process, where conclusions are reached based on symbolic logic; and (4) AI means **acting rationally**, i.e. performing actions to achieve one's goal, based on one's understanding and beliefs about the world.

In terms of how to build AI systems, there have been two basic schools of AI since its emergence in the 1950s: first, the top-down or symbolic-logic school, and second, the bottom-up or data-driven school. According to the symbolic-logic school, to achieve AI, human knowledge would be collected and codified, deriving new knowledge from such initial knowledge using the rules of logic. The methods in this school are based on symbolic representations of problems, logic and search. This approach to AI was the dominant paradigm from the birth of the discipline in the 1950s until the late 1980s. The canonical example of the top-down school are expert systems, which were the first successful example of commercialisation of AI systems.

The methods developed in the bottom-up, data-driven school, are inspired from biology: biological intelligent beings learn from their interactions with their environment, from experience. Hence, bottom-up approaches to AI focus on developing methods that learn from data as opposed to modelling symbolic descriptions of the environment. The canonical example of a bottom-up method are neural networks.

Bottom-up, data-driven methods in AI have experienced an unprecedented exponential growth in the past 15 years mainly due to three factors:

- the existence of massive amounts of non-structured data (referred to as 'big data') which is the result of both our interactions with the digital world and the increased digitisation of the physical world;
- the availability of large-scale computing at low cost, as a consequence of Moore's law;
- the development of sophisticated machine learning algorithms, inspired by the neural networks from the 1950s, but significantly more complex, called deep neural networks or deep learning (LeCun et al., 2015), which have the flexibility and the power to learn from large-scale data by leveraging high performance computing.

Because of these three factors, we have witnessed tremendous achievements in data-driven machine learning algorithms applied to numerous areas, including computer vision, audio processing, natural language processing, time series analysis, recommendations, reinforcement learning and control, robotics and uncertainty quantification. Thus, it should not come as a surprise that these methods are at the core of most of the AI-enabled systems that we use in our phones, our homes, our cities and our cars.

The domains most likely to be disrupted, transformed and enriched by these new AI approaches are data-rich, challenges related to identifying patterns and trends in non-structured data (images, videos, audio, text, sensor data, etc.), challenges that require making predictions about future phenomena and/or would benefit from data-driven decisions.

Thus, these advances are valuable to address many of the challenges related to the 17 SDGs. In fact, in recent years several research papers have been published (Vinueasa et al., 2018) and initiatives have been launched to identify projects that investigate the use of AI in the context of the 17 SDGs. Examples of such initiatives include the SDG AI Repository managed by the UN's International Telecommunication Union (ITU) agency[8]; the database of the AI for Sustainable Development Goals (AI4SDGs) Think Tank[9] and the database of the University of Oxford's Research Initiative AIxSDGs[10], which lists 108 projects.

But what are the concrete opportunities that AI offers in the context of the SDGs? How can AI methods help us to achieve such an ambitious global agenda? What are the challenges associated with leveraging AI for social good?

The following section provides an overview of the challenges and opportunities for AI in each of the SDGs, except SDG 17, which refers to the importance of establishing partnerships and collaborations across regions, countries and institutions in pursuit of all the goals by 2030. Therefore, it is not included in the discussion.

SDG 1 – No poverty

After declining for 20 years, global extreme poverty rose again in 2020 due to a variety of factors, including the impact of the COVID-19 pandemic and climate change[11]. The World Bank estimates that up to 1.9 billion people in the world today live below the societal poverty line, which combines the USD 1.9/day absolute poverty line with a country-dependent component based on the median consumption or income in the country. Most of the poor live in rural areas and poverty is a long-lasting reality in many parts of the world. However, obtaining granular, high-quality data on poverty to inform policy making is still a challenge.

AI techniques have been used to automatically analyse satellite (Jean et al., 2016), mobile (Syndsoy et al., 2016; Soto et al., 2011; Blumenstock and Cadamuro, 2015) or digital transaction and real state online advertisements (Cruz et al., 2019) to automatically infer poverty or socio-economic levels in developing and developed countries.

Beyond leveraging AI methods to assess poverty, AI-powered, evidence-based decision-support systems could inform public decisions relative to poverty eradication programmes both to measure the success of such programmes and to guide resource allocation depending on the estimated current and predicted levels of poverty in different regions. Moreover, data-driven AI is emerging as a driver to improve the overall quality of life[12].

8 https://www.itu.int/en/ITU-T/AI/Pages/ai-repository.aspx
9 https://ai-for-sdgs.academy/about
10 https://www.aiforsdgs.org/
11 https://www.worldbank.org/en/topic/poverty/overview
12 E. O. of the President National Science and T. C. committee on technology. Preparing for the future of AI. https://obamawhitehouse.archives.gov/sites/default/fil es/whitehouse_files/microsites/ostp/NSTC/preparing_for_the_future_of_ai.pdf, 2016.

SDG 2 – Zero hunger

Hunger refers to the generalised lack of access to food by a community or a population in a sustained manner. Hunger still prevails in many developing countries, and it is often exacerbated by extreme weather events (e.g. severe draughts), poverty and/or wars. The early detection of hunger is typically an effective strategy to prevent or mitigate it (Holley, 2018).

Weather (United States Agency for International Development, 2010), satellite, demographic (Quinn et al., 2010) and socio-economic (Okori and Obua, 2011) data have been analysed using AI techniques to make an early detection of hunger in developing countries, such as Uganda. Other authors have used machine learning techniques to predict food demand in areas impacted by natural disasters (Xiaoyan et al., 2010).

There are several examples where AI techniques have been used to predict the yield of crops from climate and agriculture data (Gandhi and Armstrong, 2016; Zhu et al., 2018), sometimes combined with satellite data (Badr et al., 2016). Invasive species and plagues have been automatically recognised in images by deep neural networks (Fedor et al., 2009; Mohanty et al., 2016) and machine learning techniques have been proposed to identify and recommend crops depending on the characteristics of the soil (Kulkarni et al., 2018).

Several international organisations, including UN agencies, the World Bank, NGOs (such as Mercy Corps, Save the Children and Oxfam) and data institutions (such as the UN Centre for Humanitarian Data, the Integrated Food Security Phase Classification, IPC, or the Famine Early Warning Systems Network, FEWS) have partnered in the Famine Action Mechanism (FAM)[13], a global initiative to end famine. FAM was launched in 2018 and focuses on three data-driven areas of collaboration to anticipate and address food security crises: food security crisis risk analysis, anticipatory and early action financing, and programming. The Group on Earth Observations Global Agricultural Monitoring Initiative (GEOGLAM)[14] is an open community created to increase market transparency and improve food security by producing and sharing relevant, timely and actionable data on agricultural conditions and outlooks of food production at different scales (national, regional and global).

Finally, there are two emergent, relevant concepts: precision agriculture (Zhang et al., 2002) and smart farming (Sundmaeker et al., 2016; Wolfert et al., 2017), which focus on leveraging data captured by a variety of pervasive sensors and state-of-the-art technology to optimise the yield of crops while preserving resources. According to the Food and Agriculture Organization (FAO) (2017), smart farming refers to the use of modern digital technology – including internet-of-things sensors, autonomous drones (Faulkner and Cebul, 2014), robots to feed cattle (Grobart, 2012) and AI techniques to analyse the data captured by the sensors – to improve agricultural production systems. The European Commission has established Horizon 2020 programmes to promote smart farming.

SDG 3 – Good health and well-being

Having good health is a human right and a key contributor to growth and prosperity[15]. The levels of health and well-being in a population are a proxy indicator of the nation's level of progress. Unfortunately, we are still far from achieving good health everywhere on the planet.

13 https://www.worldbank.org/en/programs/famine-early-action-mechanism
14 https://earthobservations.org/geoglam.php
15 https://irp-cdn.multiscreensite.com/be6d1d56/files/uploaded/SDSN%20Health%20Solutions.pdf, 2019.

AI for public policy making during the COVID-19 pandemic: the Valencian experience

In March 2020, the Valencian government created the Data Science against COVID-19 taskforce, composed of over 20 volunteer scientists from several Valencian research institutions (universities and research centres), working on four areas to support the Government's decision-making during the pandemic:

- large-scale human mobility modelling via the analysis of large-scale data derived from the mobile network infrastructure;
- computational epidemiological models to predict the evolution of the pandemic curve, not only under the current conditions but also under different scenarios of non-pharmaceutical interventions;
- machine learning-based predictive models of hospital and intensive care occupancy;
- a large-scale, online citizen survey via the COVID-19 Impact Survey, which is one of the largest surveys in the world about COVID-19, with over 700 000 answers.

The work of this taskforce has received national and international visibility and recognition, including winning first prize at the 500k XPRIZE Pandemic Response Challenge competition, sponsored by Cognizant. It is the first time that a team from Spain (ValenciaIA4COVID) has won an XPRIZE competition. As part of the XPRIZE challenge, the team developed a novel deep learning-based epidemiological model able to predict the number of COVID-19 cases in 236 countries and regions in the world and a non-pharmaceutical intervention prescriptor, recommending up to 10 different public policies that would have the optimal trade-off between the cost of the public policies and their impact on containing the number of COVID-19 cases. This work also received the best paper award at ECML-PKDD 2021.

This initiative is an example of the use of AI for social good, by means of a collaboration between academia and the scientific community, society at large (through the citizen survey) and a government to achieve evidence-driven decision-making.

The intersection between data, AI and health is rich and full of opportunity, as highlighted by many authors (Singh, 2019; Guo and Li, 2018). Broadly speaking, AI methods are redefining healthcare from at least three perspectives.

The first perspective is by accelerating the discovery and design of effective treatments and vaccines, enabling the prediction of expected results and side-effects, in addition to automating the discovery of new pharmacological compounds (Ong et al., 2020; Schneider, 2018) and protein folding (Senior et al., 2020).

The second is by assisting in clinical decision-making related to, e.g., the diagnosis of cancer (Esteva et al., 2017; Fauw et al., 2018), COVID-19 (Oh et al., 2020) or tuberculosis (Doshi et al., 2017) in radiological tests, potentially providing expert feedback and diagnoses to patients where human medical experts might not be available; improving pregnancy, post-partum (Rodriguez et al., 2016; Poon et al., 2009) and infant care and thus preventing deaths (Malak et al., 2018; Adegbosin et al., 2019); and predicting the efficacy of treatments (Pham et al., 2017) or the probability of needing intensive care (Kaji et al., 2019).

The third is by supporting policy-making related to public health – including mental health (Walsh et al., 2017) and infectious diseases, such as malaria (Wasolowski et al., 2012), influenza (Kagashe et al., 2017), Ebola (Wasolowski et al., 2014) and COVID-19 (Oliver et al., 2020) – via the analysis of multi-dimensional data captured by the mobile network infrastructure, social media platforms and pervasive sensors.

Moreover, the increased availability of wearable devices at affordable prices (e.g. activity wristbands, smartwatches, etc.) enables the collection of large-scale, longitudinal data about daily activities, sleep habits and physiological signals, which, analysed via machine learning techniques, could be extremely valuable in the early diagnosis of disease and the realisation of personalised, preventive and predictive medicine (Clifton et al., 2013).

In fact, precision (predictive, personalised, preventive) medicine will not be achievable without the use of AI techniques applied to genomic, behavioural, contextual (e.g. pollution, weather) and medical data (Collins and Varmus, 2015).

On the negative side, in addition to numerous ethical and technical challenges discussed below, we need to consider that data-driven AI methods are at the core of the digital services and social media platforms that we use today, so they can personalise the user experience, recommend relevant content and increase engagement. Unfortunately, these services, which are designed to maximise our engagement, could lead to an excessive (and possibly addictive) use by their users with potential negative consequences for our well-being (Zheng and Lee, 2016).

SDG 4 – Quality education

Education is a key pillar for sustainable development and prosperity. While the world has made progress in reducing the education gap, particularly for women and girls, there are still today over 260 million children of primary and secondary school age worldwide who do not attend any school, 130 million children who can barely read and write despite attending school and 75 million children aged 3-18 years old who live in countries facing violence and war, needing educational support.

AI has the potential to contribute to education in several ways. First, by enabling a personalisation of the learning experience, moving from a generalist, one-to-many education model to an individual, one-to-one model. Intelligent tutoring systems (ITS) via software agents, chatbots or social robots can personalise both the content and the strategies used to teach students, to maximise their learning. In addition, AI-powered intelligent educational interfaces enable the early detection of students with physical or mental disabilities (David and Balakrishnan, 2010) and provide the necessary tools to help them to learn more effectively (Abdul Hamid et al., 2018). Second, data-driven AI methods are used to enable more efficient academic management (e.g. automatically create the schedules for teachers, support teachers in grading, provide 24/7 support via chatbots, etc.) and to evaluate the quality of the education (Nieto et al., 2019).

Conversely, the potential risks of the use of AI in education would need to be further studied. Such risks include the violation of privacy, the subliminal manipulation of the students' behaviours via personalised algorithms, different kinds of discrimination and potential negative effects on the students' physical and mental health along with their behavioural development (Zanett et al., 2019).

SDG 5 – Gender equality

Gender equality is a fundamental human right. It is also a foundational element to achieving a more sustainable, peaceful and prosperous world. In recent decades, significant advances towards gender equality have taken place: today, more girls attend school and fewer girls are forced into early marriage, more women occupy leadership positions and legislation is being approved to advance gender equality. Despite this progress, women continue to be underrepresented in leadership positions, one every five women and girls aged 15-49 reports having experienced physical or psychological violence within a 12-month period and discriminatory cultural and social norms and laws remain pervasive.

AI methods can be used to automatically identify gender bias (Feldman and Paeke, 2021), analyse the role of women in meetings through speech recognition, natural language processing and conversation analysis and automatically identify differences in gender representation, coverage and gender biases in newspaper coverage or commercial films via text, image, video and speech analysis (Jang et al., 2019; Kagan et al., 2020).

Data-driven AI decision-making systems are not exempt from limitations, including gender discrimination and bias, as later described in this chapter. Hence, while AI can help us better diagnose and fight against gender inequality, it might also contribute to perpetuating or even exacerbating pre-existing patterns of inequality. Thus, it is of paramount importance to ensure that the AI tools that we use provide non-discrimination guarantees.

SDG 6 – Clean water and sanitation

Access to clean water and proper sanitation are necessary to ensure adequate living conditions. However, according to a report by the World Health Organization (WHO) and the United Nations Children's Fund (UNICEF)[16], in 2019 more than 785 million people did not have access to at least basic water services and more than 884 million people did not have access to clean, safe water to drink. Moreover, more than 2 000 million people worldwide did not have access to basic sanitation and approximately 3 000 million people lack proper facilities to safely wash their hands at home. Here, sub-Saharan Africa is the most affected region in the world with 75 % of the population lacking basic handwashing facilities.

16 https://www.unicef.org/reports/progress-on-drinking-water-sanitation-and-hygiene-2019

The consequences of such statistics are daunting: annually there are 1700 million cases of diarrhoea among children younger than 5 years old, causing the death to 440 000 children; 3 million cases of cholera resulting in 95 000 deaths and 11 million cases of typhoid fever which cause 129 000 deaths. Parasitic worms found in contaminated soil and associated with a lack of proper sanitation facilities infect around 1 500 million people worldwide. In addition, a lack of access to adequate sanitation facilities for girls reaching puberty makes them significantly more likely to miss school than boys.

SDG 6 aims at achieving universal access to drinking water at affordable prices and to proper sanitation services; improving the quality of water, reducing pollution; making an efficient and sustainable use of water resources, to be managed in an integrated manner; protecting and re-establishing water ecosystems and increasing the international cooperation in the context of water and sanitation.

Data-driven AI methods have been used to optimise and predict the efficacy of water desalination plants (Dargam et al., 2020), to predict groundwater levels in coastal aquifers (Yoon et al., 2011) and/or their salinity (Sahoura et al., 2020), to model groundwater level changes in agricultural regions (Sahoo et al., 2017), to detect and track major sources of water contamination (Wu et al., 2021) – including drinking water networks (Dogo et al., 2019), to forecast wastewater quality indicators (Granata et al., 2017), to automatically detect water leakage (Kang et al., 2018) and cyber-attacks (Chandy et al., 2017) in water distribution systems and hence avoid wasting water, to predict water consumption in cities and thus better anticipate demand (Brentan et al., 2017) and to forecast water levels in multiple temperate lakes (Zhu et al., 2020), which is a vital indicator of the health of the lake ecosystems and their management. Precipitation and extreme water-related events which could lead to floods can also be modelled using state-of-the-art data-driven AI methods, as described below in the context of SDG 16 (climate action).

SDG 7 – Affordable and clean energy

Access to affordable and clean energy is undoubtedly essential to progress, yet it is one of the biggest challenges that the world faces today. It is estimated that 13 % of the world's population – mostly located in sub-Saharan Africa and India – does not have access to electricity. In 2016, 3 000 million people in the world depended on highly polluting fuels to perform basic, daily tasks, such as cooking. In addition to the environmental and climate impact, the burning of solid fuels (e.g. wood, charcoal, coal, dung and crop residues) poses a serious public health issue, as it fills the houses and huts with smoke that causes pneumonia, heart disease, lung cancer, stroke and chronic obstructive pulmonary disease.

This SDG aims to achieve by 2030 universal access to modern and affordable energy, a significant increase in the production of renewable energy, double the world's rate of energy efficiency, investment in R&D related to clean energy and investment in the necessary infrastructure to provide modern and sustainable energy in developing economies.

AI has a fundamental role to play in the context of SDG 7. In fact, many of its ambitious goals will not be achievable without the help of data-driven AI techniques. Smart grids depend on AI methods to, e.g., predict demand and optimise the maintenance and functioning of the grid (Raza and Khosravi, 2015), to significantly increase the grid's reliability and efficiency via the automatic detection of failures (Mishra and Rout, 2018) and cyberattacks (Karimipour et al., 2019) and the prediction of load (Hosei and Hosein, 2017). Semi-autonomous or fully autonomous robots are and will be used to inspect and maintain renewable energy plants (Iqbal et al., 2019), such that they could be placed in remote or dangerous locations yet with optimal energy production prospects.

The application of AI in the nuclear engineering domain has been limited to date. However, in recent years several authors have proposed using machine learning and deep neural networks to predict the behaviour of nuclear reactors, perform predictive maintenance of nuclear infrastructures or improve fire hazard models (Fernandez et al., 2017).

Finally, there are numerous examples of how data-driven AI methods are key enablers to creating efficient renewable energy (wind, solar, geothermal, hydro, ocean, bioenergy and hybrid) systems by providing accurate predictions of the expected behaviour of the renewable energy source and hence enabling the optimisation of the energy generation systems (Jha et al., 2017).

SDG 8 – Decent work and economic growth

The creation of high-quality jobs is still a challenge in most countries in the world. While the global unemployment rate is estimated to be 5.5 %, there are many countries in both the developing and the developed world where having a job is no guarantee of being above the poverty line or having a decent life.

AI is having and will have a profound impact in the labour market and economic growth. The adoption of AI will affect a wide range of professions, including those that require high levels of qualifications (Mitchell and Brynjolfsson, 2017) in the medical (Barlow, 2016), finance (Dunis et al., 2016), legal and education (Woolf et al., 2013) sectors.

There are numerous studies that have analysed the impact of AI on the labour market, both in terms of the displacement of entire jobs (Frey and Osborne, 2017) or the automatisation of certain tasks within jobs (Arntz et al., 2016). Most authors concur in predicting a significant level of job or task displacements due to AI automatisation. According to Arntz et al. (2016), the percentage of jobs that are susceptible to being displaced by AI range from 6 % in South Korea to 59 % in Germany, with an average value for Europe between 45 % and 60 % (Bowles, 2014). This transformation of the job market could lead to an increase in the polarisation of labour (Autor et al., 2010) and migrations to urban centres, which would contribute to geographic and social inequality (Frank et al., 2018). At the same time, AI techniques have been used and will be used to help reduce inequalities, as explained in the SDG 10 section.

SDG 9 – Industry, innovation and infrastructure

Sustainable economic growth relies on the availability of high-quality infrastructure for, e.g., transport, energy, water supply and communication and ambitious investments in innovation to contribute to prosperity, guarantee competitiveness and enable the ability to tackle future challenges.

Data-driven AI techniques are particularly valuable for monitoring, analysing and predicting failures in existing infrastructure by, for example, analysing aerial images using deep learning and machine learning techniques (Bao et al., 2019; Rafiei and Adeli, 2017; Ren et al., 2020; Xu et al., 2019; Gopalakrishnan et al., 2017) or detecting energy consumption anomalies and the production of pollutants in industry (Xu et al., 2015) and the construction of infrastructure. Digital twins are increasingly used as a digital representation of the physical world, including digital twins to predict the behaviour of large infrastructure, such as bridges (Ye et al., 2019).

Another clear area of impact of AI related to SDG 9 are transportation systems, including the use of data-driven AI methods to predict and better regulate transport flows (Zhao et al., 2019); Yao et al., 2019; Pan et al., 2019; Li et al., 2017), to assist in planning more efficient public transport routes (Saracco, 2018) and to deploy autonomous vehicles for passenger and freight land (Niestadt, 2019), rail (Schut and Wisniewski, 2015) or even aerial transport.

SDG 10 – Reduced inequality

In the last 25 years, total global inequality (i.e. the inequality across all individuals in the world) has been declining[17], meaning that the average incomes in developing economies are increasing at a faster rate than those in developed countries. However, inequality within countries has worsened, such that 71% of the world's population live in countries where inequality has increased. With the 21st century, we are witnessing an unprecedented concentration of income and wealth in the hands of the very few: in 2018, the 26 richest people in the world had as much wealth as the bottom half of the world's population.

While AI has been attributed to contributing to inequality[18] due to algorithmic bias and the 'winner-takes-all' phenomenon associated with technological development, data-driven AI methods can be used to reduce inequality. For example, AI algorithms can improve child welfare systems by automatically identifying when children might be in need of welfare (Schwartz et al., 2017), can foster financial inclusion by building alternative credit scores (San Pedro et al., 2015) or by shedding light on the factors for mobile money adoption (Centellegher et al., 2018), and can drive measurable positive change in the lives of minorities and vulnerable groups[19] and ensure fair decision-making (Zemel et al., 2013).

SDG 11 – Sustainable cities and communities

For the past few centuries, the world has experienced a process of urbanisation, that is, the displacement of the population from rural to urban areas, leading to the creation and growth of towns and cities. More than half of the world's population today lives in urban areas and by 2030 it is expected that this figure will raise to about 5 000 million people[20]. People tend to migrate from rural to urban areas looking for a better life and more opportunities to prosper. Indeed, cities have the potential to contribute to higher levels of well-being, education, resource efficiency and economic growth. However, urbanisation is not exempt from challenges, including inequality and poverty, overcrowding, criminality, energy consumption and environmental impact, pollution, waste generation and lack of appropriate living standards.

Data-driven AI techniques have been used to improve urban planning by estimating urban density from aerial images (Lu et al., 2010), informing decisions related to road (Krol, 2016) and public transport (Mukai et al., 2008; Froehlich et al., 2009), planning traffic, detecting traffic incidents (Dia and Rose, 1997; Dia, 2001) and predicting future traffic conditions (Huang et al., 2014; More et al., 2016) or mobility needs (Held, 2018).

Urban intelligent transport systems are only possible thanks to data-driven AI methods, which lead to safer, more inclusive and efficient public transport (Liao et al., 2018; Yao et al., 2018).

17 https://openknowledge.worldbank.org/bitstream/handle/10986/25078/9781464809583.pdf?sequence=24&isAllowed=y
18 https://www.cs.dartmouth.edu/~ccpalmer/teaching/cs89/Resources/Papers/AIs%20White%20Guy%20Problem%20-%20NYT.pdf
19 https://d4bl.org/about.html
20 https://www.unfpa.org/urbanization

AI pervades modern commercial vehicles, which include AI systems to increase safety in intersections, to detect incoming traffic and pedestrians (Enzweiler and Gavrila, 2009), to avoid collisions by, e.g., detecting inattentive drivers (Mandal et al., 2017), predicting driver manoeuvres (Oliver and Pentland, 2000; Jain et al., 2016), predicting pedestrian behaviour (Wu et al., 2018) or warning drivers when invading other lanes (Kim et al., 2016), and to assist drivers in adverse weather conditions (Tuma et al., 2020).

Smart cities depend on AI. There are numerous initiatives worldwide to realise the vision of achieving smart cities, including projects that analyse data captured by internet-of-things devices to measure and optimise energy consumption, recycling levels, pollution and refuse collection in cities (see, e.g., the Urbo[21] project by Telefonica). Urban safety is a critical area that contributes to the quality of life in cities. Machine learning methods have been applied to automatically detect and predict crime hotspots in cities (Bogomolov et al., 2014). The World Council on City Data provides the Open City Data Portal[22], which enables comparison of different metrics across multiple cities.

The newly created Urban AI[23] is a think tank that proposes ethical modes of governance and sustainable uses of AI in the context of cities. Its focus is to develop and deploy AI systems that embrace the diversity of cultures in the world, to contribute to making cities sustainable and vibrant and to preserve our social contract.

SDG 12 – Responsible consumption and production

This SDG aims at making an efficient use of energy and resources, improving access to basic services, building and maintaining infrastructures that are environmentally respectful and creating well-paid jobs with good working conditions.

It is related to many of the other SDGs, including the goals related to poverty, hunger, gender equality, clean water and sanitation, affordable and clean energy, decent work, industry innovation, climate action and reduced inequality.

Thus, only areas of AI impact that complement those described in the sections corresponding to the rest of SDGs are highlighted here.

In terms of contributing to a sustainable and responsible use of natural resources, beyond the impact of AI in the context of renewable energy and agriculture, data-driven AI methods can be used to forecast consumption patterns yielding more efficient production systems with minimal excess production, to automatically create land-use maps to provide a more accurate picture of the state and actual use of natural resources (Talukdar et al., 2020) or to estimate the impact of logging in forests to optimise the logging processes and ensure their sustainability (Hethcoat et al., 2019).

According to the UN Environment Programme[24], approximately one third of the food produced in the world for human consumption is wasted or gets lost, accounting for almost USD 1 000 million globally. Hence, reducing food waste is an important endeavour.

21 https://smartcity.telefonica.com
22 https://www.dataforcities.org/data-portal
23 https://urbanai.fr/
24 https://www.unep.org/thinkeatsave/get-informed/worldwide-food-waste (retrieved in July 2021)

Household waste can be minimised thanks to machine learning methods applied to internet-of-things captured data (Dubey et al., 2020) and the factors that determine household food waste behaviours can be automatically modelled and understood via data-driven AI methods (Setti et al., 2016). Regarding other types of waste generation, machine learning methods can be applied to, for example, predicting solid waste in municipalities and hence enabling more efficient waste planning (Kannangara et al., 2018).

AI enables smart production systems (Petrillo et al., 2020) that, e.g., minimise energy consumption, anticipate demand, detect manufacturing failures, automate tasks and perform systematic evaluations to detect areas of improvement. Digital twins can also be used to optimise production systems via machine learning methods (Min et al., 2019).

Finally, socially responsible consumption and disposal behaviour can be inferred automatically via machine learning algorithms (Song et al., 2018), This information could be used to foster and reinforce consumer behaviours that contribute to sustainability.

SDG 13 – Climate action

The potential of AI to help address the climate emergency is unquestionable (Rolnick et al., 2022). In fact, we will not be able to combat climate change without the help of AI.

Data-driven AI methods are used to model climate and weather, identify patterns and make accurate predictions based on the analysis of multi-dimensional weather and climate datasets (Haidar and Verma, 2018; Ham et al., 2019).

Deep learning models have been used to represent sub-grid processes in climate models (Rasp et al., 2018), to predict global temperature changes (Ise and Oba, 2019) and weather (Weyn et al., 2020) and to model weather phenomena, such as rainfall (Sonderby et al., 2020). In addition to being used to build more accurate climate models and predictions, AI methods can also be applied to improve state-of-the-art weather modelling systems by enabling, e.g., the separation of noise in climate observations (Barnes et al., 2019) or the automatic labelling of climate data (Chattopadhyay et al., 2020).

Extreme weather events are increasing in frequency and intensity due to climate change. AI has also proven to be a valuable ally to predict extreme weather events and their impacts, such as heavy rain (Lee et al., 2020), hail (Gagne II et al., 2019), wildfires (Radke et al., 2019), floods (Pastor-Escuredo et al., 2014) and earthquakes (Wang et al., 2020) and to enable a more efficient, prompt response to natural disasters. Autonomous drones have been used to monitor heat and prevent fires (Allison et al., 2016) and to search for survivors in floods and earthquakes (Arntz et al., 2016). In this domain, the AI for Disaster Response (IADR)[25] project at Qatar Computing Research Institute (QCRI) provides a free online tool that analyses social media messages related to emergencies, humanitarian crises and disasters. It uses machine learning to tag up thousands of messages per minute automatically, acting as an early warning system.

Beyond the direct application of AI techniques to model and predict climate, AI methods may be applied to industries or sectors that have a negative environmental impact to enable the reduction of greenhouse gas (GHG) emissions.

25 http://aidr.qcri.org

According to a report commissioned by Microsoft from PwC[26], the use of AI in environmentally related use cases could contribute up to USD 5.2 billion to the global economy by 2030 while reducing GHG emissions by 4%, which is equivalent to the 2030 estimated annual emissions of Japan, Canada and Australia combined.

Examples of such scenarios include using AI methods to yield more efficient energy generation – particularly in highly polluting sectors, such as the petrochemical sector (Han et al., 2019) – and to better manage the electric grid by means of accurate energy consumption forecasts (Almalaq and Edwards, 2017).

Data-driven AI approaches could also be used to accurately predict both carbon emissions and the factors contributing to them (Huang et al., 2019), thus enabling prompt action.

Moreover, there are major private and public institutional programmes aimed at exploring the use of AI to help combat climate change. In Europe, the Cordis database of funded research reveals over 100 funded projects related to AI and climate change, covering topics that range from the detection of extreme events to using AI to accelerating the transition of cities to carbon neutrality by means of AI. The European Space Agency has launched the Digital Twin Earth[27] to accelerate the identification of solutions to predict the impact of climate change. The European Lab for Learning and Intelligent Systems (ELLIS), one of Europe's leading AI associations, has launched a research programme on machine learning for Earth and climate sciences that aims to 'model and understand the Earth system via machine learning methods'.

In the private sector, most technology companies have deployed initiatives aimed at using AI to help combat climate change.

For example, the Canadian AI company ElementAI has launched a climate programme[28] as a cross-company initiative to support private and public sector efforts that tackle the climate crisis and help to build a sustainable and resilient future; Microsoft's AI for Earth initiative[29] is a 5-year USD 50 million endeavour to put Microsoft's cloud and AI tools in the hands of those working to solve global environmental challenges; in October 2020, Facebook announced a partnership with Carnegie Mellon University[30] to assist scientists in using AI tools to develop renewable energy and combat climate change; and Google's 'AI for social good' programme recently issued an open call[31] to organisations around the world to submit their ideas for how they could use AI to help address societal challenges. Among the 20 organisations that are supported by Google, there are projects related to using AI to estimate emissions of fossil fuel in power plants.

Conversely, data-driven AI systems have a significant CO_2 footprint contribution which would need to be systematically measured and mitigated, as described in the next section.

26 https://www.pwc.co.uk/sustainability-climate-change/assets/pdf/how-ai-can-enable-a-sustainable-future.pdf
27 https://www.esa.int/ESA_Multimedia/Images/2020/09/Digital_Twin_Earth
28 https://www.elementai.com/ai-for-climate
29 https://www.microsoft.com/en-us/ai/ai-for-earth
30 https://www.cnet.com/news/facebook-plans-to-use-ai-to-help-fight-climate-change/
31 https://ai.google/social-good/impact-challenge/

SDG 14 and SDG 15 – Life below water and life on land

Healthy oceans, seas and land are essential to ensure the necessary living conditions on our planet. However, the quality of the waters and terrestrial ecosystems has significantly worsened in the past decades.

Regarding waters, the acidity of the oceans – which is key for climate regulation and to sustain entire ecosystems – is expected to increase by 100% to 150% by the end of the 21st century, according to the current trends. Moreover, each year at least 14 million tons of plastic end up in the oceans[32], which is 80% of all marine debris, threatening life in the oceans, human health, food safety and quality and contributing to climate change. In terms of land, each year tens of millions of hectares of forests and natural terrestrial environments disappear because of logging, wildfires, desertification due to climate change and human intervention.

Advances in computer vision (object detection in images and videos, image classification) together with other data-driven AI methods can be used to automatically monitor the quality of our oceans and our land.

For example, deep learning methods have been used to estimate the volume of plastic debris in coastal areas (Martin et al., 2018), detect oil spills (Jiao et al., 2019) or estimate the CO_2 flux (which plays an important role in ocean acidification) in the oceans by analysing aerial images (Chen et al., 2019).

Similarly, deforestation (de Bem et al., 2020), forest quality (Zhao et al., 2019), aboveground biomass (Madhab Ghosh and Behera, 2018) and the risk of wildfires (Oulad Sayad et al., 2019) can be automatically estimated via deep neural networks applied on aerial images alone or combined with other data sources.

Illegal wildlife trade can be automatically detected by analysing social media data via machine learning methods (Di Minin et al., 2019) and wildlife species can be automatically classified using deep neural networks on aerial or motion-activated camera images (Tabak et al., 2019).

AI also enables **smart fishing**, which combats overfishing and fosters sustainable fishing by the automatic classification of species, biomass estimation, prediction of the quality of the water and of the behaviours of aquatic animals; together with **precision agriculture** and **smart farming**, as described in the SDG 2 section.

SDG 16 – Peace, justice and strong institutions

Conflicts, insecurity, weak institutions and limited access to justice are clear barriers for sustainable development. While overall the world population is healthier, better connected and wealthier than ever before, there are numerous places in the world where people's lives are severely impacted by wars and insecurity, a lack of access to fair justice systems and the violation of human rights.

32 https://www.iucn.org/resources/issues-briefs/marine-plastics

According to the International Committee of the Red Cross (ICRC)[33], it was estimated that in 2018 roughly 2 000 million people in the world were affected by conflict, violence or fragility and by 2030 these people will most likely endure extreme-poverty living conditions. Approximately 120 million people worldwide depend on humanitarian aid. A recent report by the UN refugee agency (UNHCR) estimates that a record number of 80 million people in the world were displaced in 2020 by wars and violence, including almost 30 million refugees.

Data-driven AI techniques can be used to accelerate and promote peace, safety, justice and stronger institutions. For example, institutional corruption can be detected automatically by data-driven machine learning algorithms applied to financial transactions (Chang-Tien and Siriat, 2004; West and Bhattacharya, 2016; Hajek and Henriques, 2017), public tender processes (Lismont et al., 2018) and government corruption (Adam and Fazekas, 2018). In addition, institutions may significantly increase their efficiency by applying AI techniques that enable the complete or partial automatisation of administrative tasks and processes (Etscheid, 2019).

Mathematical tools have been used to detect and predict crime for decades, and today many of such techniques include data-driven AI methods. Machine learning methods can be used to identify illegal drug trafficking (Baveja et al., 1997; Li et al., 2019) and crime hotspots in cities (Bogomolov et al., 2014); and semantic and natural language processing techniques have been applied to social media content to detect extremist behaviours (Johansson et al., 2017).

Without a doubt, the domain where AI is playing a crucial role is in the detection and prevention of cybercrime (Siddiqui et al., 2018), which, increasingly leverages AI methods as well.

33 https://www.icrc.org/en/document/global-trends-war-and-their-humanitarian-impacts-0

3. Limitations and barriers

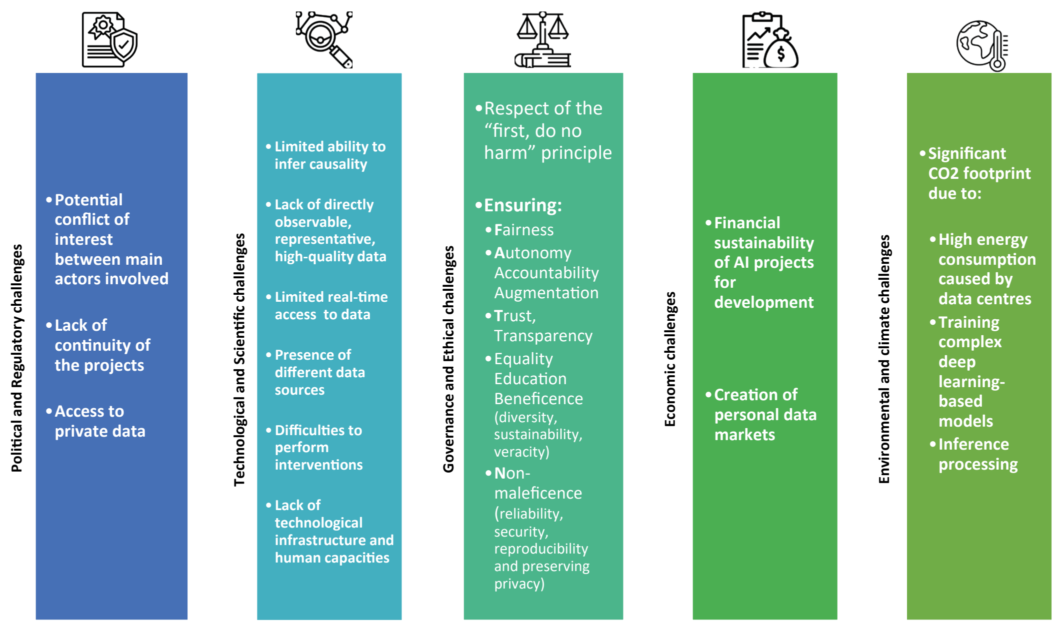
As previously described, the opportunities for data-driven AI methods to help us better measure and accelerate the achievement of the SDGs are paramount. Data- or evidence-informed decision-support systems, where machine-learning algorithms play a central role, have been referred to by some authors as 'human AI' systems (Letouze and Pentland, 2018). The concept of human AI systems is aligned with, but broader than, the 'human-centric AI' approach adopted by the European Commission.

Human-centric AI refers to designing and deploying AI systems that are aligned with core human values. Human AI systems add to this concept a vision where humans – alone or supported by AI systems – can make more informed, evidence-based decisions thanks to AI, supporting behaviours and decisions that are likely to yield positive outcomes while discouraging those that would not.

However, despite this immense opportunity, today's reality is far from this vision. To date, there have been few successful examples of real-world systems which **systematically** leverage large-scale data and AI methods to support humans in making better decisions for the public good. More than a decade into the (big) data revolution and half a decade into the 17 SDGs, major barriers remain, including difficulties related to the access and analysis of valuable data, which in many cases are privately held. In addition, there is lack of well-defined ethical principles, potential legal and regulatory barriers, technical limitations, competing commercial interests and the non-negligible carbon footprint of today data and computation-greedy AI systems.

In this context, there are five types of challenges and barriers that should be considered to ensure that AI is positively used for sustainable development in a safe and ethical manner. Most of these barriers are extensively described in (Letouze et al., 2019), a summary of which is presented next.

Figure 11-1: **Five types of challenges and barriers**



Political and regulatory challenges

The use of data-driven AI methods to support the achievement of the 17 SDGs would typically require the collaboration of three groups of actors: private organisations, public institutions and citizens. These three parties have potentially conflicting interests, constraints and priorities.

Thus, tackling barriers in this political dimension requires striking a balance between the private, public (e.g. governments) and individual interests, which implies understanding their underlying dynamics (Letouze et al., 2015).

The first group of stakeholders are private organisations, which in most legal frameworks are the legal owners or custodians of a significant portion of the data of interest, such as mobile network, financial transaction, satellite, energy consumption, employment or social media data.

The second group of stakeholders consists of the institutions that require access to the data to derive meaningful insights from it in the context of one or more of the 17 SDGs. Such institutions could be governmental – e.g. ministries, regional or local governments and national statistical offices (NSOs), academia or civil society organisations. In the case of NSOs, there is a strong movement related to using non-traditional data sources to compute official statistics, for example to estimate population density or poverty in a more efficient and frequent manner. However, there are very few examples of such a use in a systematic manner. While the potential value of data to help NSOs to build a more accurate picture of reality is clear, appropriate consultation and technological and governance safeguards are of critical importance to minimise the risks related to potentially breaking the citizens' trust, alienating private companies, breaching individual or group privacy and/or impacting the reputation of the institutions involved, particularly if the use of the data yields unintended negative consequences.

An example of reputational impact is the negative press received by a project launched by the Spanish National Statistics Institute, where they analysed aggregate insights derived from mobile network data from the three largest telcos in Spain without the knowledge or explicit consent of mobile users[34].

Incidentally, the project later became instrumental during the COVID-19 pandemic as it enabled teams of experts, working in collaboration with Spanish policy-makers, to model large-scale human mobility[35] and thus measure the compliance and impact of the confinement measures on the population's behaviour and the spread of COVID-19.

Another barrier in this regard relates to a potential lack of continuity of the projects, particularly if there are no guarantees that the necessary data and/or resources will be available over time. Specific regulations and multi-year partnerships could help address these concerns.

Finally, there are the individuals whose data is already analysed for many (commercial) purposes, in principle with their consent but possibly – or probably – not with their understanding. Key principles and rights – such as fairness, transparency, autonomy, veracity, reproducibility, reliability, control and privacy – would need to be demonstrably preserved. In Europe, the new proposal for a regulation on AI[36] addresses such principles and rights. It is a pioneering example of a legal framework

34 https://www.elconfidencial.com/tecnologia/2019-10-29/ine-operadoras-recopilacion-datos-moviles-proteccion-leyes_2304120/

35 https://infocoronavirus.gva.es/es/grup-de-ciencies-de-dades-del-covid-19-de-la-comunitat-valenciana

36 https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1623335154975&uri=CELEX%3A52021PC0206

on AI, formulating a risk-based regulation that positions Europe in a leading role globally with a human-centric approach.

Given the evident monetary value of the data, many authors and projects have proposed the creation of personal data markets (Staiano et al., 2014), where individuals would have control over their own data and decide whom to share it with, for which purposes and at what cost.

In terms of data privacy, the European General Data Protection Regulation (GDPR) and ePrivacy Directive place a premium on obtaining consent from users and require data controllers to implement the necessary measures to allow users to know and keep track of which data and for which purposes is being captured. Note that the GDPR allows for the lawful processing and sharing of privately held data in certain use cases, including the computation of statistics that are no longer considered personal data, which enables the analysis of data for research and policymaking purposes without requiring consent. Ideally, data-centric initiatives for sustainable development would be opted out by default (as opposed to opted in) and should be **opted out** at any time with ease by users, regardless of the intended purpose. A key challenge in this regard concerns obtaining such user consent: data subjects would need to be convinced that it is not only safe, but also in their interests to agree to make their data available for the purposes of public good – either by opting in or not opting out. Given concerns expressed in many countries, significant efforts still need to be undertaken to show evidence of the value – i.e. the positive social impact – that would result from the data analysis and to ensure that the technology and the methods behind it are sound and safe to generate public trust.

Thus, the next set of challenges concern developing the necessary technology and science to enable turning data into reliable, accurate and actionable knowledge.

Technological and scientific challenges

As previously illustrated, data-driven AI methods have tremendous potential to positively contribute to the achievement of the 17 SDGs. However, they are not exempt from technical limitations and risks that could yield negative (un)intended consequences impacting the lives of millions of people.

A particularly important type of risks concerns the computational violation of individual privacy that would result from the analysis of data via data-driven AI methods, even if the data is fully anonymised. Several research works have shown that human individual behaviours are unique. Thus, it is possible to de-identify an individual even when using anonymised and coarsened data (Blondel et al., 2013). Additional research efforts have focused on understanding the limits of human privacy and how it could be protected (Rocher et al., 2019). However, according to the current state-of-the-art, anonymising personal data is not sufficient to ensure the protection of individual privacy.

Differential privacy (Dwork and Roth, 2014) is a promising technical approach to preserving privacy. It consists of performing a statistical analysis of the datasets that may contain personal data, such that when observing the output of the data analysis, it is impossible to determine whether any specific individual's data was included or not in the original dataset. The behaviour of an algorithm applied to a differentially private dataset is guaranteed not to change when an individual is present or not in the dataset. This guarantee holds for any individual and for any dataset. Hence, regardless of the specific details of an individual's data (even if such an individual is an outlier), the guarantee of differential privacy should still hold.

Beyond privacy, there are additional technical and scientific challenges related to the analysis of data via AI methods that need to be addressed, including: the frequent lack of ground truth[37] that would enable the proper validation of supervised, data-driven AI models applied to tackle the 17 SDGs; difficulties with real-time access and analysis of the data, despite the fact that in many impactful use cases within the SDGs real-time access would be imperative (e.g. helping in the early detection of pandemics; predicting a natural disaster or supporting an immediate, proportionate response to natural disasters or emergencies, etc.); complexities derived from having to combine datasets from different sources; the difficulty of inferring causality – but rather identifying correlations – with the implications that this limitation may have for policy- and decision-making; the potential lack of representativeness of the available data, its generalisation capabilities and inherent biases; the lack of certification standards to guarantee the quality of the algorithms applied to the data, including non-discrimination guarantees; limited transparency, explainability and interpretability of complex machine-learning (notably deep learning-based) algorithms that might be applied to tackle a certain SDG; questions about the quality and veracity of the data; and difficulties in ensuring the reproducibility of results as they heavily depend on the data used to train the AI models and the parameter setting using when training.

Further technical challenges derive from the lack of the necessary technological infrastructure and human capacities to systematically store, analyse and effectively apply the insights derived from the data analysis.

Thus, appropriate investments in technical infrastructure and human resources are necessary to successfully realise the potential that data-driven AI methods have in the context of the 17 SDGs. Importantly, such resources would need to be allocated **prior** to the inception of any project. Given that the underlying reality is extremely complex and dynamic, projects would need multi-disciplinary teams of experts, including local talent, devoted fully to the projects on a continuous basis and located in the countries/regions where the projects are deployed.

Many of the scenarios where AI could enable and accelerate the achievement of the SDGs are in areas of consequential importance in people's lives, such as healthcare, education or immigration. Thus, the third critical set of barriers to overcome relate to the governance and ethical challenges derived from using data-driven methods to support human decision-making.

Governance and ethical challenges

Numerous governance challenges and ethical dilemmas emerge when applying data-driven AI methods to support decision-making processes and systems with impact on the lives of millions of people.

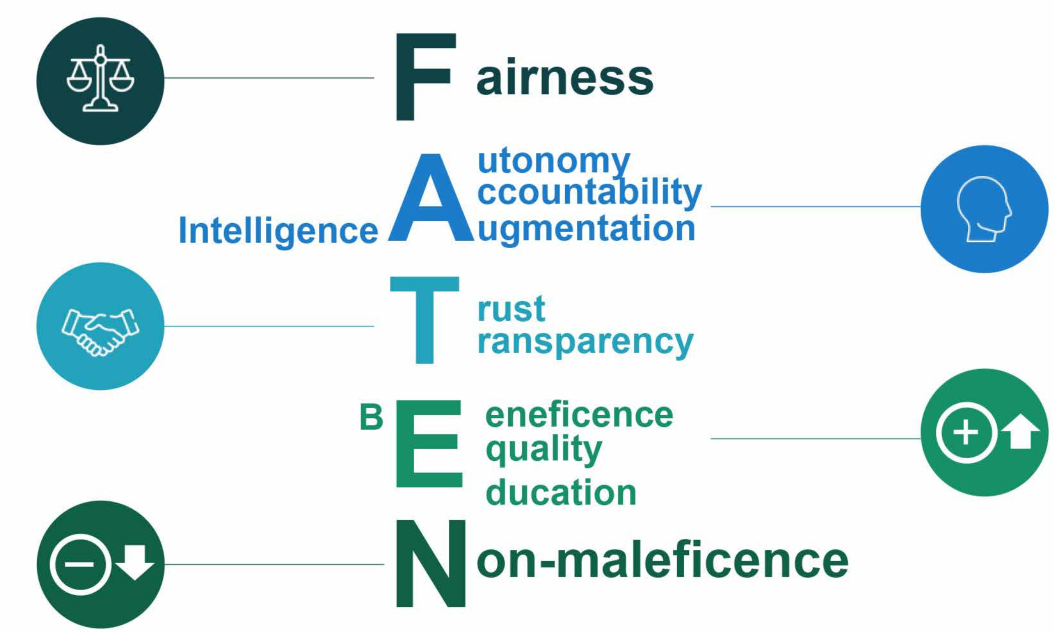
In this context, the 'first, do no harm' principle used in humanitarian scenarios is particularly relevant. Today, we have a much better understanding of the risks – even in the case of well-intentioned projects – that AI poses to human autonomy, privacy, equality, dignity, fairness and transparency than we did a decade ago. How can we be sure that applying AI to support the achievement of the 17 SDGs will do no harm? Will data-driven decisions used in this context be outside of our control? Who is accountable for such decisions, particularly in cases where they may be the result of analysing multiple datasets by complex software and social systems developed by potentially different parties? Will these systems include the necessary security mechanisms to prevent cyberattacks? What about the malicious use of

37 Ground truth refers to data obtained by direct observation (i.e. empirical evidence) as opposed to obtained by inference (e.g. by a machine learning algorithm). In supervised and semi-supervised machine learning, ground truth is needed to train and validate the models.

the data to serve the interests of non-democratic governments or organised crime? These are complex questions to tackle. Thus, ethical principles and standards of governance for data-driven initiatives for public good need to be both clearly defined and meticulously complied with.

In the past decade, many proposals have been published related to the ethical guidelines and principles to apply to the broad use of AI in society. Such proposals include the principles of the Menlo Report (Dittrich and Kenneally, 2012); the ethical principles included in the national AI strategies of over 50 countries in the world; the report by the European Commission for the development of trustworthy AI (European Commission, 2019); the OECD[38] principles for the development of AI; and the ethics in AI initiatives within professional organisations, such as the Institute of Electrical and Electronics Engineers (IEEE)[39] and the Association for Computing Machinery (ACM)[40]. Most of the previously proposed principles might be grouped using the FATEN (Oliver, 2019) acronym, which is an extension of the four basic principles of medical ethics (Gillon, 1994).

Figure 11-2: **The FATEN principles**



38 OECD, OECD Principles on AI, OECD, Paris, France, 2019.

39 The Institute of Electrical and Electronics Engineers, Ethically Aligned Design, IEEE, Piscataway, NJ.

40 Association for Computing Machinery, Code of Ethics and Professional Conduct, ACM, New York, NY, 2018.

F for fairness, i.e. without discriminating. Data-driven AI systems might discriminate for several reasons, including biases in the data used to train the algorithms, an inappropriate choice of an algorithm or model for the problem at hand, and a biased interpretation of the results. In the past 5 years, many highly impactful cases of algorithmic discrimination in social good areas have been made public, such as in the areas of criminal justice (Angwin et al., 2016), credit granting (Blattner and Nelson, 2021), human resources and hiring[41], education[42] and healthcare (Ledford, 2019). The detection and measurement of algorithmic bias and the development of fair machine-learning algorithms are fertile areas of research, as illustrated by the newly created ACM Conference on Fairness, Accountability and Transparency (ACM FAccT)[43], the ELLIS research programme on human-centric machine learning[44] or the newly created Institute of Humanity-centric AI[45] in Spain, which is one of the 34 ELLIS units launched since December of 2019.

A for autonomy, **accountability and intelligence augmentation**. The principle of autonomy is at the core of Western ethics. According to this principle, every person should be able to freely choose their own thoughts and actions. However, using data-driven AI methods today we can build computational models of our personalities, interests, tastes, needs, strengths/ weaknesses and behaviour that could be – and probably are – used to subliminally influence our decisions, choices and actions.

Thus, we should ensure that AI systems that have a direct or indirect impact on people's lives always respect the principles of human autonomy and dignity. The letter A in FATEN also stands for accountability, i.e. having clarity with respect to the attribution of responsibility related to the consequences of using AI methods.

Finally, A stands for intelligence augmentation – rather than replacement: AI systems should be used to support and augment human decision-making and not to replace humans altogether. This view is fully aligned with the previously described human AI concept.

T for trust and transparency. Trust is a fundamental pillar in our relationships, not only with other humans but also with/between institutions. Trust is typically established in the context of a specific purpose. We might trust an institution or an individual to be custodians of our money, but not necessarily of our children, for example. Trust emerges when three conditions are met:

- competence, i.e. the ability to successfully carry out the committed task;
- reliability, i.e. sustained competence over time;
- honesty and transparency. Hence, the T in FATEN is also for transparency.

A data-driven decision-making system is transparent when non-experts can observe it and easily understand it. Data-driven decision-making systems might not be transparent for at least three reasons (Burnell, 2016):

- **intentionally**, to protect the intellectual property of the system's creators;

41 https://www.reuters.com/article/us-amazon-com-jobs-automation-insight/amazon-scraps-secret-ai-recruiting-tool-that-showed-bias-against-women-idUSKCN1MK08G (retrieved in July 2021)

42 https://www.brookings.edu/blog/the-avenue/2019/09/26/ai-is-coming-to-schools-and-if-were-not-careful-so-will-its-biases/ (retrieved in July 2021)

43 https://facctconference.org/

44 https://ellis.eu/programs/human-centric-machine-learning

45 https://ellisalicante.org

- due to the **digital illiteracy** of their users, which prevents them from understanding how the models work;
- **intrinsically**, given that certain data-driven AI approaches – particularly deep learning methods – are extremely complex and difficult to interpret.

Transparent, interpretable and explainable AI models are necessary in most of the use cases related to the SDGs.

E for bEneficence and equality. The principle of bEneficence refers to maximising the positive impact in the use of data-driven decision-making algorithms with sustainability, diversity and veracity. We cannot obviate the environmental cost of technological development, particularly when it comes to AI algorithms, given their need for large amounts of data to learn from and massive amounts of computation needed to process and be trained by such data. As this is a fundamental challenge, it is described later in more detail.

Diversity is also of paramount importance, from at least two perspectives. First, by ensuring that the teams developing data-driven AI systems that are used for sustainable development are diverse, which is not the case today. Diversity is needed to maximise the probability of finding innovative solutions to the immense challenges that we face – as diverse teams tend to be more innovative than non-diverse teams[46] – and of developing inclusive solutions that would be relevant in the communities where they will be deployed. Second, by incorporating diversity criteria into the algorithms we design, we can minimise the prevalence of filter bubbles and echo-chamber effects (Geschke et al., 2019) which might contribute – at least partially – to the polarisation of public opinion.

We also need to ensure the **veracity** of the data that is and will be used for sustainable development scenarios. Today, we can algorithmically generate fake text, audio, photos and videos by means of deep neural networks (**deep fakes**) that are indistinguishable to humans from real content. If we are using data to inform decisions that impact the lives of millions of people, we need to ensure that such data is indeed truthful and a reflection of the underlying reality that the models are attempting to model.

E also stands for equity. The development and wide adoption of the internet and the World Wide Web during the Third and Fourth Industrial Revolutions has undoubtedly been key to democratising the access to information. However, the original principles of universal access to knowledge and the democratisation of technology are in danger today due to the extreme dominance of technology giants in the USA (Apple, Amazon, Microsoft, Facebook and Alphabet/Google) and China (Tencent, Alibaba, Baidu). Together, these non-European technology companies have a market value of more than USD 5 trillion and a US market share of more than 90% in internet searches (Google), more than 70% in social networking (Facebook) and 50% in e-commerce (Amazon). This market dominance leads to data dominance. In fact, most of these technology companies are data companies that earn thousands of millions of dollars by analysing and monetising the data they collect about their users. Note that a significant portion of the valuable human behavioural data that could be used in the context of the 17 SDGs is generated and captured by the services that these technology companies offer to their customers – services that address many aspects of our lives, including our entertainment, work, health and wellbeing, sports, education, transportation, travel, social connections, communication, shopping, information and product needs.

46 https://www.forbes.com/sites/forbesinsights/2020/01/15/diversity-confirmed-to-boost-innovation-and-financial-results/?sh=2e02e09bc4a6 (retrieved in July 2021)

In addition, in the 21st century we are observing a polarisation in the distribution of wealth, as described in the context of SDG 10. According to the Global Wealth Report 2019 by Credit Suisse (Shorrocks and Hechler-Fayd'herbe, 2019), the 100 richest people in the world are richer than the poorest 4000 million. This accumulation of wealth in the hands of very few has been at least partially attributed to technology and the Fourth Industrial Revolution. With the agrarian revolution in the Neolithic and for thousands of years afterwards, wealth was associated with ownership of land. Following the First Industrial Revolution, wealth was a result of owning capital assets, such as machines and factories. Today, one could argue that data – and more importantly, the ability to leverage it and make sense of it – is the asset that generates the most wealth, generating what is known as the data economy. Thus, if our goal is to maximise the positive impact of this abundance of data, we should develop and promote new models of data ownership, management, exploitation and regulation. Data used for sustainable development could contribute to both better measuring and reducing inequality (see the SDG 10 section).

N for non-maleficence. This means minimising the negative impact that might result from the use of data-driven AI methods. Within this principle, we include being prudent in the development of AI-based systems and highlight the need to:

- provide reliability and reproducibility guarantees
- maximise data security
- always preserve people's privacy, as previously discussed.

Once agreed upon, the ethical principles will need to be published, implemented and complied with in practice through appropriate governance. The roles and responsibilities of each of the three actors – namely, companies, public and non-profit institutions, and people – need to be clearly defined, understood and accepted.

Given the multi-disciplinary nature of data-driven projects for public good, a combination of experts from different disciplines – ranging from AI to social sciences and humanities experts – is required for the projects to succeed. This multi-disciplinary nature adds complexity, but it is necessary and particularly beneficial when it comes to the definition of, and compliance with, ethical principles since the teams would include ethicists.

Moreover, external oversight bodies are also desirable to ensure that the ethical principles are complied with. Data stewards[47] have been proposed in recent years for this purpose. Data stewards are individuals or groups of individuals within an organisation who are responsible for the quality and governance of data in data-driven projects that take place in their organisations, including initiatives for social good. Alternative options include the creation of external oversight ethics boards and/or the appointment of a chief ethics officer with oversight and auditing responsibilities to ensure that projects with social impact are aligned with the pre-defined ethical principles and human values of the societies where they are developed.

Another approach to ensure compliance with the ethical principles agreed upon is by requiring the use of open processes, code and systems, by deploying regulation that requires the ethical principles to be followed and/or by fostering knowledge sharing, including collaborations with academia and civil society organisations.

In addition, understanding the cultural and social characteristics of the societies where the projects are deployed is a must. Therefore, working with local institutions and the civil society of the

47 Verhulst, Steefaan G., The Three Goals and Five Functions of Data Stewards: Data Stewards: a new Role and Responsibility for an AI and Data Age, Medium and The Data Stewards Network, New York, NY, 2018.

countries where the projects will take place is absolutely necessary, as previously highlighted.

In sum, any use of data-driven AI methods for sustainable development should be open, transparent, accountable and always respectful of human values and rights. The results of the projects should be auditable regarding their purpose, accuracy, reproducibility, veracity and fairness, particularly given the fact that the use of AI in the context of the 17 SDGs is an overly broad, ambitious, long-term and multi-institutional endeavour.

Even when the political, technological and ethical challenges are addressed, projects that leverage data-driven AI for public good might fail if they lack a sustainable financial model. Hence, the fourth type of challenges is of an economic nature

Economic challenges

Many initiatives that have applied data-driven AI methods to support the achievement of the 17 SDGs have been in the form of pilots. Questions inevitably arise about the generalisation capability and the financial sustainability of such projects.

Several companies that have been at the forefront of the 'data and AI for social good' movement over the past 10-15 years – particularly telecommunication operators such as Telefonica and Orange – have also invested in developing their own related commercial offerings. Recently, technology companies have joined the movement of leveraging their data for purposes related to social good and sustainable development, including Facebook[48] and Google[49]. In developed countries, the granularity, volume and richness of human behavioural data collected by technology companies is undisputed.

The commercial solutions developed by these companies provide user and client pre-computed indicators derived from aggregate customer data, such as population density and mobility estimations. These estimations are also valuable in the context of the 17 SDGs.

Given this overlap between commercial and public interest purposes, companies might resist the development of solutions for sustainable development as they could cannibalise their existing data-driven services. However, there are important considerations to be made in the context of data-driven projects to support the 17 SDGs. As described in the previous section, many of the data-driven AI systems used in the context of the 17 SDGs would need to comply with strict regulations, scientific rigor, ethical frameworks and governance models appropriate to the fact that they will be used for public-good purposes. Such requirements might not apply to the same extent in the case of proprietary, commercial services.

Thus, the value proposition related to projects for sustainable development would need to be defined such that it would be complementary to, and not in competition with, the existing commercial products offered by these companies. Moreover, a sustainable financial model is needed for the projects to succeed beyond their pilot phase. Even if they are for social good, they do not necessarily need to be for free, depending on the use case. This economic dimension is thoroughly discussed in the report by the European Commission's High-level Expert Group on Business-to-Government Data Sharing[50] and in Letouze et al. (2019).

48 https://dataforgood.fb.com/

49 https://cloud.google.com/data-solutions-for-change/

50 https://digital-strategy.ec.europa.eu/en/library/meetings-expert-group-business-government-data-sharing

An additional question related to economic challenges is whether people should be able to sell their own data on a personal data market. The cases for and against such a model can be and have been argued convincingly (Speikermann et al., 2015).

Finally, as previously explained, data-driven AI methods require massive amounts of data and computation, with a potentially significant CO_2 footprint. Thus, the final set of challenges concern the environmental and climate impact of the development and wide deployment of AI in our societies.

Environmental and climate challenges

AI has tremendous potential to help us address the climate emergency (SDG 13), as previously described. However, AI is also a non-negligible contributor to GHG emissions (Garcia-Martin et al., 2019) given the high energy needs of today's data-driven methods. This is for a variety of reasons.

First, a significant factor in the carbon emissions due to the development and deployment of AI systems stems from the energy consumption caused by data centres, given that data centres are a key element in the AI pipeline, hosting the vast amounts of data needed to train and use sophisticated machine learning models. On the positive side, while the demand and size of data centres has been growing steadily in the past years, their energy consumption has not grown proportionally, thanks to the development of energy-efficient infrastructure and hardware (Lei and Masanet, 2021), the use of renewable energy sources and even the application of AI methods to reduce their energy consumption[51].

Nonetheless, a report by the European Commission[52] estimates a 28% growth in the energy consumption of data centres in Europe between 2018 and 2030. The report includes several recommendations to minimise the GHG emissions attributable to data centres, including recommendations relative to information/awareness raising measures, transparency initiatives, the development of standards and guidelines for energy-efficient cloud computing, soft-certification schemes, the inclusion of energy-consumption labels, the establishment of regulations for the non-material component of data centres and cloud services and of minimum criteria for energy-efficiency in newly built data centres in the EU, policy-awareness raising and the definition of green public procurement criteria and knowledge sharing.

Secondly, we need to consider the GHG emissions due to training complex data-driven AI (deep learning-based) models. OpenAI researchers Dario Amodey and Danny Hernandez estimate that since 2012 the amount of computing power used to train the largest data-driven AI models has been increasing exponentially, with a 3.4-month doubling time (faster than Moore's Law 2-year doubling period)[53]. A recent study (Strubell et al., 2019) found that the carbon footprint of training just one state-of-the-art deep-learning model to perform natural language processing tasks was equivalent to the amount of carbon dioxide that the average American produces in 2 years. In fact, the energy costs associated with training sophisticated machine learning algorithms has traditionally been the most expensive task when using AI to solve real-world problems.

51 https://research.google/pubs/pub42542/ (retrieved in July 2021)

52 https://digital-strategy.ec.europa.eu/en/library/energy-efficient-cloud-computing-technologies-and-policies-eco-friendly-cloud-market (retrieved in July 2021)

53 https://openai.com/blog/ai-and-compute/ (retrieved in July 2021)

Third, we have the GHG emissions caused by inference processing, i.e. using a trained data-driven AI model on new, unseen data, which has grown tremendously, representing 80-90% of the cost of neural networks, according to Nvidia.

While the growth in AI-related energy consumption is partly mitigated by hardware-aware models (Marculescu et al., 2018) and energy-efficient hardware that has been specifically designed to train data-driven AI models (deep neural networks) – such as FPGAs and ASICs, there is an urgent need to implement systematic and accurate measurements of the carbon footprint of AI systems to ensure that their positive impact is larger than their environmental cost, creating what some authors refer to as green AI (Schwartz et al., 2020). Note that understanding the carbon footprint of AI entails more than measuring the energy consumption of data centres, model training and inference activities. In fact, given the broad set of use cases where AI is having an impact and the complex, multi-layered proprietary production process of AI systems, assessing the carbon footprint of AI is certainly challenging.

Thus, several authors have recently focused on assessing the carbon footprint related to AI research and have built tools to ease its measurement (see e.g. the **experiment impact-tracker** (Henderson et al., 2020) and the **machine learning emissions** calculator (Lacoste et al., 2019) projects), given that research methods and results are generally openly available via scientific publications. Even in this case, there is a lack of systematic carbon emission measurements of AI research (Cowls et al., 2021).

While these recent works are promising and reflect an increased interest in ensuring that the GHG emissions due to AI are minimised, current practices both in research and industry are far from what these research papers propose.

From the areas of opportunity highlighted in Section 2 and the challenges just described, several recommendations emerge to accelerate the positive impact of AI on the SDGs (and thus on our societies and the planet itself) while minimising its potential negative impact.

4. Recommendations

In this section, I formulate key recommendations related to each of the barriers described above to accelerate the achievement of the SDGs thanks to AI.

Data. Data is a fundamental asset for the SDGs. First, as a digital representation of an underlying reality that we need to measure so that we can assess the level of achievement of each SDG. Second, as a key element to enable the development of data-driven AI methods to find patterns, make predictions, detect outliers, automate tasks, etc. Thus, first and foremost, we should develop ambitious programmes to enable access to high-quality, relevant data, and invest in secure frameworks that provide access to data and/or actionable insights derived from the data, even when the data is privately held. Support for more effective and accessible use of existing datasets is also important, as many existing datasets are not properly leveraged due to difficulty of access. Finally, data gaps would need to be identified and actions to fill them would need to be taken.

R&D. The opportunities in the intersection of AI and the SDGs are immense. However, most of these opportunities still entail significant investment in research. Hence, ambitious and sustained investment in research and innovation on the topic of AI for sustainable development would be of paramount importance if we want to leverage the potential of AI to help us to achieve the SDGs. Moreover, many of the promising results have been achieved in small-scale studies with offline data. There is a lack of large-scale, real-world evidence of the systematic and sustained use of AI to support the achievement of the SDGs. Therefore investments to leverage research and pilot results and deploy them in the wild over long time periods are necessary.

Vulnerability analysis. As societies increasingly rely on AI systems, it becomes important to carry out vulnerability analyses of such dependencies and to deploy redundancy and backup systems to be able to gracefully recover in case of failures, malfunctioning or hacking of the AI systems.

Governance. Promote corporate governance and engagement models – including the appointment of data stewards, chief ethics officers and oversight boards – in public administrations, NGOs and private companies working on AI for SDG projects. Adopt and evaluate compliance with ethical frameworks to ensure that the use of the AI systems deployed to support the SDGs are aligned with the FATEN framework previously described.

Openness and transparency. Develop open, participatory systems and standards to enable data- and knowledge sharing across companies, sectors and countries with inputs and oversights from relevant stakeholders.

Education. Invest ambitiously in education, capacity building and outreach to obtain the support and contributions from all private and public actors (including citizens) in Europe and beyond. The development of local capacities would be of paramount importance to ensure the sustainability and actual impact of the projects.

Multi-disciplinary projects and diverse teams. Foster multi-disciplinary projects where AI experts collaborate closely with domain experts and policy makers to maximise the opportunities to have impact.

Best practices and centres of excellence. The recently created NAIXUS (https://ircai.org/global-network-of-ai-excellence-centers/) global network of AI excellence centers is a promising example of a multi-institutional, international effort to bring Sustainable Development to the AI research agenda. Support local and regional centres of excellence that leverage data and AI for the SDGs in key cities in Europe. Identify and share best practices.

Incentives and regulation. Implement incentives, remove regulatory barriers and define enabling regulations with the aim of accelerating the use of AI for sustainable development following ethical principles that are complied with and accounted for. Invest in the necessary infrastructure and capacities to audit the compliance of AI systems with such ethical principles.

Sustainable AI. Invest in and incentivise sustainable AI systems. Develop regulations that require the systematic measurement and publishing of their carbon footprint.

Funding. Provide necessary funding to enable a financial model for AI for sustainable development projects. Foster public-private long-term collaborations to accelerate the achievement of the SDGs by leveraging AI methods.

5. Conclusion

We live in a time of prosperity, but we also face tremendous global challenges that threaten our own existence as a species – from poverty and hunger to climate change and the destruction of entire ecosystems. Effectively tackling these challenges requires an ambitious and coordinated commitment from most nations in the world, as reflected by the 17 SDGs. AI – and specifically data-driven AI methods – has the potential to significantly accelerate the achievement of the SDGs. However, to realise such a potential, we need to address five types of barriers related to the use of AI in this context: institutional, technical, ethical, financial and environmental. It is therefore of paramount importance to invest ambitiously in tackling such barriers so we can effectively leverage the power of AI to help us improve living conditions in our planet. An opportunity that we must not miss, as it might be our best (and last) chance to ensure not just the sustainability of our societies and our planet but our own survival. As Theodore Roosevelt said: 'A revolution is sometimes necessary'. As there is no planet B, I invite you to join the 'AI for sustainable development' revolution.

References

Abdul Hamid, S. S., Admodisastro, N., Manshor, N., Kamaruddin, A., Ghani, A. A. A. (2018), *Dyslexia adaptive learning model: student engagement prediction using machine learning approach*, In International Conference on Soft Computing and Data Mining, pp. 372-384. Springer, Cham.

Adam, I., and M. Fazekas (2018), *Are emerging technologies helping win the fight against corruption in developing countries?*, Pathways for Prosperity Commission, Background Paper Series, (21).

Adegbosin, A. E., Stantic, B., Sun, J. (2019), 'Predicting under-five mortality across 21 low and middle-income countries using deep learning methods', *medRxiv*, 19007583.

Allison, R. S., Johnston, J. M., Craig, G., Jennings, S. (2016), 'Airborne optical and thermal remote sensing for wildfire detection and monitoring', *Sensors*, 16(8), 1310.

Almalaq, A., Edwards, G. (2017), *A review of deep learning methods applied on load forecasting*, In 2017 16th IEEE international conference on machine learning and applications (ICMLA), pp. 511-516. IEEE.

Angwin, J., Larson, J., Mattu, S., Kirchner, L. (2016), *Machine bias: There's software used across the country to predict future criminals. And it's biased against blacks*, ProPublica.

Arntz, M., T. Gregory, U. Zierahn, (2016), *The Risk of Automation for Jobs in OECD Countries: A Comparative Analysis*, OECD Social, Employment and Migration Working Papers, No. 189, OECD Publishing, Paris, https://doi.org/10.1787/5jlz9h56dvq7-en.

Autor, D. (2010), *The polarization of job opportunities in the US labor market: Implications for employment and earnings*, Center for American Progress and The Hamilton Project(6), pp. 11-19.

Badr, G., Klein, L. J., Freitag, M., Albrecht, C. M., Marianno, F. J., Lu, S., … Hamann, H. F. (2016), 'Toward large-scale crop production forecasts for global food security', *IBM Journal of Research and Development*, 60(5/6), pp. 5-1.

Bao, Y., Tang, Z., Li, H., Zhang, Y. (2019), 'Computer vision and deep learning–based data anomaly detection method for structural health monitoring', *Structural Health Monitoring*, 18(2), pp. 401-421.

Barlow, M. (2016), *AI and medicine: Data-driven strategies for improving healthcare and saving lives*, O'Reilly Media.

Barnes, E. A., Hurrell, J. W., Ebert Uphoff, I., Anderson, C., Anderson, D. (2019), 'Viewing forced climate patterns through an AI lens', *Geophysical Research Letters*, 46(22), pp. 13389-13398.

Baveja, A., Caulkins, J. P., Liu, W., Batta, R., Karwan, M. H. (1997), 'When haste makes sense: Cracking down on street markets for illicit drugs', *Socio-Economic Planning Sciences*, 31(4), pp. 293-306.

Blattner, L., Nelson, S. (2021), *How costly is noise? data and disparities in consumer credit*, arXiv preprint arXiv:2105.07554.

Blondel, Vicent D., De Montjoye Y-A, Hidalgo, C. A., V. Michel, (2013), *Unique in the Crowd: The privacy bounds of human mobility*, Belgium: "Communauté française de Belgique" on Information Retrieval in Time Evolving Networks

Blumenstock, J., Cadamuro, G., On, R. (2015), 'Predicting poverty and wealth from *mobile phone metadata', Science, 350(6264),* pp. 1073-1076.

Bogomolov, A., Lepri, B., Staiano, J., Oliver, N., Pianesi, F., Pentland, A. (2014), *Once upon a crime: towards crime prediction from demographics and mobile data*, In Proceedings of the 16th international conference on multimodal interaction (pp. 427-434)

Bowles, J. (2014), *The computerisation of European jobs*, Bruegel, https://www.bruegel.org/2014/07/the-computerisation-of-european-jobs/

Brentan, B. M., Luvizotto Jr., E., Herrera, M., Izquierdo, J., Pérez-García, R. (2017), 'Hybrid regression model for near real-time urban water demand forecasting', *Journal of Computational and Applied Mathematics*, (309), pp. 532-541, https://doi.org/10.1016/j.cam.2016.02.009

Burrell, J. (2016), 'How the machine 'thinks': Understanding opacity in machine learning algorithms', *Big Data & Society*, 3(1), 2053951715622512.

Centellegher, S., Miritello, G., Villatoro, D., Parameshwar, D., Lepri, B., Oliver, N. (2018), 'Mobile money: Understanding and predicting its adoption and use in a developing economy', *Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies*, 2(4), pp. 1-18.

Chandy, S. E., Rasekh, A., Barker, Z. A., Campbell, B., Shafiee, M. E. (2017), *Detection of cyber-attacks to water systems through machine-learning-based anomaly detection in SCADA data*, In World Environmental and Water Resources Congress 2017, pp. 611-616.

Chang-Tien, K. Y. L., Sirirat, S. (2004), *Survey of fraud detection techniques in networking, sensing and control*, In IEEE International Conference(2), pp. 749-754).

Chattopadhyay, A., Hassanzadeh, P., Pasha, S. (2020), 'Predicting clustered weather patterns: A test case for applications of convolutional neural networks to spatio-temporal climate data', *Scientific reports*, 10(1), pp. 1-13.

Chen, S., Hu, C., Barnes, B.B, Wanninkhof, R., Cai, W.J, Barbero, L., Pierrot, D., (2019), 'A machine learning approach to estimate surface ocean pCO_2 from satellite measurements', *Remote Sensing of Environment*, (228), pp 203-226, https://doi.org/10.1016/j.rse.2019.04.019

Clifton, L., Clifton, D. A., Pimentel, M. A., Watkinson, P. J., Tarassenko, L. (2013), 'Predictive monitoring of mobile patients by combining clinical observations with data from wearable sensors', *IEEE journal of biomedical and health informatics*, 18(3), pp. 722-730.

Collins, F. S., Varmus, H. (2015), 'A new initiative on precision medicine', *New England journal of medicine*, 372(9), pp. 793-795.

Cowls, J., Tsamados, A., Taddeo, M., Floridi, L. (2021), 'The AI gambit: leveraging artificial intelligence to combat climate change – opportunities, challenges, and recommendations', *Ai & Society*, pp. 1-25.

Cruz, E., Vaca, C., Avendaño, A. (2019), *Mining top-up transactions and online classified ads to predict urban neighborhoods socioeconomic* *status*, In 2019 IEEE International Conference on Big Data (Big Data), pp. 4055-4062. IEEE.

Dargam, F., Perz, E., Bergmann, S., Rodionova, E., Sousa, P., Souza, F. A. A., … Bonachela, P. Z. (2020), *Supporting operational decisions on desalination plants from process modelling and simulation to monitoring and automated control with machine learning*, In International Conference on Decision Support System Technology, pp. 150-164.

David, J.M., and K. Balakrishnan (2010), 'Machine Learning Approach for Prediction of Learning Disabilities in School-aged Children', *Int. Journal of Computer Applications*, 9(11), pp. 975-8887

De Bem, P. P., de Carvalho Junior, O. A., Fontes Guimarães, R., Trancoso Gomes, R. A. (2020), 'Change detection of deforestation in the Brazilian Amazon using landsat data and convolutional neural networks', *Remote Sensing*, 12(6), pp. 901.

De Fauw, J., Ledsam, J. R., Romera-Paredes, B., Nikolov, S., Tomasev, N., Blackwell, S., … Ronneberger, O. (2018). Clinically applicable deep learning for diagnosis and referral in retinal disease. *Nature medicine*, 24(9), pp. 1342-1350.

Di Minin, E., Fink, C., Hiippala, T., Tenkanen, H. (2019), 'A framework for investigating illegal wildlife trade on social media with machine learning', *Conservation Biology*, 33(1), pp. 210.

Dia, H. (2001), 'An object-oriented neural network approach to short-term traffic forecasting', *European Journal of Operational Research*, 131(2), pp. 253–261

Dia, H., Rose, G. (1997), 'Development and evaluation of neural network freeway incident detection models using field data', *Transportation Research Part C: Emerging Technologies*, 5(5), pp. 313-331.

Dogo, E. M., Nwulu, N. I., Twala, B., Aigbavboa, C. (2019), 'A survey of machine learning methods applied to anomaly detection on drinking-water quality data', *Urban Water Journal*, 16(3), pp. 235-248.

Doshi, R., Falzon, D., Thomas, B. V., Temesgen, Z., Sadasivan, L., Migliori, G. B., Raviglione, M. (2017), 'Tuberculosis control, and the where and why of artificial intelligence', *ERJ Open Research*, 3(2).

Dubey, S., Singh, P., Yadav, P., Singh, K. K. (2020), 'Household waste management system using IoT and machine learning', *Procedia Computer Science*, 167, pp. 1950-1959.

Dunis, C., Middleton, P., Karathanasopolous, A., Theofilatos, K. (2016), *Artificial intelligence in financial markets*, London: Palgrave Macmillan.

Dwork, C., Roth, A. (2014), 'The algorithmic foundations of differential privacy', *Found. Trends Theor. Comput. Sci.*, 9(3-4), pp. 211-407.

Enzweiler, M., Gavrila, D. M. (2008), 'Monocular pedestrian detection: Survey and experiments', *IEEE transactions on pattern analysis and machine intelligence*, 31(12), pp. 2179-2195.

Esteva, A., Kuprel, B., Novoa, R. A., Ko, J., Swetter, S. M., Blau, H. M., Thrun, S. (2017), 'Dermatologist-level classification of skin cancer with deep neural networks', *Nature*, 542(7639), pp. 115-118.

Etscheid, J. (2019),'Artificial Intelligence in Public Administration. Int. Conf. on Electronic Government (EGOV)', *Lecture Notes in Comptuer Science*, 11685, pp 248-261.

European Commission, Directorate-General for Communications Networks, Content and Technology, (2019). *Ethics guidelines for trustworthy AI*, Publications Office. https://data.europa.eu/doi/10.2759/177365

FAO (2017), *Smart farming is key for the future of agriculture*, https://www.fao.org/family-farming/detail/es/c/897026

Faulkner, A., Cebul, K., McHenry, G. (2014), *Agriculture gets smart: the rise of data and robotics*, Cleantech Group: San Francisco, CA, USA.

Fedor, P., Vaňhara, J., Havel, J., Malenovský, I., Spellerberg, I. (2009), 'Artificial intelligence in pest insect monitoring', *Systematic Entomology*, 34(2), pp. 398-400.

Feldman, T., Peake, A. (2021), *End-To-End Bias Mitigation: Removing Gender Bias in Deep Learning*, arXiv preprint arXiv:2104.02532.

Fernandez, M. G., Tokuhiro, A., Welter, K., Wu, Q. (2017), 'Nuclear energy system's behavior and decision making using machine learning', *Nuclear Engineering and Design*, 324, pp. 27-34.

Frank, M. R., Sun, L., Cebrian, M., Youn, H., Rahwan, I. (2018), 'Small cities face greater impact from automation', *Journal of the Royal Society Interface*, 15(139), 20170946.

Frey, C. B., Osborne, M. A. (2017), 'The future of employment: How susceptible are jobs to computerisation?', *Technological forecasting and social change*, 114, pp. 254-280.

Froehlich, J., Neumann, J., and N. Oliver (2009), *Sensing and predicting the pulse of the city through shared bicycling*, IJCAI'09: Proceedings of the 21st international joint conference on Artificial Intelligence, pp. 1420–1426

Gagne II, D. J., Haupt, S. E., Nychka, D. W., Thompson, G. (2019), 'Interpretable deep learning for spatial analysis of severe hailstorms', *Monthly Weather Review*, 147(8), pp. 2827-2845.

Gandhi, N., Armstrong, L. (2016), *Applying data mining techniques to predict yield of rice in humid subtropical climatic zone of India*, In 2016 3rd International Conference on Computing for Sustainable Global Development (INDIACom), pp. 1901-1906. IEEE.

García-Martín, E., Rodrigues, C. F., Riley, G., Grahn, H. (2019), 'Estimation of energy consumption in machine learning', *Journal of Parallel and Distributed Computing*, 134, pp. 75-88.

Geschke, D., Lorenz, J., Holtz, P. (2019), 'The triple-filter bubble: Using agent based modelling to test a meta theoretical framework for the emergence of filter bubbles and echo chambers', *British Journal of Social Psychology*, 58(1), pp. 129-149.

Gillon, R. (1994), 'Medical ethics: four principles plus attention to scope', *Bmj*, 309(6948), pp. 184.

Gopalakrishnan, K., Khaitan, S. K., Choudhary, A., Agrawal, A. (2017), 'Deep convolutional neural networks with transfer learning for computer vision-based data-driven pavement distress detection', *Construction and building materials*, 157, pp. 322-330.

Granata, F., Papirio, S., Esposito, G., Gargano, R., De Marinis, G. (2017), 'Machine learning algorithms for the forecasting of wastewater quality indicators', *Water*, 9(2), pp. 105.

Grobart, S. (2012), *Big dairy enters the era of big data*, https://www.bloomberg.com/news/articles/2012-10-18/big-dairy-enters-the-era-of-big-data

Guo, J., Li, B. (2018), 'The application of medical artificial intelligence technology in rural areas of developing countries', *Health equity*, 2(1), pp. 174-181.

Haidar, A., Verma, B. (2018), 'Monthly rainfall forecasting using one-dimensional deep convolutional neural network', *IEEE Access*, 6, pp. 69053-69063.

Hajek, P., Henriques, R. (2017), 'Mining corporate annual reports for intelligent detection of financial statement fraud–A comparative study of machine learning methods', *Knowledge-Based Systems*, 128, pp. 139-152

Ham, Y. G., Kim, J. H., Luo, J. J. (2019), 'Deep learning for multi-year ENSO forecasts', *Nature*, 573(7775), pp. 568-572.

Han, Y., Wu, H., Jia, M., Geng, Z., Zhong, Y. (2019), 'Production capacity analysis and energy optimization of complex petrochemical industries using novel extreme learning machine integrating affinity propagation', *Energy Conversion and Management*, (180), pp. 240-249.

Held, M., Küng, L., Çabukoglu, E., Pareschi, G., Georges, G., Boulouchos, K. (2018), *Future mobility demand estimation based on sociodemographic information: A data-driven approach using machine learning algorithms*, In 18th Swiss Transport Research Conference (STRC 2018). STRC.

Henderson, P., Hu, J., Romoff, J., Brunskill, E., Jurafsky, D., Pineau, J. (2020), 'Towards the systematic reporting of the energy and carbon footprints of machine learning', *Journal of Machine Learning Research,* 21(248), pp. 1-43.

Hethcoat, M.G., Edwards, D.P., Carreiras, J.M.B, Bryant, R.G., França, F.M and S. Quegan (2019), 'A machine learning approach to map tropical selective logging', *Remote Sensing of Environment*, (221), pp 569-582, https://doi.org/10.1016/j.rse.2018.11.044

Holley, P. (2018), *The World Bank's latest tool for fighting famine: Artificial intelligence*, The Washington Post, 23.

Hosein, S., Hosein, P. (2017), *Load forecasting using deep neural networks*, In 2017 IEEE Power Energy Society Innovative Smart Grid Technologies Conference (ISGT), pp. 1-5. IEEE. https://irp-cdn.multiscreensite.com/be6d1d56/files/uploaded/SDSN%20Health%20Solutions.pdf 2019

Huang, W., Song, G., Hong, H., Xie, K. (2014), 'Deep architecture for traffic flow prediction: deep belief networks with multitask learning', IEEE Transactions on *Intelligent Transportation Systems*, 15(5), pp. 2191-2201.

Huang, Y., Shen, L., Liu, H. (2019), 'Grey relational analysis, principal component analysis and forecasting of carbon emissions based on long short-term memory in China', *Journal of Cleaner Production*, 209, pp. 415-423.

Iqbal, J., Al-Zahrani, A., Alharbi, S. A., Hashmi, A. (2019), 'Robotics inspired renewable energy developments: prospective opportunities and challenges', *IEEE Access*, 7, pp. 174898-174923.

Ise, T., Oba, Y. (2019), 'Forecasting climatic trends using neural networks: an experimental study using global historical data', *Frontiers in Robotics and AI*, 32.

Jain, A., Singh, A., Koppula, H. S., Soh, S., Saxena, A. (2016), *Recurrent neural networks for driver activity anticipation via sensory-fusion architecture*, In 2016 IEEE International Conference on Robotics and Automation (ICRA), pp. 3118-3125.

Jang, J. Y., Lee, S., Lee, B. (2019), 'Quantification of gender representation bias in commercial films based on image analysis', *Proceedings of the ACM on Human-Computer Interaction*, 3(CSCW), pp. 1-29.

Jean, N., Burke, M., Xie, M., Davis, W. M., Lobell, D. B., Ermon, S. (2016), 'Combining satellite imagery and machine learning to predict poverty', *Science*, 353(6301), pp. 790-794.

Jha, S. K., Bilalovic, J., Jha, A., Patel, N., Zhang, H. (2017), 'Renewable energy: Present research and future scope of Artificial Intelligence', *Renewable and Sustainable Energy Reviews*, 77, pp. 297-317.

Jiao, Z., Jia, G., Cai, Y. (2019), 'A new approach to oil spill detection that combines deep learning with unmanned aerial vehicles', *Computers & Industrial Engineering*, 135, pp. 1300-1311.

Johansson, F., Kaati, L., Sahlgren, M. (2017), *Detecting linguistic markers of violent extremism in online environments*, In Artificial intelligence: Concepts, methodologies, tools, and applications, pp. 2847-2863. IGI Global.

Kagan, D., Chesney, T., Fire, M. (2020), 'Using data science to understand the film industry's gender gap', *Palgrave Communications*, 6(1), pp. 1-16.

Kagashe, I., Yan, Z., Suheryani, I. (2017), 'Enhancing seasonal influenza surveillance: topic analysis of widely used medicinal drugs using Twitter data', *Journal of medical Internet research*, 19(9), pp. 7393.

Kaji, D. A., Zech, J. R., Kim, J. S., Cho, S. K., Dangayach, N. S., Costa, A. B., Oermann, E. K. (2019), 'An attention based deep learning model of clinical events in the intensive care unit', *PloS one*, 14(2), e0211057.

Kang, J., Park, Y. J., Lee, J., Wang, S. H., Eom, D. S. (2017), 'Novel leakage detection by ensemble CNN-SVM and graph-based localization in water distribution systems', *IEEE Transactions on Industrial Electronics*, 65(5), pp. 4279-4289.

Kannangara, M., Dua, R., Ahmadi, L., Bensebaa, F. (2018), 'Modeling and prediction of regional municipal solid waste generation and diversion in Canada using machine learning approaches', *Waste Management*, Volume 74, pp 3-15, https://www.sciencedirect.com/science/article/abs/pii/S0956053X17309406?via%3Dihub

Karimipour, H., Dehghantanha, A., Parizi, R. M., Choo, K. K. R., Leung, H. (2019), 'A deep and scalable unsupervised machine learning system for cyber-attack detection in large-scale smart grids', *IEEE Access*, 7, pp. 80778-80788.

Kenneally, E., Dittrich, D. (2012), *The Menlo Report: Ethical principles guiding information and communication technology research*, Available at SSRN 2445102.

Kim, H., Lee, Y., Woo, T., Kim, H. (2016), *Integration of vehicle and lane detection for forward collision warning system*, In 2016 IEEE 6th International Conference on Consumer Electronics-Berlin (ICCE-Berlin), pp. 5-8.

Król, A. (2016), 'The Application of the Artificial Intelligence Methods for Planning of the Development of the Transportation Network', *Transportation Research Procedia*, 14, pp. 4532–4541.

Kulkarni, N. H., Srinivasan, G. N., Sagar, B. M., Cauvery, N. K. (2018), *Improving crop productivity through a crop recommendation system using ensembling technique*, In 2018 3rd International Conference on Computational Systems and Information Technology for Sustainable Solutions (CSITSS), pp. 114-119.

Lacoste, A., Luccioni, A., Schmidt, V., Dandres, T. (2019), *Quantifying the carbon emissions of machine learning*, arXiv preprint arXiv:1910.09700.

LeCun, Y., Bengio, Y., Hinton, G. (2015), 'Deep learning', *Nature* 521, pp. 436–444. https://doi.org/10.1038/nature14539

Ledford, H. (2019), 'Millions of black people affected by racial bias in health-care algorithms', *Nature*, 574(7780), pp. 608-610.

Lee, K., Choi, C., Shin, D. H., Kim, H. S. (2020), 'Prediction of heavy rain damage using deep learning', *Water*, 12(7), pp. 1942.

Lei, N., Masanet, E. R. (2021), 'Global Data Center Energy Demand and Strategies to Conserve Energy, *Data Center Handbook: Plan, Design, Build, and Operations of a Smart Data Center*, pp. 15-26.

Letouzé, E. and A. Pentland (2018), 'Towards a Human Artificial Intelligence for Human Development', *ITU Journal: ICT Discoveries, Special Issue*, 2.

Letouzé, E., Oliver, N. (2019), *Sharing is Caring Four Key Requirements for Sustainable Private Data Sharing and Use for Public Good*, Data-pop alliance and Vodafone Institute for Society and Communications, London.

Letouzé, E., Vinck, P., Kammourieh, L. (2015), *The law, politics and ethics of cell phone data analytics*, Data-Pop Alliance.

Li, J., Xu, Q., Shah, N., Mackey, T. K. (2019), 'A machine learning approach for the detection and characterization of illicit drug dealers on instagram: model evaluation study', *Journal of medical Internet research*, 21(6), e13803.

Liao, S., Zhou, L., Di, X., Yuan, B., Xiong, J. (2018), *Large-scale short-term urban taxi demand forecasting using deep learning*, In 2018 23rd Asia and South Pacific Design Automation Conference (ASP-DAC, pp. 428-433.

Lismont, J., Cardinaels, E., Bruynseels, L., De Groote, S., Baesens, B., Lemahieu, W., Vanthienen, J. (2018), 'Predicting tax avoidance by means of social network analytics', *Decision Support Systems*, 108, pp. 13-24.

Lu, Z., Im, J., Quackenbush, L., Halligan, K. (2010), 'Population estimation based on multi-sensor data fusion', *International Journal of Remote Sensing*, 31(21), pp. 5587-5604.

Madhab Ghosh, S., and M.D. Behera (2018), 'Aboveground biomass estimation using multi-sensor data synergy and machine learning algorithms in a dense tropical forest', *Applied Geography*, 96, pp 29-40, https://doi.org/10.1016/j.apgeog.2018.05.011

Malak, J. S., Zeraati, H., Nayeri, F. S., Safdari, R., Shahraki, A. D. (2019), 'Neonatal intensive care decision support systems using artificial intelligence techniques: a systematic review', *Artificial Intelligence Review,* 52(4), pp. 2685-2704.

Mandal, B., Li, L., Wang, G. S., Lin, J. (2016), 'Towards detection of bus driver fatigue based on robust visual analysis of eye state', *IEEE Transactions on Intelligent Transportation Systems*, 18(3), pp. 545-557.

Marculescu, D., Stamoulis, D., Cai, E. (2018), *Hardware-aware machine learning: modeling and optimization*, In Proceedings of the International Conference on Computer-Aided Design, pp. 1-8).

Martin, C., Parkes, S., Zhang, Q., Zhang, X., McCabe, M. F., Duarte, C. M. (2018), 'Use of unmanned aerial vehicles for efficient beach litter monitoring', *Marine pollution bulletin*, 131, pp. 662-673.

Min, Q., Lu, Y., Liu, Z., Su, C., Wang, B. (2019), 'Machine Learning based Digital Twin Framework for Production Optimization in Petrochemical Industry', *International Journal of Information Management*, 49, pp 502-519, https://www.sciencedirect.com/science/article/abs/pii/S0268401218311484?via%3Dihub

Mishra, M., Rout, P. K. (2018), 'Detection and classification of micro-grid faults based on HHT and machine learning techniques' *IET Generation, Transmission & Distribution*, 12(2), pp. 388-397.

Mitchell, T., Brynjolfsson, E. (2017), 'Track how technology is transforming work', *Nature*, 544(7650), pp. 290-292.

Mohanty, S. P., Hughes, D. P., Salathé, M. (2016), 'Using deep learning for image-based plant disease detection', *Frontiers in plant science*, 7, pp. 1419.

R Montes, F.J. Melero, I Palomares, S Alonso et al, Artificial Intelligence and Digital Technologies for the Sustainable Development Goals, *Spanish Royal Academy of Engineering*.

More, R., Mugal, A., Rajgure, S., Adhao, R. B., Pachghare, V. K. (2016), *Road traffic prediction and congestion control using Artificial Neural Networks*, In 2016 International Conference on Computing, Analytics and Security Trends (CAST), pp. 52-57. IEEE.

Mukai, N., Watanabe, T., Feng, J. (2008), *Route optimization using Q-learning for on-demand bus systems*, In International Conference on Knowledge-Based and Intelligent Information and Engineering Systems, pp. 567-574. Springer.

Niestadt, M., Debyser, A., Scordamaglia, D., Pape, M. (2019), *Artificial intelligence in transport: Current and future developments, opportunities and challenges*, European Parliamentary Research Service.

Nieto, Y., García-Díaz, V., Montenegro, C., Crespo, R. G. (2019), 'Supporting academic decision making at higher educational institutions using machine learning-based algorithms', *Soft Computing*, 23(12), pp. 4145-4153.

Oh, Y., Park, S., Ye, J. C. (2020), 'Deep learning COVID-19 features on CXR using limited training data sets', IEEE transactions on medical imaging, 39(8), pp. 2688-2700.

Okori, W., Obua, J. (2011), *Machine learning classification technique for famine prediction, In Proceedings of the world congress on engineering*, 2(1).

Oliver, N. (2019), *Governance in the Era of Data-driven Decision-making Algorithms*, in Women shaping Global Economic Governance, Center for Economic Policy Research Press (CEPR)

Oliver, N. and A.P. Pentland (2000), 'Graphical models for driver behavior recognition in a smart car', *Proc. of the IEEE Intelligent Vehicles Symposium*, pp 7-12.

Oliver, N., Lepri, B., Sterly, H., Lambiotte, R., Deletaille, S., De Nadai, M. others. (2020), 'Mobile Phone Data for Informing Public Health Actions across the COVID-19 Pandemic Life Cycle', *Science Advances*, 6.

Ong, E., Wong, M. U., Huffman, A., He, Y. (2020), 'COVID-19 coronavirus vaccine design using reverse vaccinology and machine learning', *Frontiers in immunology*, pp. 1581.

Pan, Z., Liang, Y., Wang, W., Yu, Y., Zheng, Y., Zhang, J. (2019), *Urban traffic prediction from spatio-temporal data using deep meta learning*, In Proceedings of the 25th ACM SIGKDD International Conference on Knowledge Discovery & Data Mining, pp. 1720-1730.

Pastor-Escuredo, D., Morales-Guzmán, A., Torres-Fernández, Y., Bauer, J. M., Wadhwa, A., Castro-Correa, C., ... Luengo-Oroz, M. (2014), *Flooding through the lens of mobile phone activity*, In IEEE Global Humanitarian Technology Conference (GHTC 2014), pp. 279-286.

Petrillo, A., Travaglioni, M., De Felice, F., Cioffi, R., Piscitelli, G. (2020), 'Artificial Intelligence and Machine Learning Applications in Smart Production: Progress, Trends, and Directions' *Sustainability*, 12(2), pp. 492. https://doi.org/10.3390/su12020492

Pham, T., Tran, T., Phung, D., Venkatesh, S. (2017), 'Predicting healthcare trajectories from medical records: A deep learning approach', *Journal of biomedical informatics*, 69, pp. 218-229.

Poon, L. C., Kametas, N. A., Maiz, N., Akolekar, R., Nicolaides, K. H. (2009), 'First-trimester prediction of hypertensive disorders in pregnancy', *Hypertension*, 53(5), pp. 812-818.

Quinn, J. A., Okori, W., Gidudu, A. (2010), *Increased-specificity famine prediction using satellite observation data*, In Proceedings of the First ACM Symposium on Computing for Development, pp. 1-6.

Radke, D., Hessler, A., Ellsworth, D. (2019), *FireCast: Leveraging Deep Learning to Predict Wildfire Spread*, In IJCAI, pp. 4575-4581.

Rafiei, M. H., Adeli, H. (2017), 'A novel machine learning-based algorithm to detect damage in high-rise building structures', *The Structural Design of Tall and Special Buildings*, 26(18), e1400.

Rasp, S., Pritchard, M. S., Gentine, P. (2018), 'Deep learning to represent subgrid processes in climate models', *Proceedings of the National Academy of Sciences*, 115(39), pp. 9684-9689.

Raza, M. Q., Khosravi, A. (2015), 'A review on artificial intelligence based load demand forecasting techniques for smart grid and buildings', *Renewable and Sustainable Energy Reviews*, 50, pp. 1352-1372.

Ren, Y., Huang, J., Hong, Z., Lu, W., Yin, J., Zou, L., Shen, X. (2020), 'Image-based concrete crack detection in tunnels using deep fully convolutional networks', *Construction and Building Materials*, 234, 117367.

Rocher, L., Hendrickx, J. M., De Montjoye, Y. A. (2019), 'Estimating the success of re-identifications in incomplete datasets using generative models', *Nature communications*, 10(1), pp. 1-9.

Rodríguez, E. A., Estrada, F. E., Torres, W. C., Santos, J. C. M. (2016), *Early prediction of severe maternal morbidity using machine learning techniques*, In Ibero-American Conference on Artificial Intelligence, pp. 259-270.

Rolnick, D., Donti, P. L., Kaack, L. H., Kochanski, K., Lacoste, A., Sankaran, K., ... Bengio, Y. (2022), 'Tackling climate change with machine learning', *ACM Computing Surveys (CSUR)*, 55(2), pp. 1-96.

Sahoo, S., Russo, T. A., Elliott, J., Foster, I. (2017), *Machine learning algorithms for modeling groundwater level changes in agricultural regions of the US Water,* Resour Res 53, pp. 3878–3895.

Sahour, H., Gholami, V., Vazifedan, M. (2020), 'A comparative analysis of statistical and machine learning techniques for mapping the spatial distribution of groundwater salinity in a coastal aquifer', *Journal of Hydrology*, 591, 125321.

San Pedro, J., Proserpio, D., Oliver, N. (2015), *MobiScore: Towards Universal Credit Scoring from Mobile Phone Data*, In: Ricci F., Bontcheva K., Conlan O., Lawless S. (eds) User Modeling, Adaptation and Personalization. UMAP. Lecture Notes in Computer Science, 9146. Springer, Cham. https://link.springer.com/chapter/10.1007/978-3-319-20267-9_16

Saracco, R. (2018). *Digital twins take the train.*

Sayad, Y. O., Mousannif, H., Al Moatassime, H. (2019), 'Predictive modeling of wildfires: A new dataset and machine learning approach', *Fire safety journal*, 104, pp. 130-146.

Schneider, G. (2018), 'Automating drug discovery', *Nature reviews drug discovery*, 17(2), pp. 97-113.

Schut, D., Wisniewski, J. (2015), A global vision of railway development, Paris: International Union of Railways (UIC)

Schwartz, I. M., York, P., Nowakowski-Sims, E., Ramos-Hernandez, A. (2017), 'Predictive and prescriptive analytics, machine learning and child welfare risk assessment: The Broward County experience', *Children and Youth Services Review,* 81, pp. 309-320.

Schwartz, R., Dodge, J., Smith, N. A., Etzioni, O (2020), *Green AI*, Communications of the ACM, 63 (12), pp 54–63, https://doi.org/10.1145/3381831

Senior, A. W., Evans, R., Jumper, J., Kirkpatrick, J., Sifre, L., Green, T., ... Hassabis, D. (2020), 'Improved protein structure prediction using potentials from deep learning', *Nature,* 577(7792), pp. 706-710.

Setti, M., Falasconi, L., Segrè, A., Cusano, I., & Vittuari, M. (2016), 'Italian consumers' income and food waste behavior', *British Food Journal.*

Shorrocks, A., and N. Hechler-Fayd'herbe (2019), Global Wealth Report 2019: Global wealth rises by 2.6% driven by US China, despite trade tensions, Zurich, Switzerland: Credit Suisse

Siddiqui, M. Z., Yadav, S., Husain, M. S. (2018), 'Application of artificial intelligence in fighting against cyber crimes: a review', Int. J. Adv. Res. *Comput. Sci*, 9(2), pp. 118-122.

Singh, J. A. (2019), 'Artificial intelligence and global health: opportunities and challenges', *Emerging Topics in Life Sciences*, 3(6), pp. 741-746.

Sønderby, C. K., Espeholt, L., Heek, J., Dehghani, M., Oliver, A., Salimans, T., ... Kalchbrenner, N. (2020), *Metnet: A neural weather model for precipitation forecasting*, arXiv preprint arXiv:2003.12140.

Song, S. Y., Kim, Y. K. (2018), 'Theory of virtue ethics: do consumers' good traits predict their socially responsible consumption?', *Journal of Business Ethics*, 152(4), 1159-1175.

Soto, V., Frias-Martinez, V., Virseda, J., Frias-Martinez, E. (2011), 'Prediction of socioeconomic levels using cell phone records', In *International conference on user modeling, adaptation, and personalization*, pp. 377-388.

Spiekermann, S., Acquisti, A., Böhme, R., Hui, K. L. (2015), 'The challenges of personal data markets and privacy', *Electronic markets*, 25(2), pp. 161-167.

Staiano, J., Oliver, N., Lepri, B., de Oliveira, R., Caraviello, M., Sebe, N. (2014), *Money walks: a human-centric study on the economics of personal mobile data*, In Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing, pp. 583-594.

Strubell, E., Ganesh, A., McCallum, A. (2019), *Energy and policy considerations for deep learning in NLP*, arXiv preprint arXiv:1906.02243.

Sundmaeker, H., Verdouw, C. N., Wolfert, J., Freire, L. P. (2016), *Internet of food and farm 2020*, In Digitising the industry, 49, pp. 129-150. River Publishers, en https://www.iof2020.eu/

Sundsøy, P., Bjelland, J., Reme, B. A., Iqbal, A. M., Jahani, E. (2016), D*eep learning applied to mobile phone data for individual income classification*, In Proceedings of the 2016 International Conference on Artificial Intelligence: Technologies and Applications, Bangkok, Thailand, pp. 24-25.

Tabak, M. A., Norouzzadeh, M. S., Wolfson, D. W., Sweeney, S. J., Vercauteren, K. C., Snow, N. P., Miller, R. S. (2019), 'Machine learning to classify animal species in camera trap images: applications in ecology', *Methods Ecol. Evol*, 10, pp. 585-590.

Talukdar, S., Singha, P., Mahato, S., Pal, S., Liou, Y. A., Rahman, A. (2020), 'Land-use land-cover classification by machine learning classifiers for satellite observations – A review', *Remote Sensing*, 12(7), pp. 1135.

Tumas, P., Nowosielski, A., Serackis, A. (2020), 'Pedestrian detection in severe weather conditions', *IEEE Access*, 8, pp. 62775-62784.

USAID (2010), *Uganda food security outlook*. Famine Early Warning Systems Network. Technical Report

Vinuesa, R., Azizpour, H., Leite, I., Balaam, M., Dignum, V., Domisch, S., ... Fuso Nerini, F. (2020), 'The role of artificial intelligence in achieving the Sustainable Development Goals', *Nature communications*, 11(1), pp. 1-10.

Walsh, C. G., Ribeiro, J. D., Franklin, J. C. (2017), 'Predicting risk of suicide attempts over time through machine learning', *Clinical Psychological Science*, 5(3), pp. 457-469.

Wang, Q., Guo, Y., Yu, L., Li, P. (2017), 'Earthquake prediction based on spatio-temporal data mining: an LSTM network approach', *IEEE Transactions on Emerging Topics in Computing*, 8(1), pp. 148-158.

Wesolowski, A., Buckee, C. O., Bengtsson, L., Wetter, E., Lu, X., Tatem, A. J. (2014), 'Commentary: containing the Ebola outbreak-the potential and challenge of mobile network data', *PLoS currents*, 6.

Wesolowski, A., Eagle, N., Tatem, A., Smith, DL., Noor, AM. et al. (2012), 'Quantifying the Impact of Human Mobility on Malaria', Science, 338(6104), pp. 267-272, DOI: 10.1126/science.1223467

West, J., Bhattacharya, M. (2016), 'Intelligent financial fraud detection: a comprehensive review', Computers & security, 57, pp. 47-66

Weyn, J. A., Durran, D. R., Caruana, R. (2020), 'Improving data-driven global weather prediction using deep convolutional neural networks on a cubed sphere', *Journal of Advances in Modeling Earth Systems*, 12(9).

Wolfert, S., Ge, L., Verdouw, C., Bogaardt, M. J. (2017), 'Big data in smart farming–a review', *Agricultural systems*, 153, pp. 69-80.

Woolf, B. P., Lane, H. C., Chaudhri, V. K., Kolodner, J. L. (2013), 'AI grand challenges for education', *AI magazine*, 34(4), pp. 66-84.

Wu, J., Ruenz, J., Althoff, M. (2018), *Probabilistic map-based pedestrian motion prediction taking traffic participants into consideration*, In 2018 IEEE Intelligent Vehicles Symposium (IV), pp. 1285-1292.

Wu, J., Song, C., Dubinsky, E. A., Stewart, J. R. (2021), 'Tracking Major Sources of Water Contamination Using Machine Learning', *Frontiers in microbiology*, 3623.

Xu, M., Cai, H., Liang, S. (2015), 'Big data and industrial ecology', *Journal of Industrial Ecology*, 19(2), pp. 205-210.

Xu, X., Qi, Y., Hua, Z. (2010), 'Forecasting demand of commodities after natural disasters', *Expert systems with applications*, 37(6), pp. 4313-4317.

Xu, Y., Bao, Y., Chen, J., Zuo, W., Li, H. (2019), 'Surface fatigue crack identification in steel box girder of bridges by a deep fusion convolutional neural network based on consumer-grade camera images', *Structural Health Monitoring*, 18(3), pp. 653-674.

Yao, H., Tang, X., Wei, H., Zheng, G., Li, Z. (2019), *Revisiting spatial-temporal similarity: A deep learning framework for traffic prediction*, In Proceedings of the AAAI conference on artificial intelligence, 33(01), pp. 5668-5675).

Yao, H., Wu, F., Ke, J., Tang, X., Jia, Y., Lu, S., ... Li, Z. (2018), *Deep multi-view spatial-temporal network for taxi demand prediction*, In Proceedings of the AAAI Conference on Artificial Intelligence, 32(1).

Ye, C., Butler, L., Calka, B., Iangurazov, M., Lu, Q., Gregory, A., ... Middleton, C. (2019), *A digital twin of bridges for structural health monitoring*, In 12th International Workshop on Structural Health Monitoring 2019. Stanford University.

Yoon, H., Jun, S. C., Hyun, Y., Bae, G. O., Lee, K. K. (2011), 'A comparative study of artificial neural networks and support vector machines for predicting groundwater levels in a coastal aquifer', *Journal of hydrology*, 396(1-2), pp. 128-138.

Zanetti, M., Iseppi, G., Cassese, F. P. (2019), 'A "psychopathic" artificial intelligence: The possible risks of a deviating AI in education', *Research on Education and Media*, 11(1), pp. 93-99.

Zemel, R., Wu, Y., Swersky, K., Pitassi, T., Dwork, C. (2013), *Learning fair representations*, In International conference on machine learning, pp. 325-333.

Zhang, N., Wang, M., Wang, N. (2002), 'Precision agriculture – a worldwide overview', *Computers and electronics in agriculture*, 36(2-3), pp. 113-132.

Zhao, L., Song, Y., Zhang, C., Liu, Y., Wang, P., Lin, T., ... Li, H. (2019), 'T-gcn: A temporal graph convolutional network for traffic prediction', *IEEE Transactions on Intelligent Transportation Systems*, 21(9), pp. 3848-3858.

Zhao, Q., Yu, S., Zhao, F., Tian, L., Zhao, Z. (2019), 'Comparison of machine learning algorithms for forest parameter estimations and application for forest quality assessments', *Forest Ecology and Management*, 434, pp 224-234, https://doi.org/10.1016/j.foreco.2018.12.019

Zheng, X., and M.K.O. Lee (2016), 'Excessive use of mobile social networking sites: Negative consequences on individuals', *Computers in Human Behavior*, Volume 65, pp 65-76, https://doi.org/10.1016/j.chb.2016.08.011

Zhu, N., Liu, X., Liu, Z., Hu, K., Wang, Y., Tan, J., ... Guo, Y. (2018), 'Deep learning for smart agriculture: Concepts, tools, applications, and opportunities' International *Journal of Agricultural and Biological Engineering*, 11(4), pp. 32-44.

Zhu, S., Hrnjica, B., Ptak, M., Choiński, A., Sivakumar, B. (2020), 'Forecasting of water level in multiple temperate lakes using machine learning models', *Journal of Hydrology*, 585, 124819

CHAPTER 12

PRODUCTIVITY GROWTH AFTER THE PANDEMIC: UNDERSTANDING LONG-TERM TRENDS TO TACKLE THE COVID-19 CHALLENGES

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Summary

The pandemic is an unprecedented demand and supply shock that has generated a strong push towards the digitalisation of firms and generated novel opportunities for start-ups, particularly in the online trade sector. Yet, the ability of firms to invest in digital and intangible assets has been very heterogeneous. Indeed, investment in firm digitalisation has been driven by larger and ex-ante more digitalised firms. As a result, the digital divide between more productive and less productive firms has likely increased over the last 2 years. Policies that can mitigate the long-term effects of these developments are discussed, pointing to the importance of ensuring a stronger and more inclusive recovery.

1. Introduction

This chapter summarises existing research on the impact of the COVID-19 crisis on productivity, analysing it in the context of pre-existing trends in productivity, concentration and business dynamics.

Over the last two decades, in most European economies, aggregate productivity growth slowed down, business dynamics (entry and job-creation rates) declined steadily, industry concentration increased and the divide between the most productive firms (frontier firms) and the less productive ones (laggards) rose significantly.

Recent evidence highlights how one key determinant of these trends is the rise of the digital and knowledge-intensive economy. To be used effectively, digital technologies require complementary intangible investments, such as investments in organisational capital, software and databases, and upskilling of workers and managers. The difficulty of financing these investments through loans (due to the low pledgeability of intangibles) and their high scalability (due to a low-margin/high fixed-costs structure) imply a greater gain for better managed, larger and more productive firms. This results in an increased productivity divide, possibly lower competition and reduced incentives to innovate and to enter new markets, and, ultimately, slowing growth.

Against this backdrop, the COVID-19 crisis has represented an unprecedented economic shock that significantly affected both supply and demand. Prompt and large policy interventions in many European countries to support wage-payments and firms' debts effectively prevented a liquidity crisis during 2020. However, uncertainty over the end of the pandemic remains high, demand is still subdued, and problems in the re-activation of global value chains are tightening the supply of goods.

While economic crises generally increase the incentives for firms to restructure, this pandemic shock determined a specific push towards firms' digitalisation. Indeed, the social restrictions imposed by governments to contain the spread of the virus have prompted firms to invest in advanced digital technologies to adapt production and to move the labour force effectively to remote working. Survey evidence from several

OECD countries points to a general increase in digital technology adoption by firms. The acceleration in the digitalisation of the economy has been coupled with investments in complementary intangible assets. National accounts data show that intangible investments, which encompass software and databases, remained stable during 2020, while tangible investments experienced a significant slump. New firms have also contributed to the increased digitalisation of the economy: the rebound in entry rates experienced in several countries was driven by digital-intensive start-ups, mostly in the trade sector, that were exploiting online markets to sell their products and services.

Nevertheless, the ability of firms to invest in digital and intangible assets has been far from homogeneous. Larger, more productive and more digitalised firms have all suffered comparatively less from the shock. These firms have been able to invest more in the digitalisation of their production as well as in complementary intangibles and workers' skills than smaller less tech-savvy firms. Thus, the aggregate boost in the digitalisation of production masks significant heterogeneity across firms, pointing to the risk that the crisis may further exacerbate the productivity divide and increase concentration, with detrimental effects on technology diffusion and long-term productivity growth.

The chapter concludes by discussing how policies can mitigate these long-term risks and ensure a stronger and more inclusive recovery. Governments may support investments in intangible assets and skills by less productive firms, while fostering competition and boosting innovation among frontier firms.

2. Productivity growth and productivity divergence: long-term trends and their determinants

Over the last two decades OECD countries have experienced a set of worrying trends. First, productivity growth has slowed down. The drop has been mainly driven by a within-sector decline rather than the cross-sectoral reallocation of resources. The former accounts for over 80 % of the total slowdown in productivity growth experienced by EU economies. Second, business dynamism declined across economies. According to estimate from 18 OECD and non-OECD countries, firm entry rates dropped by 3 percentage points over the period 2000-2015, while job creation rates declined by 5 percentage points (Calvino, Criscuolo and Verlhac, 2020). Third, an increasing number of studies have highlighted how industry concentration increased in several OECD countries, and this trend went hand in hand with a rise in markups (Bajgar et al., 2019; Bajgar, Criscuolo and Timmis, 2021; Calligaris, Criscuolo and Marcolin, 2018).

Seminal OECD research has highlighted how these trends were accompanied by increasing dispersion in productivity distribution, including within narrowly-defined industries (Andrews, Criscuolo and Gal, 2016; Berlingieri, Blanchenay and Criscuolo, 2017). Evidence shows that slower productivity growth of the least productive firms (the laggards) is the fulcrum of the increase in dispersion (Berlingieri, Blanchenay and Criscuolo, 2017). This points to a slowdown in the diffusion of productivity gains among laggard firms (Berlingieri et al., 2020).

OECD analyses have highlighted how increased productivity dispersion, rising concentration and markups, declining business dynamism and productivity-growth slowdown all seem linked to the rise of the digital and knowledge-based economy. Indeed, to adopt digital technologies in the production process effectively, firms need to complement them with key complementary intangible assets and skills. However, several features of intangibles – their scalability, sunkenness, complementarity, non-rivalry and non-excludability – reduce the ability of smaller and less productive firms to invest in them (Haskel and Westlake, 2017).

As a result, technology diffusion may be subdued, particularly at the bottom of the productivity distribution, dampening the productivity growth of laggard firms. Moreover, the resulting increase in market power by technology leaders may reduce the incentives to innovate by productive (even though not-yet leading) firms and depress entry rates.

Several empirical analyses have provided findings consistent with this hypothesis, and have corroborated the relationship between intangibles, digital technology diffusion and macro-economic trends.

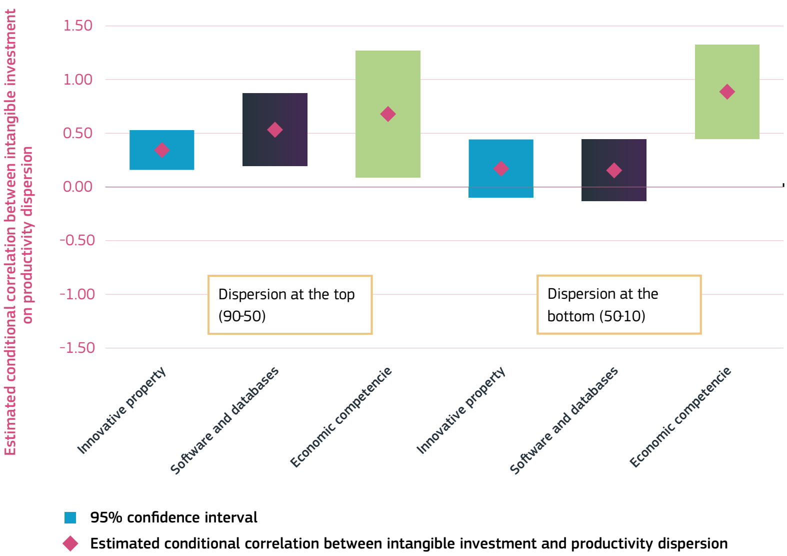
Research has shown that laggard firms catch up more slowly to the productivity frontier in more digital and more knowledge-intensive industries (Berlingieri et al., 2020). Exploiting detailed sector-level information on investments in intangibles merged with the MultiProd database, Corrado et al. (2021) confirm that intangible-intensity is positively correlated with higher productivity dispersion between firms. Among intangibles, the study highlights the key role of economic competencies (e.g. organisational capital and firm-specific skills), which explains divergence throughout the productivity distribution. Instead, intangibles more directly related to innovative activities (such as

R&D and intellectual property, IP, assets) and software and data explain solely the divergence at the top of the productivity distribution (Figure 1). Thus, competencies and skills seem key to support technology diffusion also among laggards, while productivity growth among firms belonging to the central part of the productivity distribution seems to be linked also to investments in innovative activities.

Country-level in-depth analyses may allow dissection of how skills and intangibles complement digital technologies, highlighting heterogeneity in complementarities across firms and technologies. Calvino et al. (2022) studies the case of Italy to identify the causes of the lower digitalisation of its business sector relative to other OECD countries. The study (joint with the Italian National Institute of Statistics and the Bank of Italy) exploits a unique data infrastructure that combines data on firm balance sheets, digital technology adoption, intangibles and matched firm-worker and firm-manager data.

Results show that adoption rates in Italy are extremely skewed, with small and young firms having lower levels of digital technology adoption in comparison with other OECD countries. Moreover, these firms are less likely to adopt bundles of different digital technologies, which are associated with higher productivity gains and are usually key to adopting other advanced technologies.

Figure 12-1: Correlation between intangibles and dispersion at the top and the bottom of the productivity distribution, by type of intangibles



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Source: Corrado et al. (2021)

Note: The figure plots the results from a regression at the country-A38 industry level of productivity dispersion on lagged intangible intensity, controlling for country-sector and year fixed effects as well as average inputs usage. Productivity dispersion at the top (bottom) is defined as the log difference in multi-factor productivity between the 90th and the 50th percentile of the productivity distribution (between the 50th and the 10th percentile). Intangible intensity is defined as the ratio between intangible investments and employment at the sector level. Countries included are Austria, Belgium, Denmark, Finland, France, Germany, Ireland, Italy, the Netherlands, Portugal. Following Corrado, Hulten and Sichel (2009), intangibles are divided into three groups: economic competencies (advertising, market research, training, organisational structure), innovative property (R&D, new products/systems, design, mineral exploration, entertainment and artistic originals), software and databases. Confidence intervals of 95% based on cluster-robust standard errors that allow for serial correlation at the sector-industry level are provided as shaded areas.

Stats.: https://ec.europa.eu/assets/rtd/srip/2022/figure-12-1.xlsx

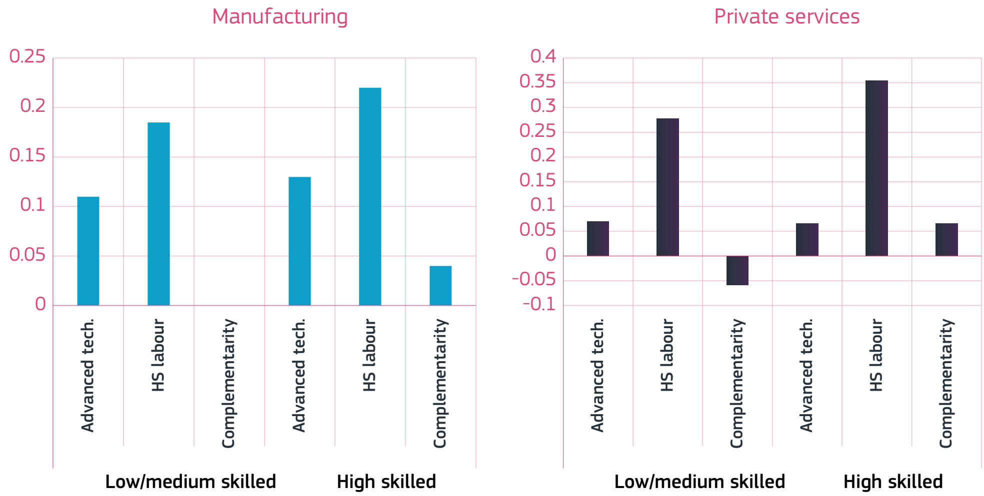
The analysis highlights that three complementary factors are key to boosting adoption rates and the returns of digital technologies among SMEs: worker skills, management capabilities and investments in intangibles.

A skilled workforce and a high-quality management are significantly related to increased adoption of digital technologies. High-skilled and well-managed firms, especially micro and small ones, realise larger productivity gains from adopting more advanced digital technologies since their managers are better able to deal with the increasing complexity of digital technologies and complement the workforce's skills when leveraging these new technologies in production (Figure 2).

Among intangible assets, R&D expenditures are key to boosting a firm's ability to realise the full potential of digital technology adoption. Digital technologies also tend to increase the likelihood that R&D activities will result in a new patent, pointing again to complementarities between digital and intangible assets.

Evidence from cross-country firm-level data both confirms that intangible investment boosts productivity growth and supports firms' catch-up towards the productivity frontier and highlights the role of financial frictions in preventing less productive firms from investing in these assets. Indeed, in a recent paper, Calvino, Koegel, Manaresi and Verlhac (2021) estimate that the speed of catch-up towards

Figure 12-2: Returns on advanced technology, high-skilled labour and their complementarity by skill of the manager in manufacturing and services, Italy, 2018



Source: Calvino et al. (2022)

Note: The figure plots the estimated elasticities of output to advanced digital technologies, high-skilled labour and their interaction. Elasticities are obtained from a production function estimated separately for high- and low/medium-skilled managers. Advanced digital technologies include are measured as a dummy =1 if the firm has invested over the period 2016-2018 in at least one of the following technologies: internet-of-things, big data, advanced automation, 3D printing, AR/VR, computational simulations. High-skilled labour is the (log) number of workers that are tertiary educated. Low-, medium- and high-skilled managers are defined as top executives (CEOs) that have, respectively, a primary, secondary or tertiary education. The Cobb-Douglas production function includes the following additional inputs, also interacted with advanced technologies: low-skilled labour, medium-skilled labour, tangible capital and intangible capital. It also includes management software, cloud computing, e-sales and enabling technologies (broadband, 4G/5G connections, cybersecurity) as additional digital technologies. The production function is estimated for the year 2018 on Italian data using the De Loecker and Warzynski (2012) methodology.

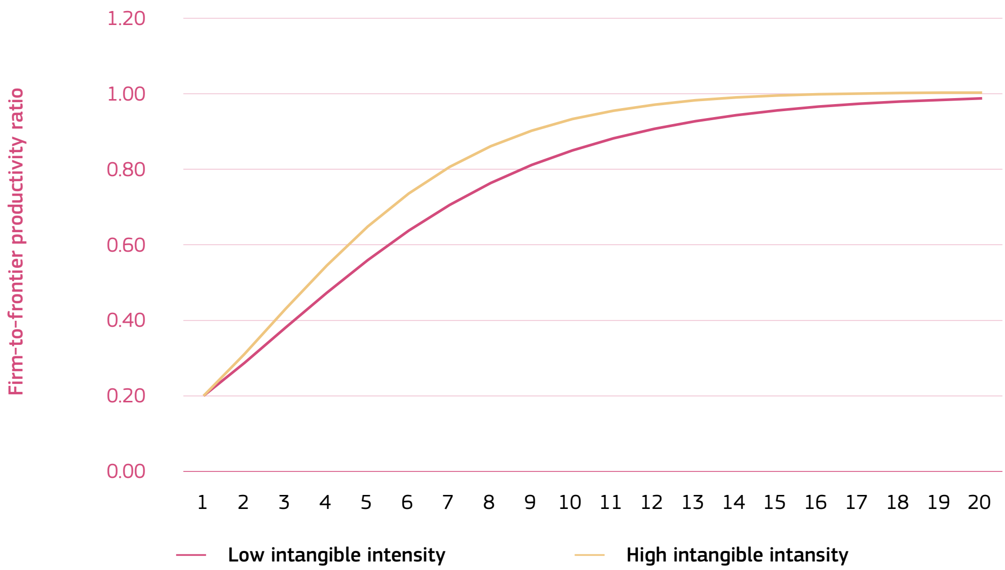
Stats.: https://ec.europa.eu/assets/rtd/srip/2022/figure-12-2.xlsx

the productivity frontier is significantly higher for firms that have larger intangible intensity (Figure 3). Importantly, this result also holds when intangible intensity is instrumented using changes in corporate R&D tax rates. This result points both to the causal role of intangibles in explaining the speed of catch-up and to the effectiveness of R&D tax credits.

The analysis also highlights the role of financial frictions in preventing less productive firms from investing in intangible assets: firms that are credit constrained (as identified through several state-of-the-art methodologies) are unable to invest in intangible assets, and thus catch up at a lower rate. This result points to the importance of developing credit market solutions to finance intangibles (e.g. through IP-based collaterals) as well as supporting access to financial markets for all firms.

Other key macroeconomic trends have been linked to the digital transformation and the rise of the intangible economy. Firms in digital- and intangible-intensive industries are found to experience a more rapid decline in business dynamism (Calvino, Criscuolo and Verlhac, 2020). Industry-level digital and intangible intensity are positively correlated with industry concentration and markups (Bajgar, Criscuolo and Timmis, 2021; Calligaris, Criscuolo and Marcolin, 2018).

Figure 12-3: Estimated catch-up towards the productivity frontier for firms with low vs high intangible intensity of capital



Source: Calvino, Koegel, Manaresi, Verlhac (2021)

Note: The figure reports results from estimating a dynamic panel model of firm convergence towards the productivity frontier. The dependent variable is the ratio between the firm productivity and the average productivity of the national frontier (the top 5 % of the national productivity distribution within each sector-year). The model controls for the growth of the productivity frontier and for firm and country-year unobserved heterogeneity. The Figure reports the convergence coefficient by intangible intensity. Low intangible intensity refers to the 25th percentile of the intangible distribution, while high intangible intensity refers to the 75th percentile of the intangible distribution. The model is estimated on Orbis data over the period 2000-2015 for the following countries: Austria, Belgium, Denmark, Germany, Spain, Estonia, Finland, France, United Kingdom, Hungary, Italy, Japan, the Netherlands, South Korea, Portugal, Slovenia, Sweden, USA.

Stats.: https://ec.europa.eu/assets/rtd/srip/2022/figure-12-3.xlsx

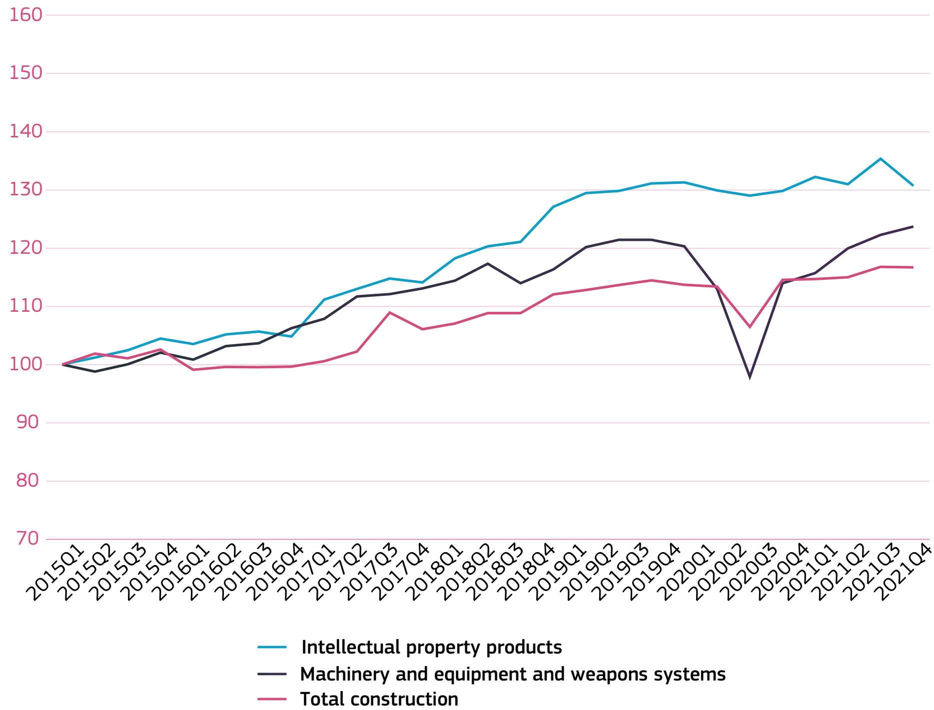
3. The COVID-19 shock

The COVID-19 crisis has profoundly hit the global economy. To curb the spread of the virus, governments imposed strict containment measures that have affected both demand and supply. While the rapid development of vaccines allowed most EU countries to partially lift the restrictions by the end of 2020, the emergence of new variants of the virus increases uncertainty over the future impact of the pandemic on economic activities and the need for further restrictions.

The containment measures generated a substantial drop in output in the second quarter of 2020, when most EU countries imposed lockdowns. This drop, however, was accompanied by an increase in aggregate labour productivity as hours worked decreased more than output (Criscuolo 2021).

Sectoral reallocation has also positively contributed to the increase in aggregate productivity (Bloom et al., 2020; Ascari, Colciago and Silvestrini, 2021; Criscuolo, 2021). Indeed, sectors characterised by ex-ante lower productivity have been the most affected by the crisis, while high-productive sectors (such as information and communications) were able to cushion the impact of COVID-19.

Figure 12-4: Investments by tangibility of assets: EU-27 average, quarterly data – Q1 2015=100



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Source: Authors' calculations based on Eurostat national accounts database.

Note: Average investments (gross fixed capital formation) are averaged across the EU-27 countries. Six countries are excluded from the sample because of data issues (Ireland, Belgium, the Netherlands, Cyprus, Malta, Estonia).

Stats.: https://ec.europa.eu/assets/rtd/srip/2022/figure-12-4.xlsx

The pandemic has favoured the digitalisation of the economy, with potential positive effects on productivity growth. Indeed, in order to cope with restrictive measures imposed by governments, firms have accelerated the adoption of digital technologies, put employees into teleworking and moved sales and purchases online, with a significant share of European enterprises, surveyed by the EIB Investment Survey, expecting the use of digital technologies to further intensify after the COVID-19 crisis (EIB, 2021). A growing body of evidence shows similar trends across the EU, the USA, the United Kingdom and several emerging countries (McKinsey Global Institute, 2021; World Bank, 2021; Riom and Valero, 2020).

Increased adoption of digital technologies has gone hand in hand with investments in complementary intangible assets. Consistently, national accounts data show that investments in IP assets (which comprise R&D expenditures, software and databases, and expenditures related to intellectual property products) remained largely unaffected by the initial shock (declining by 1.7 % in the second quarter of 2020 relative to the beginning of the year, against a 18.6 % drop in machinery and equipment and a 6.4 % drop in construction – Figure 4).

The pandemic has thus contributed to accelerating the shift to a more digital and knowledge-intensive economy. At one side, this might have been a stimulus for smaller and less productive firms to accelerate their process for catching-up to more productive firms. On the other side, if larger, already digital and more productive firms with complementary intangible assets were more likely to adopt new digital technologies and better exploit their returns, the crisis might have exacerbated the existing trend of productivity divergence and possibly strengthened the market power of more digital-intensive firms.

4. COVID-19 and business dynamics

Business dynamism has been significantly affected by the COVID-19 crisis. In the first half of 2020, the drop in demand and increased uncertainty reduced the number of new firms entering the market. Across OECD countries, entry dropped indeed markedly, ranging from around -3% in the Netherlands to around -70% in Portugal and Spain (Figure 5), reflecting the restrictions imposed by governments on activities. Indeed, evidence for five euro-area countries (Belgium, Finland, Italy, the Netherlands and Portugal) shows that sectors with a higher share of employment with face-to-face contact with customers registered a larger decline in new business registrations, both in the second and the fourth quarters of 2020 (Criscuolo, 2021).

Digitalisation has helped new firms to cushion the impact of the crisis. Especially in the first months of the crisis, the drop in firms' entry has been less severe in sectors with higher ICT task-intensity of jobs, ICT skills of workers and teleworking potential (OECD, 2021a; Criscuolo, 2021).

Since June 2020, firms' entry has generally recovered, with a positive outlook for job creation and innovation. The rebound in firms' entry displays, however, substantial differences across OECD countries. Figure 5 shows that some countries, such as Belgium, France, the Netherlands, the United Kingdom and the USA, have experienced a V-type recovery, i.e. a significant rebound in entry offsetting the reduction observed in the early months of 2020; in some of these countries, such as the USA, the number of new firms in 2021 even exceeded 2019 levels. Other countries, including Italy, Portugal and Spain, continue to struggle with a L-type recovery, still displaying considerably fewer entries at the end of 2020 than in 2019.

Subdued entry registrations observed in southern European countries may further exacerbate the secular declining trend in business dynamism and may have negative implications for employment: according to OECD estimates, a decline in firms' entry by 18%, such as the one experienced by southern countries in 2020, could generate a reduction in aggregate employment of between 0.4% and 0.6% after 3 years and between 0.3% and 0.5% after 10 years (Criscuolo, 2021).

Recent studies have shown, instead, that the increase in entry registrations observed in V-type countries has been mainly dominated by the trade sector. Country-level evidence from the USA, the United Kingdom and the Netherlands shows that the rebound has indeed been driven by online retail, i.e. by start-ups that are selling their products and services in online markets (Haltiwanger, 2021; Bahaj et al., 2021; Fareed and Overvest, 2021). The rising role of these new e-sellers likely reflects the increased incentives for firms to adopt digital technologies to shield from the effects of the COVID-19 shock and to respond to changes in consumers preferences for online transactions.

The support and regulatory measures implemented by governments to cushion the impact of the crisis have also markedly reduced firm exit, and in particular bankruptcies. Evidence from 12 OECD and non-OECD countries show that bankruptcies dropped by more than 30% in 2020 relative to their 2019 levels (OECD, 2021a).

The delay in bankruptcies may be beneficial in the short-term as it may have helped viable firms not to exit the market, but it also brings the risk of firms being kept in business despite being unproductive, with negative implications for resource reallocation and productivity growth in the long run. A growing body of evidence for OECD countries shows that public support measures have not slowed down the reallocation process: high-productive firms have been more resilient to the crisis, were more likely to remain in business and less likely to exit (Bighelli et al., 2021; Cros et al., 2021; Andrews et al., 2021; Kozeniauskas, Moreira and Santos, 2020).

Figure 12-5: Investments by tangibility of assets: EU-27 average, quarterly data – Q1 2015=100

Source: Criscuolo (2021)

Note: Green (blue) bars represent the percentage difference in entry in 2021 (2020) relative to the same month/quarter of 2019. Green (blue) lines represent the percentage difference with respect to 2019 in cumulative entry from January to each month of 2021 (2020).

Stats.: https://ec.europa.eu/assets/rtd/srip/2022/figure-12-5.xlsx

5. The impact of COVID-19 on technology diffusion

While the crisis has led to a general increase in firms' digitalisation, aggregate patterns in adoption of digital technologies and teleworking practices hide large heterogeneity across countries, firms and sectors.

Dispersion of digital technology adoption will most likely increase in the aftermath of the crisis. Indeed, several international studies, for the EU, the USA, the United Kingdom and emerging economies, provide evidence that larger, more productive and more digital firms have adopted more and more advanced technologies during the pandemic (EIB, 2021; McKinsey Global Institute, 2021; World Bank, 2021; Riom and Valero, 2020) and were more resilient to the shock (Valero, Riom and Oliveira-Cunha, 2021).

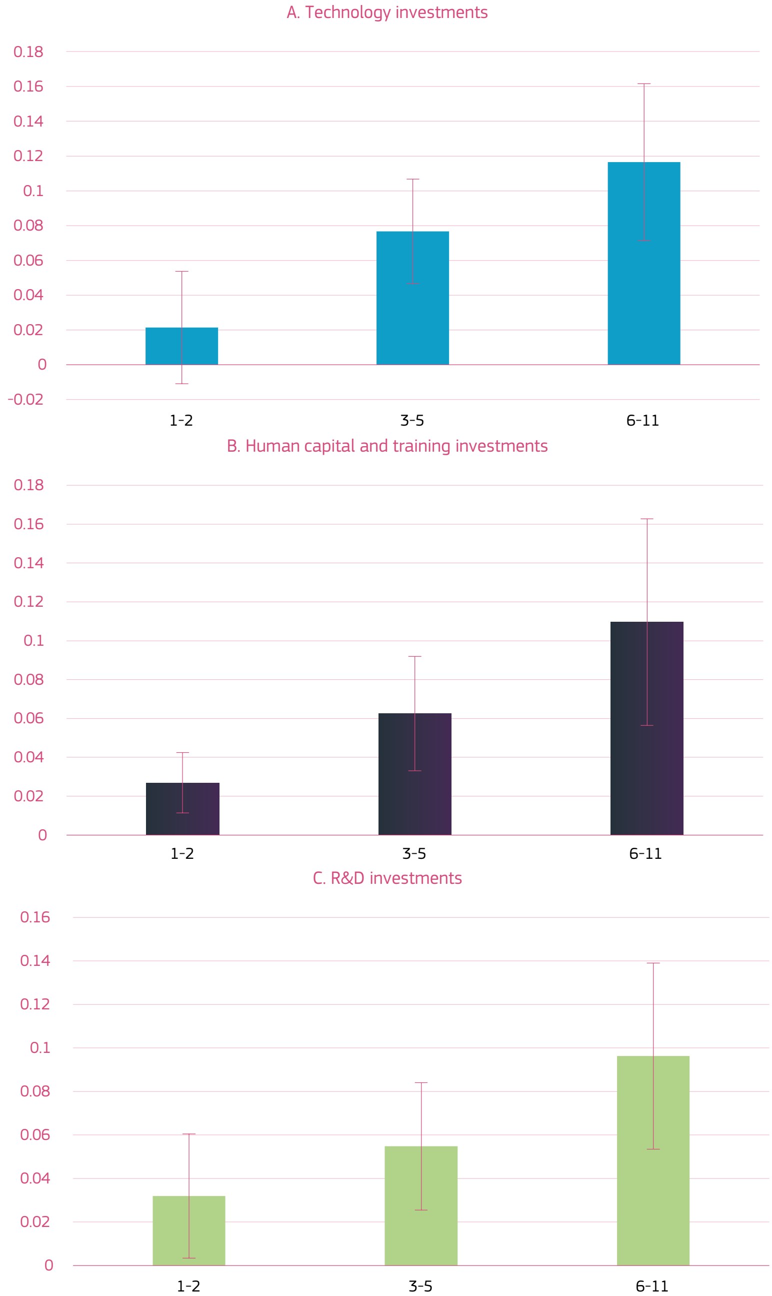
More in-depth single-country studies confirm that technology adoption during the crisis has been heterogeneous. Exploiting survey data collected in November 2020 for a representative sample of over 40 000 firms by the Italian National Statistical Institute, Calvino et al. (2022) show that firms that were using digital technologies before the pandemic were better able to cope with the crisis. Holding firm size, age, sector and location fixed, results show that these firms suffered less in terms of loss of revenues and faced a lower probability of closure. Moreover, these firms were more likely to continue investing in digital technologies and complementary intangible assets during 2020. Figure 6 shows that the probability of a firm raising its investments in new digital technologies, human capital and R&D during 2020 increases with the number of digital technologies the firm had adopted before the COVID-19 crisis.

The use of teleworking arrangements has increased markedly since the outbreak of the crisis and represented a key element of resilience among firms. However, substantial differences emerge across countries, partly reflecting pre-pandemic adoption. In euro-area countries, the share of workers teleworking ranges from around 30 % in Slovakia to more than 60 % in Belgium in June-July 2020. Despite the acceleration in its adoption, telework uptake remains positively associated with the quality of both firms' and workers' access to fast broadband infrastructure and with the ICT skills of the workforce (OECD, 2021b).

Telework adoption has also been heterogeneous across firms. Recent OECD analysis on the European Labour Force Survey has shown that larger firms (with more than 50 employees) experienced higher teleworking uptake in 2020 (Criscuolo, 2021). Firm-level evidence from Italy confirms that the use of teleworking practices during the COVID-19 pandemic was more widespread among digital firms, in particular those that already used cloud computing and had adopted advanced digital technologies (Calvino et al., 2022). This finding also holds true when measured within industry, region, size and age classes.

The COVID-19 crisis has thus provided an opportunity to boost the adoption of digital technologies and teleworking among firms. However, evidence points to a possible exacerbation of the pre-existing digital divide, with smaller and less productive companies struggling more. This might further increase productivity dispersion, lowering the incentives for new businesses to enter the market and for more productive firms to innovate.

Figure 12-6: Probability that firm increased its investments in 2020 relative to 2019 by type of expenditure and number of technologies adopted in 2018, Italy



Source: Calvino et al. (2022)

Note: The figure combines the coefficients of a regression model that estimates the probability of increasing investments in 2020 relative to 2019 by number of technologies adopted by firm in 2018 (grouped into four categories: 0, 1-2, 3-5, and 6-11). The bars indicate differences in probability compared to the base category of zero technologies. The model is estimated separately for investments in digital technology, human capital and training, and R&D. The regression includes sector and geographic-area fixed effects, and controls for labour productivity and firm size measured in 2018.

Stats.: https://ec.europa.eu/assets/rtd/srip/2022/figure-12-6.xlsx

6. COVID-19 and industry concentration

Heterogeneity in the adoption of digital technologies also poses the risk that larger, more productive firms may further reinforce their market power, with consequences for competition and concentration. Industry concentration might, thus, increase in the aftermath of the crisis particularly in digital-intensive sectors.

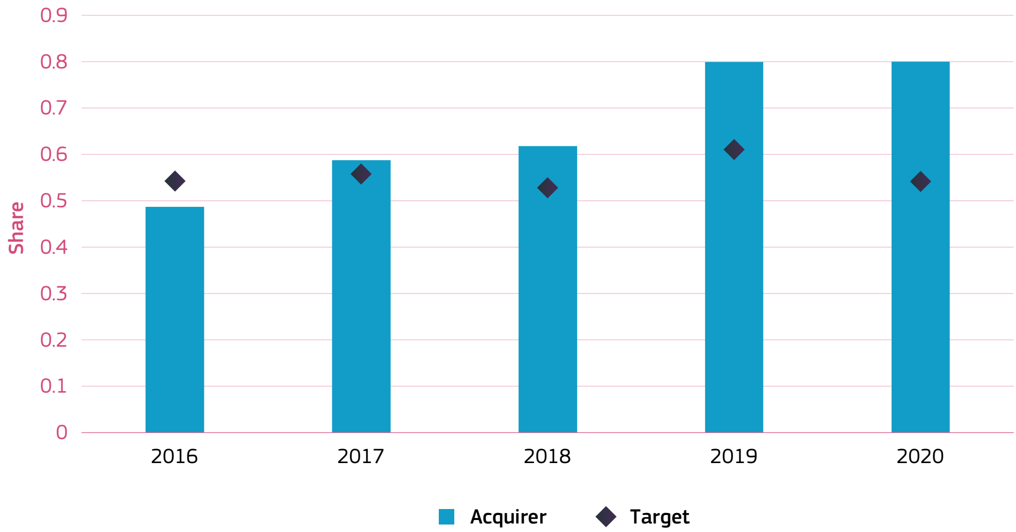
Although industry concentration data for the crisis period are not yet available, mergers and acquisitions (M&A) that occurred in 2020, for which timely data are available, provide a first insight into the consequences of COVID-19 on industry structure.

Figure 7 highlights that during the pandemic, over 80% of the total value of M&As originating in the EU had an acquirer active in highly digital-intensive sectors. Conversely, in terms of M&A targets, the share was almost equally split between high and low digital-intensive sectors.

More in-depth analysis shows that the rise in the total value of M&As with a digital acquirer was the result of an increase in the average value of deals performed by the largest firms in digital sectors (Criscuolo, 2021).

The evidence on M&A dynamics over the last years and the rising importance during the pandemic of larger players in high digital-intensive sectors, suggest that, in the aftermath of the crisis, industry concentration might increase and competition might be lowered, with potentially negative consequences for innovation.

Figure 12-7: Trends in share of total M&A value in high digital-intensity industries, 2016-2020



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Source: Calculations based on Zephyr 2021

Note: Share of M&A in high digital-intensity industries for the available EU countries. The countries include Austria, Belgium, Bulgaria, Croatia, Cyprus, Czechia, Germany, Denmark, Spain, Estonia, Finland, France, Greece, Hungary, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, the Netherlands, Poland, Portugal, Romania, Slovakia, Slovenia, Sweden. The M&A data reflects the annual total value of acquisitions (i.e. result in a majority stake), purchasing minority stakes and issuing of new share capital. The sample looks at deals where at least one acquirer (target) is located in the European Union and is active in manufacturing and services sectors (i.e. NACE rev.2 codes 10-33 and 45-83, excluding 19 and 68). M&A value is expressed in 2005 USD (exchange rates from the World Bank Development Indicators). The digital intensity of sectors is defined using the industry of the target firm and the STAN A38 global digital intensity indicator of 2013-15 constructed by Calvino et al. (2018); industries are classified as 'high-digital' if they are in the top quartile of the industry distribution in terms of digital intensity.

Stats.: https://ec.europa.eu/assets/rtd/srip/2022/figure-12-7.xlsx

7. Policy implications

The COVID-19 crisis has brought tremendous challenges for firms, but also generated new opportunities to foster the adoption of digital technologies and implement new business models.

However, evidence shows that – so far – these opportunities have been mostly seized by firms that were ex-ante more digital, more productive and larger in size. Consequently, the digital and productivity divides may be exacerbated, with consequences for competition and long-term growth. The extent to which the pandemic shock will have long-term negative impacts crucially depends on structural policy responses to ensure a more inclusive digital transformation.

To enable more firms and workers to benefit from this new wave of digitalisation, governments need to support complementary investments in skills and intangibles, especially among SMEs, and promote the diffusion of digital infrastructure.

As discussed in section 2, enhancing the skills of workers and improving the quality of management are crucial to increase the returns to technology adoption (Calvino et al., 2022; Brynjolfsson, Rock and Syverson, 2019; Sorbe et al., 2019). In the short-term, policies to support the training and upskilling of workers, as well as managerial coaching and consulting activities, can favour the digital transformation of smaller and less productive firms. Longer-term investments in education, notably in vocational secondary and in STEM and management tertiary courses, would also be key to increasing the supply of skilled workers and managers (Bianchi and Giorcelli, 2020; Calvino et al., 2022).

Supporting R&D expenditures, through direct government support or tax credits, has also been found to effectively boost firms' absorptive capacity (Berlingieri et al., 2020).

Providing high-speed and high-quality digital infrastructure is important to support the adoption of digital technologies and enable a greater share of employees to benefit from teleworking. Evidence from Italy shows that high speed connectivity complements other digitalisation policies (such as financial incentives to technology adoption), raising the performance of their beneficiaries (Calvino et al., 2022).

The crisis generated significant cross-sectoral reallocation of valued added, at least in the short-term. This, coupled with increased digitalisation of production may generate a substantial push to labour reallocation. Adjustment costs in the short-to-medium run, may result in high level of skill mismatch and frictional unemployment. To mitigate these initial frictions, policies could facilitate the transition to new occupations by providing workers with (digital) skills and supporting labour mobility.

In some OECD countries, the new opportunities brought by the pandemic have incentivised start-ups, particularly in online trade; however, firm entry remains subdued in southern European countries. Policies can encourage new business entry by reducing barriers to entry, such as red tape and regulatory uncertainty, and allowing easier access to financial resources. Additionally, the bankruptcies avoided thanks to the support measures implemented by governments may have contributed effectively to sustaining viable firms but may result in the risk of 'zombification' of the economy. To reduce this risk and smooth the process of firm entry and exit, it is important to ensure efficient insolvency procedures when phasing-out crisis measures.

The rising importance of digital technologies and intangible assets has been linked to the observed increase in concentration. The M&A dynamics observed during 2020, where larger players in digital sectors have entered in larger M&A deals, suggest that concentration might increase after the crisis, especially in digital intensive industries. Maintaining a level-playing field and supporting free entry in these markets will be crucial to ensure a competitive environment conducive to innovation and sustain long-term growth.

References

Andrews, D., C. Criscuolo, P. Gal (2016), *The Best versus the Rest: The Global Productivity Slowdown, Divergence across Firms and the Role of Public Policy*, OECD Productivity Working Papers, No. 5, OECD Publishing, Paris. https://www.oecd-ilibrary.org/economics/the-best-versus-the-rest_63629cc9-en

Ascari G., A. Colciago, R. Silvestrini (2021), *Business Dynamism, Sectoral Reallocation and Productivity in a Pandemic*, DNB Working Paper, 725.

Bahaj, S., S. Piton, A. Savagar (2021), 'Business creation during COVID-19', *mimeo.*

Bajgar, M., Berlingieri, G., Calligaris, S., Criscuolo, C. and Timmis, J. (2019), *Industry Concentration in Europe and North America*, Productivity Working Papers, 18.

Bajgar, M., C. Criscuolo, J. Timmis (2021), *Intangibles and industry concentration: Supersize me*, OECD Science, Technology and Industry Working Papers, No. 2021/12, OECD Publishing, Paris. https://www.oecd-ilibrary.org/science-and-technology/intangibles-and-industry-concentration_ce813aa5-en

Berlingieri, G., P. Blanchenay, C. Criscuolo (2017), *The Great Divergence(s)*, OECD Science, Technology and Industry Policy Papers, 39, OECD Publishing, Paris. https://doi.org/10.1787/953f3853-en

Berlingieri, G. et al. (2020), *Laggard firms, technology diffusion and its structural and policy determinants*, OECD Science, Technology and Industry Policy Papers, 86, OECD Publishing, Paris. https://www.oecd-ilibrary.org/science-and-technology/the-great-divergence-s_953f3853-en

Bianchi, N., & Giorcelli, M. (2020), 'Scientific education and innovation: from technical diplomas to university STEM degrees', *Journal of the European Economic Association*, 18(5), pp. 2608-2646.

Bighelli, T., T. Lalinksky and F. di Mauro (2021a), *Covid-19 government support may have not been as unproductively distributed as feared*, VOXEU, 19 August, available at https://voxeu.org/article/covid19-government-support-may-have-not-been-unproductively-distributed-feared

Bloom, N., Bunn, P., Mizen, P., Smietanka, P., Thwaites, G. (2020), *The impact of Covid-19 on productivity*, w28233, National Bureau of Economic Research.

Brynjolfsson, E., Rock, D., Syverson, C. (2019), *Artificial Intelligence and the Modern Productivity Paradox: A Clash of Expectations and Statistics* p. 23-60, University of Chicago Press.

Calligaris, S., C. Criscuolo, L. Marcolin (2018), *Mark-ups in the digital era*, OECD Science, Technology and Industry Working Papers, No. 2018/10, OECD Publishing, Paris. https://doi.org/10.1787/4efe2d25-en

Calvino, F., C. Criscuolo, R. Verlhac (2020), *Declining business dynamism: structural and policy determinants*, 94, OECD Publishing, Paris. https://doi.org/10.1787/77b92072-en

Calvino, F. et al. (2022), 'Closing Italian Digital Gap: The role of skills, intangibles, and policies', *mimeo.*

Calvino, F. Koegel, C. Manaresi, F. Verlhac, R. (2021), 'Keeping up with the frontier: technology diffusion, intangible assets and financing constraints', *mimeo.*

Corrado, C. et al. (2021), *New evidence on intangibles, diffusion and productivity*, OECD Science, Technology and Industry Working Papers, No. 2021/10, OECD Publishing, Paris. https://doi.org/10.1787/de0378f3-en

Criscuolo, C. (2021), 'Productivity and Business Dynamics through the lens of COVID-19: the shock, risks and opportunities', *mimeo.*

Cros, M., Epaulard, A., Martin, P. (2021), *Will Schumpeter Catch Covid-19?*, Centre for Economic Policy Research Discussion Paper Series, 15834.

DeStefano, T., J. Timmis (forthcoming), *Firm Digital Adoption during COVID-19*.

EIB (2021), *Digitalisation in Europe 2020-2021: evidence from the EIB Investment Survey*, European Investment Bank. https://www.eib.org/en/publications/digitalisation-in-europe-2020-2021.

Fareed, F., Overvest, B. (2021), *Business dynamics during the COVID pandemic*, CPB Netherlands Bureau for Economic Policy Analysis COVID-19 Publication, April.

Haltiwanger, J. (2021), 'Entrepreneurship during the COVID-19 Pandemic: Evidence from the Business Formation Statistics', in Entrepreneurship and Innovation Policy, University of Chicago Press.

Haske, J., S. Westlake (2018), *Capitalism without Capital: The Rise of the Intangible Economy*, Princeton University Press, Princeton, NJ.

McKinsey Global Institute (2021), *Will productivity and growth return after the COVID-19 crisis?*

OECD (2021a), *Business dynamism during the COVID-19 pandemic: Which policies for an inclusive recovery?*, OECD Policy Responses to Coronavirus (COVID-19), OECD Publishing, Paris. https://doi.org/10.1787/f08af011-en

OECD (2021b), *Strengthening Economic Resilience Following the COVID-19 Crisis: A Firm and Industry Perspective*, OECD Publishing, Paris. https://www.oecd-ilibrary.org/industry-and-services/strengthening-economic-resilience-following-the-covid-19-crisis_2a7081d8-en

Riom, C., A. Valero (2020), *The Business Response to Covid-19: the CEP-CBI survey on technology adoption*, CEP Covid-19 Analysis, 9.

Sorbe, S., et al. (2019), *Digital Dividend: Policies to Harness the Productivity Potential of Digital Technologies*, OECD Economic Policy Papers, No. 26, OECD Publishing, Paris. https://doi.org/10.1787/273176bc-en

Valero, A. and C. Riom, J. Oliveira-Cunha (2021), *The Business Response to Covid-19 one year on: findings from the second wave of the CEP-CBI survey on technology adoption*, CEP Covid-19 Analysis, 024.

World Bank (2021), *Uneven Recovery: East Asia and Pacific Economic Update*, April 2021, World Bank, Washington D.C. https://www.worldbank.org/en/region/eap/publication/uneven-recovery-east-asia-and-pacific-economic-update-april-2021

CHAPTER 13

THE GREEN AND DIGITAL TWIN TRANSITION ACROSS EU REGIONS*

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* We thank Alessio Mitra and Julien Ravet for their helpful discussion and comments. The views expressed in this paper are those of the authors and do not necessarily reflect the views of the European Investment Bank.

Summary

The recovery from the COVID-19 pandemic provides an opportunity to accelerate the green and digital transformation and to strengthen social cohesion to make the EU economy more resilient and sustainable. Using data of the 2021 EIB Investment Survey (EIBIS), this chapter shows that firms in the EU's cohesion regions tend to invest less in digitalisation and in green measures than firms in non-cohesion regions. At the same time, firms in cohesion regions express greater concerns about the current impact of climate change on their business. They need to reassess their operating environment, innovate and adapt. Accelerating the EU's green and digital transformation will also require a policy framework that fosters climate-related and digital innovation at the technological frontier. Using patent data, we show that the EU is a global leader for patenting activities at the crossroads of digital and green technologies. We also find that cohesion regions have a relatively high share of patents in these technology domains: they hold fewer patents overall than non-cohesion regions but have a strong focus on green and digital innovation. As the potential for technological advancements in these areas accelerates, the EU will be well-placed to maintain its lead, but this will require significant investment across EU regions.

1. Introduction

Europe faces a choice. The recovery from the coronavirus pandemic provides an opportunity to accelerate the green and digital transformation and to strengthen social cohesion to make the EU economy more resilient and sustainable. Yet there are also serious risks. Due to the uncertainty created by the COVID-19 pandemic, many firms cut investment activities in 2020, postponing their plans to adopt advanced digital technologies and climate-related measures.

Much is at stake. Europe's future prosperity depends on advancing in digitalisation and keeping its lead position in climate change. The aim is to foster a more competitive and smarter Europe, by creating an inclusive environment that incentivises firms across the EU to invest in the twin green and digital transition.

Support for economic, social and geographical cohesion has been an integral part of the EU from the very start. EU integration drove economic convergence, reduced regional and social disparities and created opportunities for many people, but challenges remain. The pandemic's impact was not felt evenly across Europe, and regions are rebounding at different speeds. Increasing digitalisation and the greening of the economy will bring profound structural change. Europe risks becoming more unequal once the pandemic has receded. A process of re-adjustment awaits firms and regions that lag behind.

Using data from the 2021 EIBIS, this chapter shows that EU's cohesion regions (less developed and transition regions) have a lower share of firms that invest in digitalisation and in green measures than non-cohesion regions. At the same time, firms in cohesion regions express greater concerns about the current impact of climate change on their business. They need to reassess their operating environment and innovate and adapt. They have to invest to become more digital and to tackle physical and transition risks from climate change. This will help ensure their survival and future competitiveness in a new, greener and more digital environment.

Accelerating the EU's green and digital transformation will also require a policy framework that fosters climate-related and digital innovation at the technological frontier. Using PATSTAT data, we find that the EU is a global leader for patenting activities at the crossroads of digital and green technologies. We also show that non-cohesion regions hold a large number of patents in these domains. At the same time, cohesion regions have a relatively high share of patents in these technology domains: they hold fewer patents overall but are strongly specialised in green and digital innovation.

As the potential for technological advancements in these areas accelerates, the EU will be well-placed to maintain its lead, but it can take nothing for granted. European policymakers will have to do everything it takes to ensure that this dominant position is not rapidly lost. The strong position of the USA and China in the development of new technologies in most digital fields could make it difficult for Europe to remain on top in the areas in which it currently excels. The European Green Deal and the EU's Digital Strategy are the cornerstone of the recovery plan for Europe. Combined with the national recovery and resilience plans, the initiatives present a unique opportunity to transform the EU economy and make it greener, more digital and more innovative.

The remainder of this chapter is organised as follows. The next section introduces the two different sources of data that we use: EIBIS on the adoption of digital technologies and climate related measures and PATSTAT on innovation in green and digital technologies. Using EIBIS data, the third section identifies corporate green and digital profiles based on firms' current use of advanced digital technologies and their investments to tackle climate change. Green and digital firms tend to perform better but they also report facing different obstacles to investment than firms that are not green or digital. In the fourth section, we show that there is a high focus on innovation at the crossroads of digital and green technologies across Europe, but we also highlight that Europe's pole position risks being overtaken. The last section concludes with policy implications for the green and digital recovery from the COVID-19 crisis.

2. Data

EIBIS is an annual survey that gathers qualitative and quantitative information on investment activities by non-financial corporates, their financing requirements and the difficulties they face. Every year since 2016, the survey has collected data from more than 13 000 businesses located in all EU countries, the United Kingdom and, since 2019, the USA. The focus of this chapter is EU cohesion and thus relies only on data for the 27 EU countries. Using a stratified sampling methodology, the survey is designed to be representative at the level of the country, sector (manufacturing, construction, services and infrastructure) and firm-size class (micro, small, medium and large) [1].

EIBIS also gathers qualitative information on firms' adoption of digital technologies and their investments to tackle the impact of climate change. This chapter identifies green-digital firm profiles based on two dimensions:

- the current adoption of the state-of-the-art digital technologies;
- investments to tackle the impacts of weather events and to reduce carbon emissions.

The survey thus provides us with unique information on the adoption of digital technologies and green investments in the EU.

EIBIS data are collected in a consistent manner and with the same methodology for a large number of firms across different countries, making it possible to carry out a comparative analysis of investment activities in diverse institutional settings.

As economic convergence lies at the heart of the EU, the goal of this chapter is to compare different regions, and to analyse where their firms stand when it comes to digitalisation and investments to tackle climate change. In section 4, we also use Worldwide Patent Statistical Database (PATSTAT) data on patenting activities in the development of new green and digital technologies across different EU regions. In the following, we refer to NUTS2 regions with incomes above the EU average as 'more developed' or 'non-cohesion' regions, to those with GDP per capita between 100 % and 75 % as 'transition' regions, and to those with incomes below 75 % as 'less developed'[2].

The patent data used in this chapter are sourced from PATSTAT, a patent statistics database held by the European Patent Office (EPO) and developed in cooperation with the World Intellectual Property Organization (WIPO), OECD and Eurostat. Since 2006, PATSTAT's raw patent data are collected from more than 100 regional and national patent offices worldwide. Amongst others, PATSTAT contains information on technological domains related to the patents[3].

1 The sector classification in EIBIS is based on the NACE classification of economic activities: manufacturing: group C; construction: group F; services: group G (wholesale and retail trade) and group I (accommodation and food services activities); infrastructure: groups D and E (utilities), group H (transportation and storage) and group J (information and communication). The firm size classes in EIBIS are: micro (5-9 employees); small (10-49 employees); medium-sized (50-249 employees); large (250 employees).

2 NUTS2 refers to the Nomenclature of Territorial Units for Statistics. NUTS2 regions are the basic regions for EU regional policies. According to regions' income classification, the availability of co-financing from EU funds differs, with poorer regions having the possibility to receive more financial support.

3 The data sourced for this chapter and the classification of technological domains were produced in collaboration with the Centre for Research and Development Monitoring (ECOOM) in Belgium.

2.1 Adoption of digital technologies

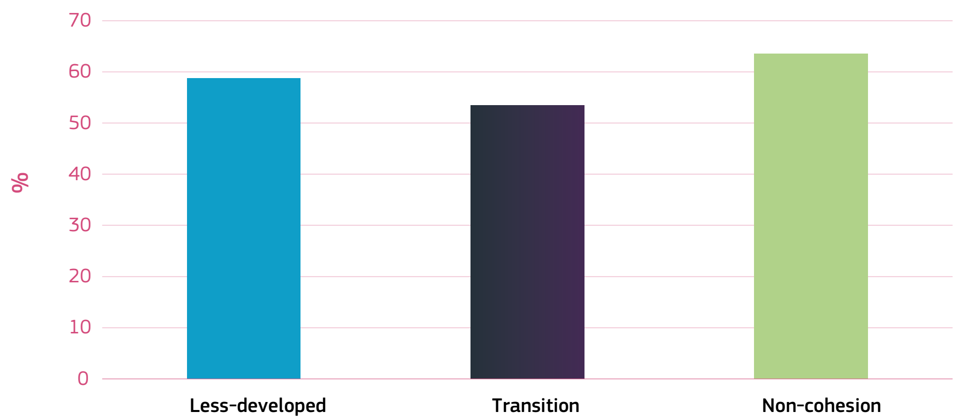
The COVID-19 crisis has led to wider recognition of the importance of digital transformation. Until recently, the implementation of advanced digital technologies was considered an important contributor to market success and usually associated with the most innovative and modern companies. The pandemic, however, has made the digital transformation an integral part of many firms' survival. Digitalisation turned out to be indispensable to prevent business disruption, organise work remotely and improve communication with customers, suppliers and employees (EIB, 2021).

Firms in non-cohesion regions tend to be more digital. In 2021, 63 % of firms in non-cohesion regions implemented at least one advanced digital technology, compared to only 53 % of firms in transition regions and 59 % in less-developed regions (Figure 1)[4]. Significant differences in digital adoption also exist across firm size classes: large firms digitalise faster across all regions.

2.2 Investments to tackle the impacts of weather events and the process of reduction in carbon emissions

Firms in non-cohesion regions are taking clearer steps to tackle the physical and transition risks from climate change (Figure 2). Specifically, EIBIS asks firms if they have already invested or if they plan to invest in the next 3 years to tackle the impacts of weather events and to deal with the process reducing

Figure 13-1: Adoption of digital technologies (% of firms), by cohesion region



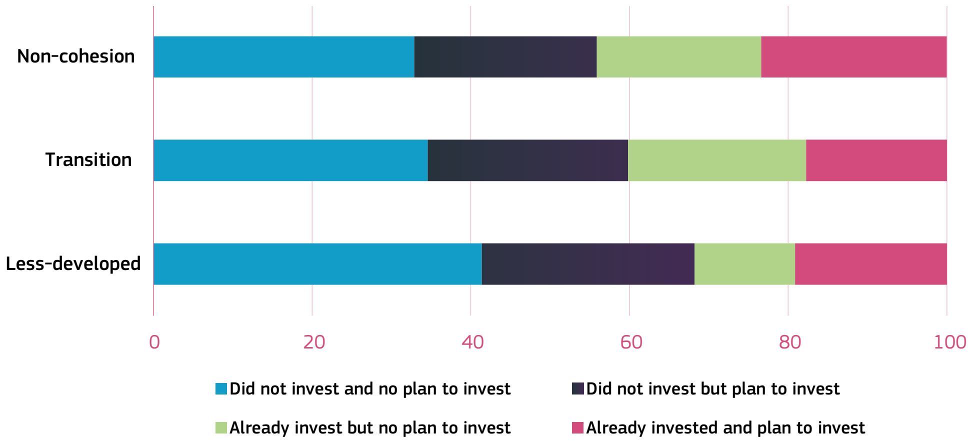
Source: EIB Investment Survey (EIBIS, 2021), firms in EU-27
Note: The figure is based on a survey asking firms to answer questions on the use of four different digital technologies in their business. A firm is identified as digital if at least one advanced digital technology was implemented in parts of the business. The state-of-the-art digital technologies considered are different across sectors. Firms in manufacturing are asked about the use of: (a) 3D printing; (b) advanced robotics; (c) internet of things (IoT); (d) big data analytics and artificial intelligence (AI). Firms in construction: (a) 3D printing; (b) drones; (c) IoT; (d) virtual reality. Firms in services: (a) virtual reality; (b) platforms; (c) IoT; (d) AI. Firms in infrastructure: (a) 3D printing; (b) platforms; (c) IoT; (d) AI.
Stats.: https://ec.europa.eu/assets/rtd/srip/2022/figure-13-1.xlsx

4 All figures relying on EIBIS data are weighted using value added to make the sample of firms representative of the economy.

carbon emissions. 44 % of firms in non-cohesion regions have already invested in green measures, compared to 40 % in transition regions and 32 % in less-developed regions. Less-developed regions have the highest share of firms that neither invested nor plan to invest to tackle the impacts of climate change.

At the same time, firms in less-developed regions are more likely to report that climate change currently has a major impact on their business than firms in the other regions. Firms in transition regions are more likely to assert that climate change has a minor impact, and firms in non-cohesion regions are more likely to say that climate change has no impact at all (Figure 3). Climate change and the related changes in weather patterns include, for example, higher temperatures, more rainfall or extreme climate events, such as such as droughts, flooding, wildfires or storms. Overall, most firms consider that this currently has an impact on their business.

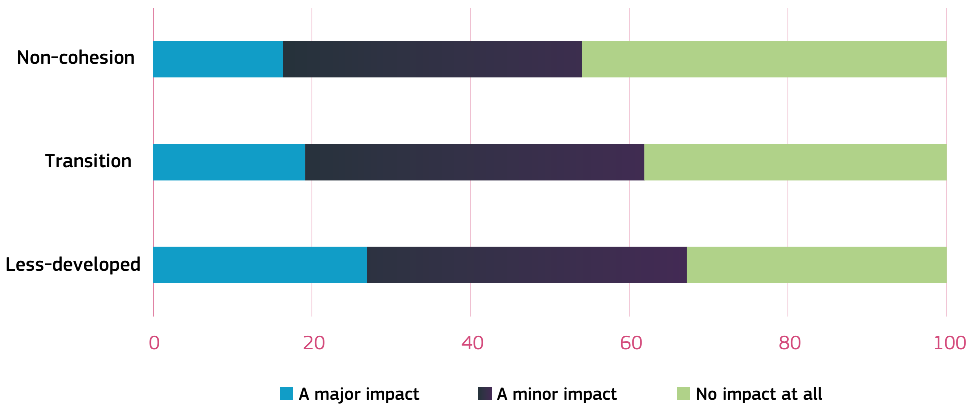
Figure 13-2: **Climate investment behaviour (% of firms) by cohesion region**



Science, Research and Innovation Performance of the EU 2022

Source: EIB Investment Survey (EIBIS, 2021), firms in EU-27
Stats.: https://ec.europa.eu/assets/rtd/srip/2022/figure-13-2.xlsx

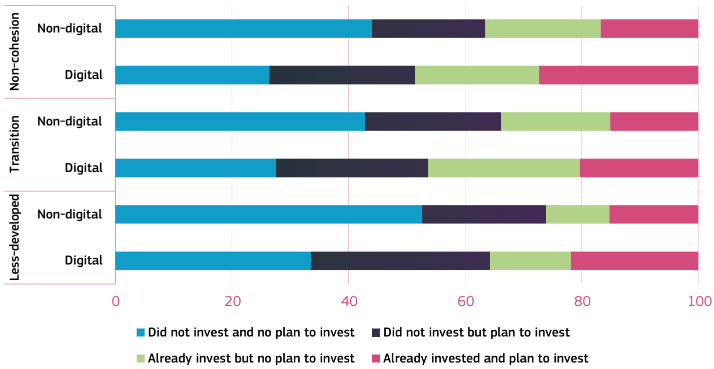
Figure 13-3: **Current impact of climate change on business (% of firms) by cohesion region**



Science, Research and Innovation Performance of the EU 2022

Source: EIB Investment Survey (EIBIS, 2021), firms in the EU-27
Stats.: https://ec.europa.eu/assets/rtd/srip/2022/figure-13-3.xlsx

Figure 13-4: Climate investment behaviour (% of firms) by digital intensity and cohesion region



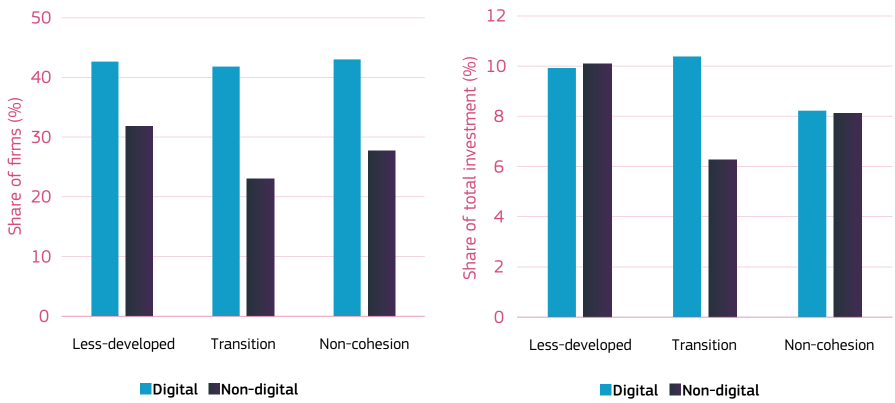
Science, Research and Innovation Performance of the EU 2022

Source: EIB Investment Survey (EIBIS, 2021), firms in the EU-27
Stats.: https://ec.europa.eu/assets/rtd/srip/2022/figure-13-4.xlsx

Digital technologies will be key enablers of the green transition under the European Green Deal that will transform the EU into a modern, resource-efficient and competitive economy (European Commission, 2019). We find that digital firms are more likely to take clear steps to tackle the physical and transition risks from climate change. In addition, digital firms are more likely to report having already invested but also having further plans to invest in green measures, a pattern that holds across all regions (Figure 4).

Furthermore, digital firms tend to invest more in measures to improve energy efficiency. However, the incidence and intensity of investment in energy efficiency are not only associated with firms' digital status but also with the region in which they are located (Figures 5a and 5b). The gap between non-digital and digital firms in energy-efficiency investment is most pronounced for firms in transition regions.

Figure 13-5: Firms investing in measures to improve energy efficiency (% of firms) and share of total investment allocated to these measures (% of total investment) by digital intensity and cohesion region



Science, Research and Innovation Performance of the EU 2022

Source: EIB Investment Survey (EIBIS, 2021)
Note: A firm is identified as digital if at least one advanced digital technology was implemented in parts of the business.
Stats.: https://ec.europa.eu/assets/rtd/srip/2022/figure-13-5.xlsx

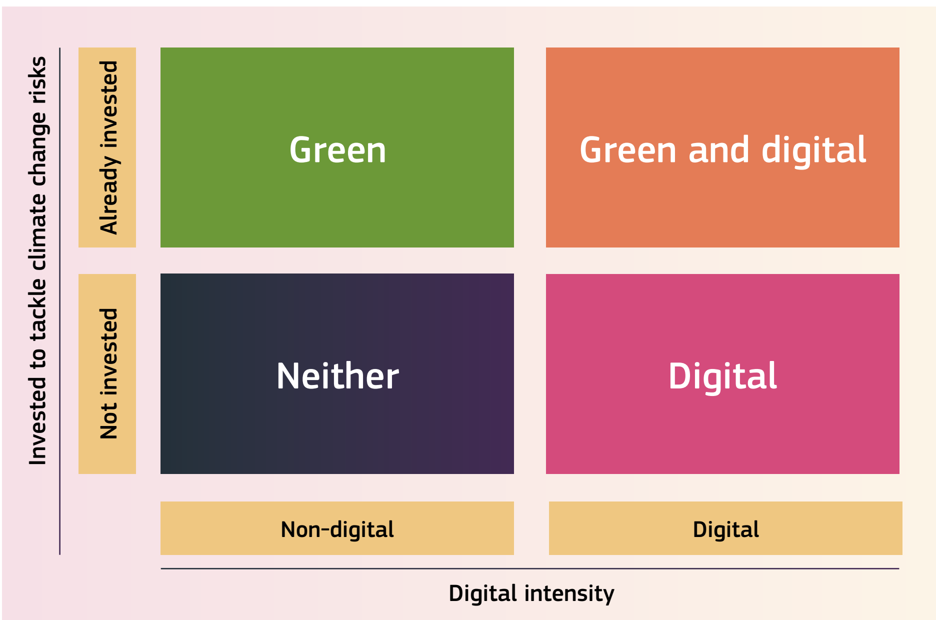
3. The green and digital corporate categories

The previous section has identified significant differences in digital and green investments across firms and regions. The next step is to understand which firms are forging ahead with digital and green adoption and which firms are falling behind. To this end, we classify firms into four profiles based on their green and digital investment activities (Figure 6).

- green and digital firms that have already invested to tackle the impacts from climate change and have implemented at least one digital technology in parts of the business (see also Figure 4);
- digital firms that have implemented at least one advanced digital technology in parts of the business but have not yet invested to tackle the impacts from climate change;
- green firms that have already invested to tackle the impacts from climate change but have not adopted advanced digital technologies;
- neither green nor digital firms that have neither invested to tackle the impacts from climate change nor adopted advanced digital technologies (listed in note to Figure 1).

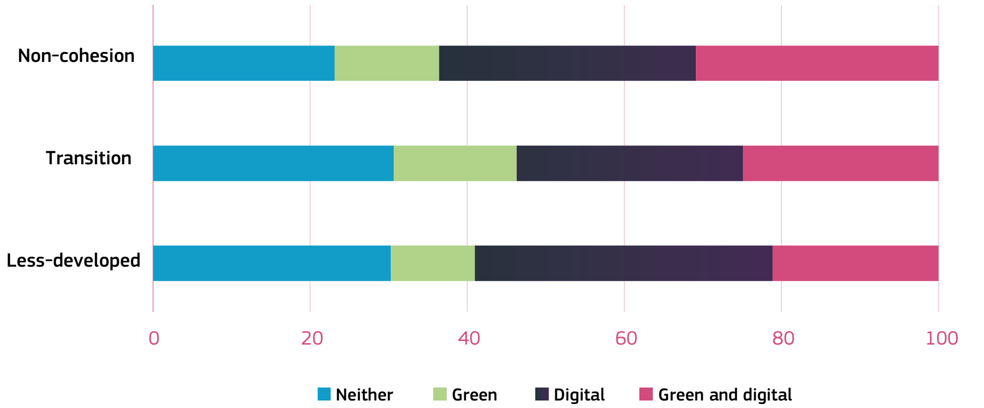
The share of green and digital firms is higher in non-cohesion regions (31 %) than transition regions (25 %) and less-developed regions (21 %). In addition, the share of firms that are neither green nor digital is higher in transition and less-developed regions than in non-cohesion regions (Figure 7).

Figure 13-6: **The four green and digital corporate profiles**



Source: authors' elaboration
Stats.: https://ec.europa.eu/assets/rtd/srip/2022/figure-13-6.xlsx

Figure 13-7: Green and digital corporate profiles (% of firms) by cohesion region

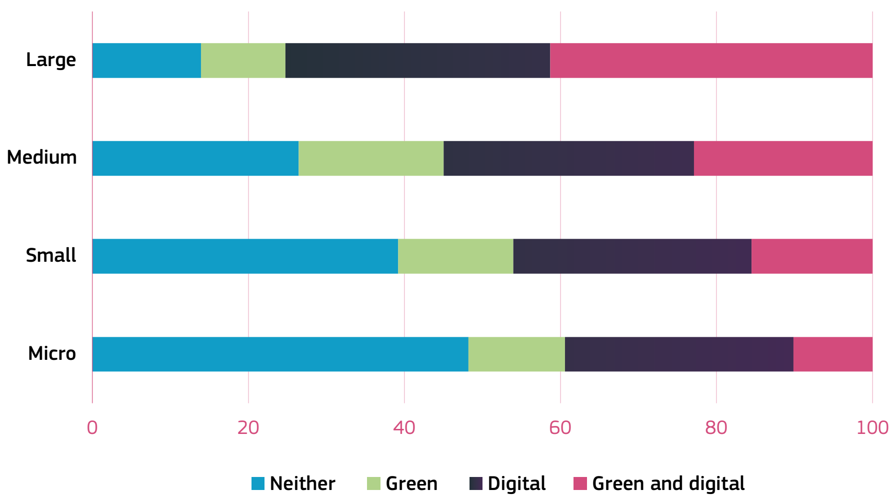


Science, Research and Innovation Performance of the EU 2022

Source: EIB Investment Survey (EIBIS, 2021)
Note: See note to Figure 6 for the definition of corporate green and digital profiles.
Stats.: https://ec.europa.eu/assets/rtd/srip/2022/figure-13-7.xlsx

Larger firms are more likely to be both digital and green than small ones (Figure 8). While only 10 % of micro firms and 16 % of small firms are green and digital, this share increases markedly for medium-sized (23 %) and large firms (41 %). Furthermore, micro firms are least likely to be both digital and green in the less developed regions. The relationship between firm size and green and digital activities can be explained by the fact that the adoption of these technologies involves high fixed costs and can be risky. Costs and risks are easier to bear if they are spread over larger revenue streams.

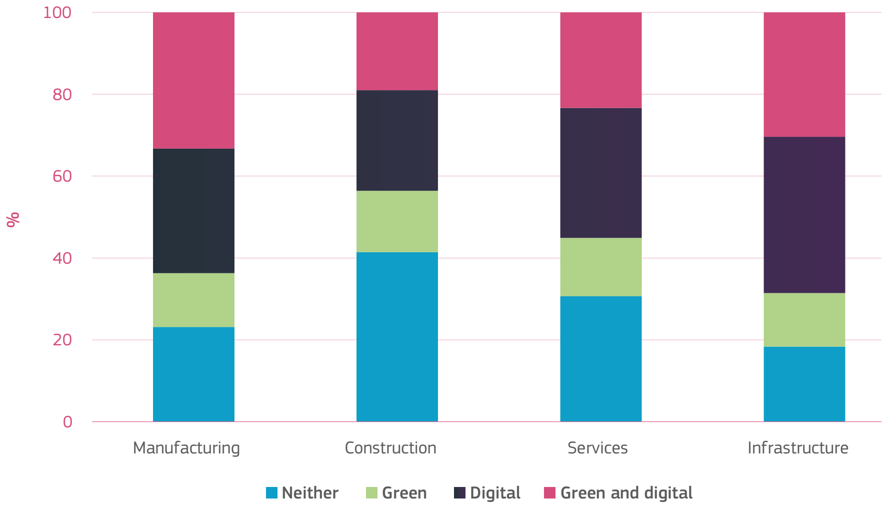
Figure 13-8: Corporate green and digital profile (% of firms) by firm size



Science, Research and Innovation Performance of the EU 2022

Source: EIB Investment Survey (EIBIS, 2021)
Note: See note to Figure 6 for the definition of corporate green and digital profiles.
Stats.: https://ec.europa.eu/assets/rtd/srip/2022/figure-13-8.xlsx

Figure 13-9: Corporate green and digital profile (% of firms) by sector



Source: EIB Investment Survey (EIBIS, 2021)
Note: See note to Figure 6 for the definition of corporate green and digital profiles.
Stats.: https://ec.europa.eu/assets/rtd/srip/2022/figure-13-9.xlsx

The manufacturing (33 %) and infrastructure (30 %) sectors have a higher share of firms that are green and digital (Figure 9). This may be partly explained by the greening of the transportation sector. At the same time, the construction sector has a particularly high share of firms that did not invest in green measures or digital technologies (41 %), followed by the service sector (31 %).

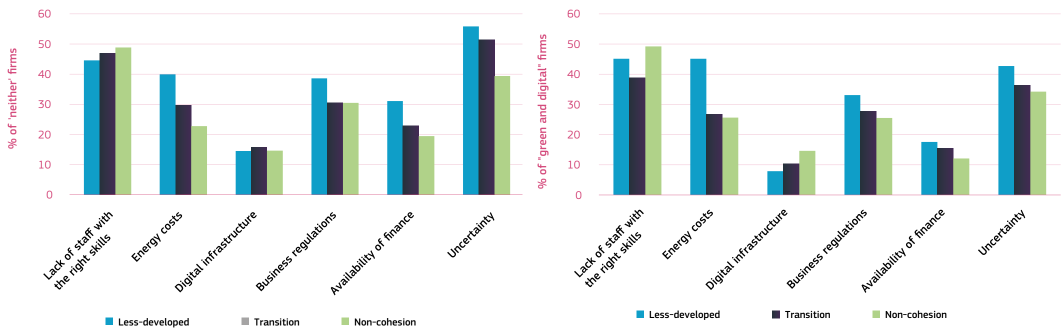
3.1 Obstacles to investment in the EU

EIBIS survey data also allow us to look at the different barriers firms perceive when thinking about investment decisions. Identifying barriers to investment activities that specifically impedes firms that are not green or digital is relevant to develop policies that will help move these firms away from their 'neither' status. Similarly, identifying the obstacles faced by firms in different regions will allow EU policymakers to accelerate investment in the green and digital transition.

The availability of staff with the right skills is the most important constraint to corporate investment in the EU, with 46 % of EU firms reporting it as major obstacle. Uncertainty about the future appears to be the most important obstacle for 'neither' firms in transition and less-developed regions. Business and labour market regulations are second-order major impediments.

When focusing on differences between different profiles, and in particular between firms that have not invested in either green or digital and firms that invested in both, we observe marked differences in the perception of major obstacles to investment. First, firms that are neither green nor digital complain more often that barriers are a major impediment (Figure 10a), compared to firms that are digital and green (Figure 10b). The difference is largest for uncertainty, where 45 % of 'neither' firms report it as a major obstacle compared to 35 % of green and digital firms. Similarly, the availability of finance is more often reported as a

Figure 13-10: Major obstacle to investment (% of firms)



Source: EIB Investment Survey (EIBIS, 2021)
Note: See note to Figure 6 for the definition of corporate green and digital profiles.
Stats.: https://ec.europa.eu/assets/rtd/srip/2022/figure-13-10.xlsx

major impediment for firms falling in the neither category than for green and digital firms (22 % vs 13 %, respectively). Furthermore, this barrier seems to be greater in less-developed regions than in non-cohesion regions.

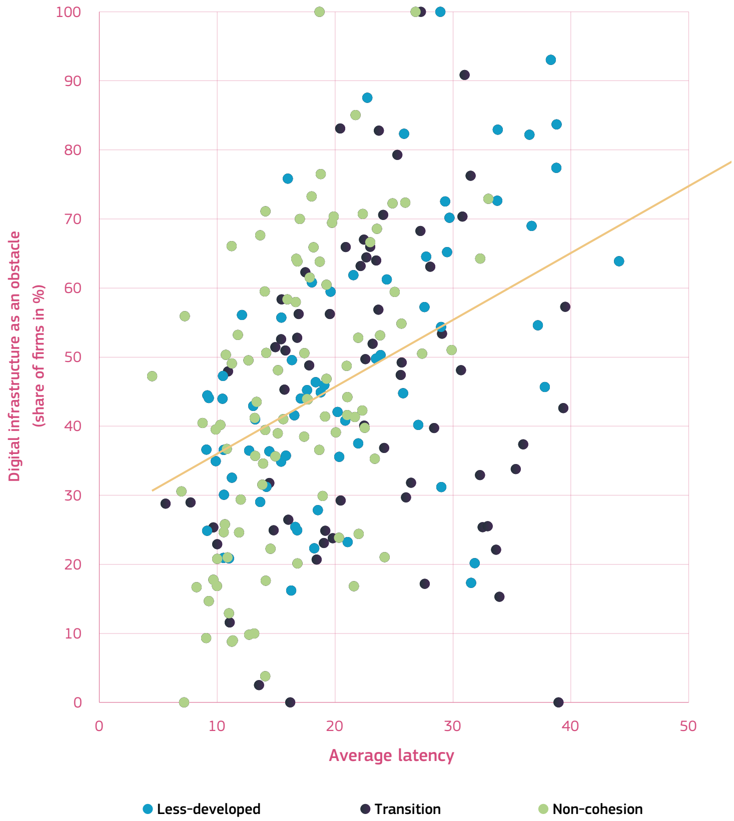
A large share of EU firms consider access to digital infrastructure as an obstacle to investment. However, the assessment varies significantly across regions. For example, firms operating in regions with low average latency (a proxy for good connection) tend to have higher rates of digital adoption (EIB, 2022). At the same time, they also have a lower share of firms complaining about digital infrastructure (Figure 11). This indicates that many EU regions have the potential to unlock investment in the digital transformation of businesses by making access to faster broadband speeds more widespread. The operating environment can have an impact on firms' decisions to become greener and more digital.

3.2 Firm performance and employment along the green digital grid

It is worrisome that a large share of European firms have not invested in the green and digital transformations as this could have long-term negative consequences for the economy. The pandemic has led to major changes in the nature and organisation of work, with implications for firm productivity, employment, wages and investment. This section explores a range of firm performance indicators along the green digital grid. For ease of exposition, we focus on firms that have not invested in either green or digital and firms that invested in both. The analysis is based on correlations and does not necessarily imply causation.

Being green and digital has clear upsides. Green and digital firms tend to be more productive across all regions in Europe

Figure 13-11: Internet quality and share of firms mentioning digital infrastructure as an obstacle (in %)



Science, Research and Innovation Performance of the EU 2022

Source: EIB Investment Survey (EIBIS, 2021) and European Data Journalism Network (2021)

Stats.: https://ec.europa.eu/assets/rtd/srip/2022/figure-13-11.xlsx

(Figure 12)[5]. The productivity premium for green and digital firms compared to 'neither' firms that do not invest in green or digital measures is significant in all regions.

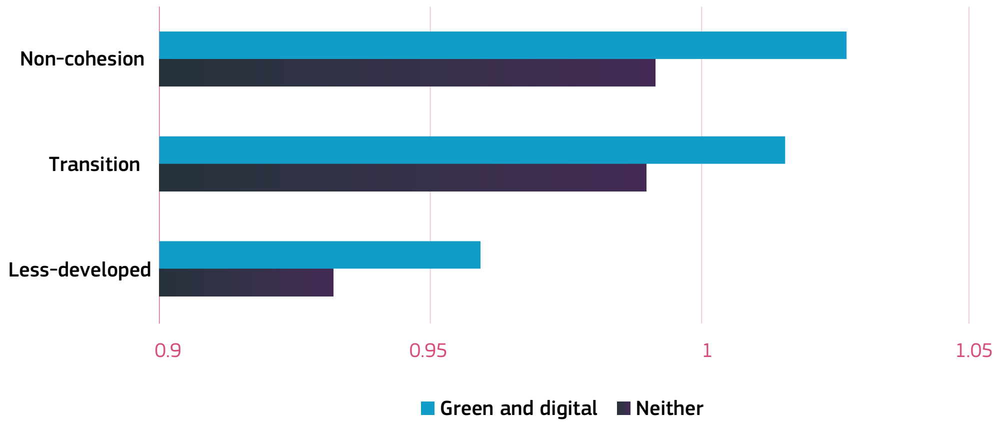
As argued by many economists, digitalisation can have an impact on shifting demand for skills, leading to job polarisation (Acemoglu and Autor, 2011; EIB, 2018; Acemoglu and Restrepo, 2020).

By comparing the current number of employees with the number of employees in the same firm a year ago, Figure 13 highlights that firms forging ahead with the green and digital transformation are more likely to have increased employment compared to before the pandemic[6]. At the same time, those that neither invested to tackle climate change nor to adopt advanced digital technologies were more likely to downsize.

5 All the associations discussed in this chapter – such as the association of green and digital investment with firm performance, employment, training or wages – also hold in multivariate regression analysis, controlling for potential factors that might confound the analysis, such as size, sector and region of the firms.

6 Across all profiles, about one in two firms reported that sales decreased due to COVID-19. The drop in sales has been more severe for firms that invested in neither digital nor green than for firms that invested in both digital and green. However, the association of employment growth with green and digital investment also holds in multivariate regression analysis controlling for impact of COVID-19 on firm sales, firm size, sector and region of the firms.

Figure 13-12: Median labour productivity (index, EU average=1) by cohesion region



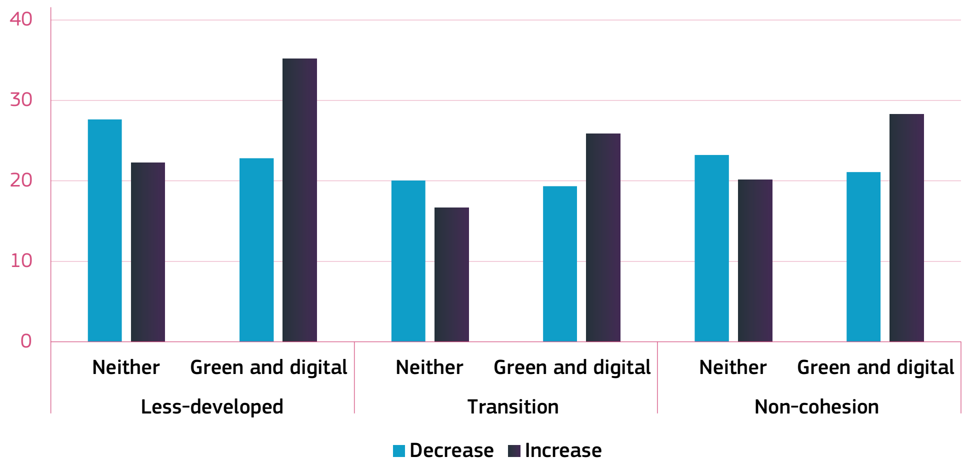
Science, Research and Innovation Performance of the EU 2022

Source: EIB Investment Survey (EIBIS, 2021)

Note: See note Figure 6 for the definition of corporate green and digital profiles.

Stats.: https://ec.europa.eu/assets/rtd/srip/2022/figure-13-12.xlsx

Figure 13-13: Employment growth (% of firms) by green digital profile and cohesion region



Science, Research and Innovation Performance of the EU 2022

Source: EIB Investment Survey (EIBIS, 2021)

Note: See note Figure 6 for the definition of corporate green and digital profiles.

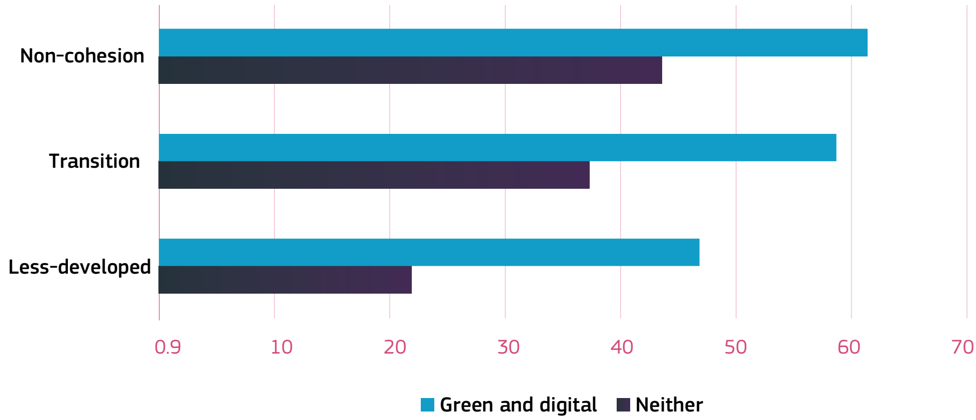
Stats.: https://ec.europa.eu/assets/rtd/srip/2022/figure-13-13.xlsx

In addition, firms undertaking structural transformation through green measures and digital technologies invest in training workers.

Presumably this is also to prepare their workforce for the future by improving their green and digital skills. The firms leading the green and digital transition invest more often in employee training compared to firms that do not invest in green or digital (Figure 14). The variation across regions may also be related to the incidence of teleworking and the ability to deliver training online, which often proved difficult, particularly for smaller firms (OECD, 2021). Furthermore, green and digital firms tend to pay higher wages on average to their employees (EIB, 2022)[7].

The digital transformation frequently goes hand in hand with the automation of routine jobs. However, this automation often comes at the expense of demand for low- and medium-skilled jobs. On the other hand, to use digital technologies, firms need to have a pool of qualified personnel with the right skills. While digitalisation can disrupt employment and tasks, the jobs created by green and digital firms often appear to be relatively well paid.

Figure 13-14: Firms investing in training (in %) by green and digital profile and cohesion region



Source: EIB Investment Survey (EIBIS, 2021)
Note: See note Figure 6 for the definition of corporate green and digital profiles.
Stats.: https://ec.europa.eu/assets/rtd/srip/2022/figure-13-14.xlsx

7 The association of wages with digital and green investment also holds in multivariate regression analysis controlling for labour productivity, firm size, sector and region of the firms.

4. Green and digital innovation

Investments to tackle the impact of climate change and the adoption of digital technologies should also go in hand with innovation at the technological frontier. An increasing number of companies are developing new technologies in these areas as they try to seize new opportunities in the fast-changing digital and economic environment.

The development and diffusion of technologies that generate environmental benefits are, by now, acknowledged to be crucial for green growth. It is evident that the challenge of climate change cannot be tackled without technological advances, and progress must be made in a variety of sectors (Aghion et al., 2019). Investing in environmentally friendly technologies and supporting innovation in the private sector are clearly stated ambitions of the European Green Deal (European Commission, 2019).

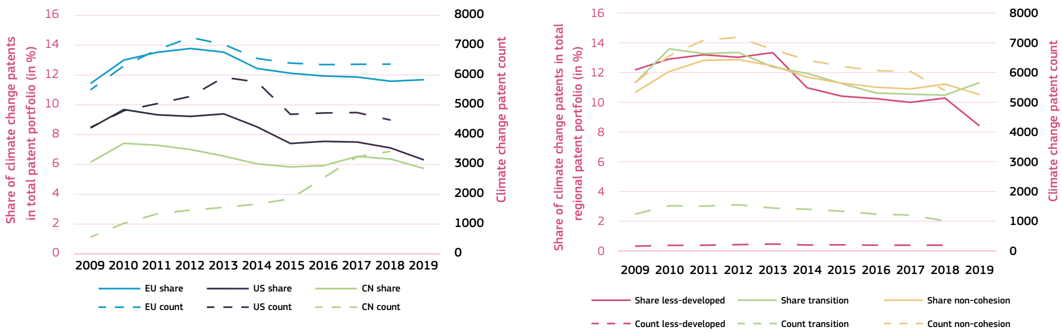
If digital technologies are properly employed, they could play an essential role in tackling environmental challenges, for example by improving food production with precision agriculture or by reducing energy consumption. Digital technologies can also be instrumental in monitoring climate change and facilitating the much-needed shift towards a circular economy. They can foster more sustainable supply chains. The cloud, in combination with mobile data and social media, can take products or even entire industries fully online. Moreover, 3D printing creates opportunities for manufacturing goods locally, leading to quicker turnaround on product designs and development (Lacy and Rutqvist, 2015). Recent reports convincingly document that the ICT sector and its recent digital advances are contributing to growing energy consumption, but that the net benefits of the sector outweigh the costs (GeSI, 2019; IPCC, 2021).

The EU is one of the main players in new technologies developed to tackle climate change. The EU has many climate change-related patents and is far ahead of the USA and China. However, Europe's climate-change innovation is stagnating and has even been declining in recent years (Figure 15a). In China and the USA, there even seems to be a persistent negative trend in the share of patents that are dedicated to climate change. This seemingly stands in stark contrast with the strong need for the development of new technologies in this area. In a way, the share of green patents (out of all patents applied for in a given year) reflects the specialisation of an economy in the development of new green technologies.

The rate of development of green technologies not only shows a large divergence across the globe, but also within Europe. In line with firm-level investments to tackle the impacts of climate change, non-cohesion regions are leading the way for green innovation, as reflected in the number of green patents applied for (Figure 15b). Nevertheless, the picture is a little more nuanced when looking into the share of patents dedicated to green technologies across regions. While non-cohesion regions are still frontrunners, the share of green patents in transition and less-developed regions follows the non-cohesion pattern very closely. Overall, while absolute innovation levels are clearly lower in cohesion regions, the focus on green technology development is comparable. This indicates that market players realise the importance of technology development in these areas, albeit at a different scale.

The EU needs to play a more prominent role in developing new digital technologies. In terms of digital innovation activities overall, as measured by the number and share of patent applications, the EU is lagging behind the USA and China

Figure 13-15: Climate change patents, 2009 to 2019



Source: PATSTAT data prepared in collaboration with ECOOM
Note: The dotted lines show the number of green patents (right axis); the solid lines show the percentage share of green patents in the total portfolio of domestic patents (left axis). The left panel shows Patent Cooperation Treaty (PCT) data, while the right panel shows EPO patent applications. In order to assess the performance of Europe in green innovation, we build on the methodology of Haščič and Migotto (2015) to classify the patented inventions.
Stats.: https://ec.europa.eu/assets/rtd/srip/2022/figure-13-15.xlsx

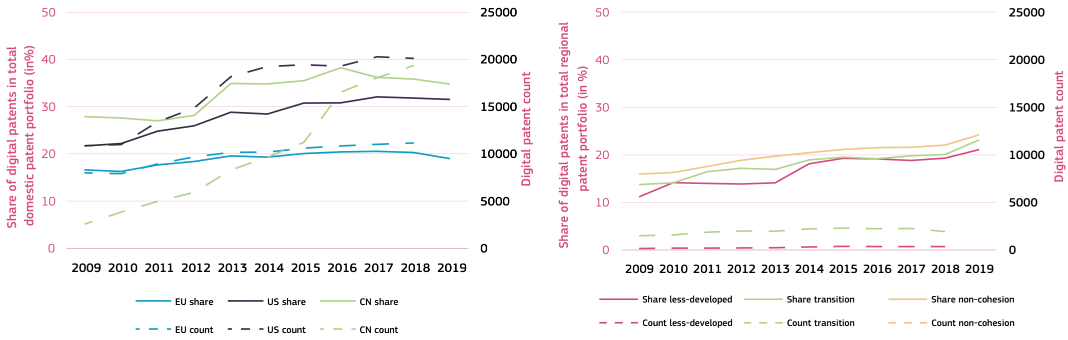
(Figure 16a). While the share of digital patents in the total patent portfolio has remained relatively stable in the EU since 2012, the US share has increased over time, widening the EU-US gap in digital innovation. In addition, over the past 15 years, China has doubled its share of digital patents, reflecting its increased focus on developing new digital technologies. This suggests that, compared to the EU, the USA and China have accelerated investments in digital innovation over the past decade.

Within the EU, digital innovation continues to be mainly driven by non-cohesion regions (Figure 16b). Nevertheless, also in the digital domain, the focus, or relative share of patenting, does not differ much across regions. Furthermore, this patent share dedicated to the development of digital technologies appears to have been increasing everywhere.

While the EU is not ahead in digital innovation overall, a different picture emerges when looking into certain subdomains where digital could play a major role. One important example is the contribution of digitalisation to the development of climate-related technologies. The EU is currently a global leader in innovation that combines digital and green applications (Figure 17a). A similar picture emerges when looking at the extent to which digital technologies are cited in green patents, showing that Europe is also more likely to adopt already existing digital technologies in its green innovations. At the same time, in recent years, patenting that combines green and digital technologies seems to have stabilised. That slow down should be a wake-up call for policymakers, as the transition will rely on green and digital innovations.

Once more, the diverse nature of the different regions is apparent in the patent data, with non-cohesion regions leading the way (Figure 17b). Not only do these regions have more patent applications, they also have a consistently higher share of patents in digital and green than the other regions.

Figure 13-16: Digital patents, 2009 to 2019



Source: PATSTAT data prepared in collaboration with ECOOM

Note: The dotted lines show the number of digital patents (right axis); the solid lines show the percentage share of digital patents in the total portfolio of domestic patents (left axis). The left panel shows PCT data, while the right panel shows EPO patent applications. The digital patent classification used in this chapter is based on a classification of Industry 4.0, published by the European Patent Office (EPO, 2017).

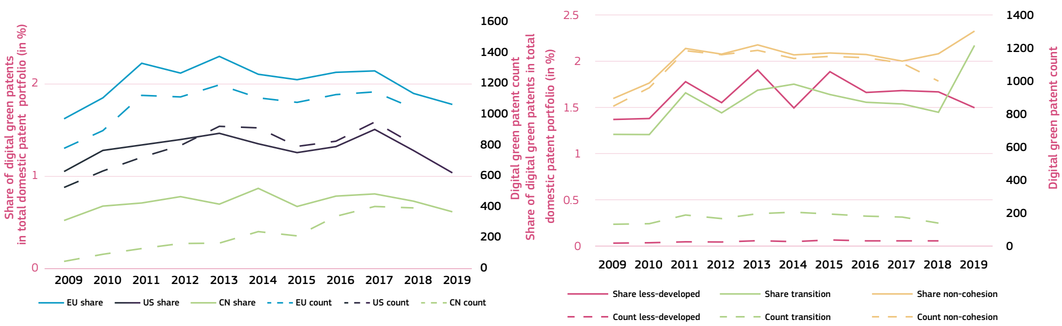
Stats.: https://ec.europa.eu/assets/rtd/srip/2022/figure-13-16.xlsx

Europe's main strengths in green and digital technologies lay in the domains of environmental management and transportation. The EU co-develops many digital innovations within these green domains. The digitalisation of the transport sector is an integral part of the European Green Deal. Even before its announcement, the European Commission pinpointed digitalisation as a priority. In addition, while Europe is lagging behind in most sectors for digital innovation and digital adoption as shown above, the transportation sector is following a different pattern and seems to enjoy a strong head start (EIB, 2022). The EU is well ahead of the USA in Industry 4.0 patents for vehicle applications, despite trailing in many other areas.

The EU is particularly strong in innovation related to electrification and energy efficiency (EIB, 2022). Compared to the USA and China, the EU has seen the highest increase in patenting in these domains compared to other regions over the past decade. A large number of innovations are needed in these domains given that energy-intensive industries, together with the transport and mobility sector, dominated and accounted for almost half of the total emissions in 2018.

What is more, digital technologies are also intensively co-developed, with innnovations focusing on carbon capture, utilisation and storage (CCUS). While the overall development of innovations in this area is moving at a relatively slow pace, the most recent IPCC (2021) report puts this type of technology at the heart of its proposed solutions to tackle the impacts of climate change. The IEA (2021) also stresses the importance of similar technologies. Of course, technological development is still required at a much larger scale to make this technology commercially viable. Digital technologies are expected to help smooth this process.

Figure 13-17: Patents related to both climate change and digital, 2009 to 2019



Source: PATSTAT data prepared in collaboration with ECOOM
Note: The dotted lines show the number of digital-green patents (right axis); the solid lines show the percentage share of digital-green patents in the total portfolio of domestic patents (left axis). The left panel shows PCT data, while the right panel shows EPO patent applications.
Stats.: https://ec.europa.eu/assets/rtd/srip/2022/figure-13-17.xlsx

5. Conclusion

The pandemic has accelerated the digital transformation for many EU firms, but policymakers should be concerned that the COVID-19 crisis may exacerbate a divide across firms and regions. They need to ensure that the opportunities of the transition to a greener and more digital economy can be realised across the EU and that the benefits are broadly shared. The political and regulatory environment will have to become more investment friendly to encourage transformative investments.

To help lagging regions to catch up, basic infrastructure also needs to be upgraded and to become more climate-friendly. This will require significant investment across the EU, especially in transition and less-developed regions. Finance and capacity gaps need to be narrowed in lockstep to maximise the impact of financial support for cohesion. Joint action to support cohesion together with the green and digital transition will be key to boost the resilience of the EU economy looking ahead.

The limited availability of skills also stands out as an obstacle to the firms driving the green and digital transition experience in particular – and most often in less developed regions. Similarly, there are also large differences in the level of employee training across firms. While the pandemic took its toll on training investment, firms that are green and digital were more likely to grow and to invest in their workforce. This indicates resilience but also that they are building the capacity to drive changes looking ahead.

In spite of its persistent lag in digital innovation, the EU is a leader in the development of climate related technologies. As the potential for technological advancements in these areas accelerate, the EU will be well-placed to maintain its lead for technologies at the crossroads of green and digital. But nothing should be taken for granted. European policymakers will have to do everything it takes to ensure that this dominant position is not rapidly lost. The strong position of the USA and China in the development of new technologies in most digital fields could make it difficult for Europe to remain on top in the areas in which it currently excels.

The twin digital and green transition represent a major economic opportunity for the EU. The European Green Deal and the EU's Digital Strategy are the cornerstone of the recovery plan for Europe. Combined with the national recovery and resilience plans, the initiatives present a unique opportunity to transform the EU economy and make it greener, more digital and more innovative.

References

Acemoglu, D., Autor, D.H. (2011), 'Skills, tasks and technologies: Implications for employment and earnings' In: Ashenfelter, O. and Card, D.E. (eds). *Handbook of Labor Economics*, Volume 4. Amsterdam: Elsevier, pp. 1043–1171.

Acemoglu, D. and Restrepo, P. (2020), 'Robots and jobs: Evidence from US labor markets', *Journal of Political Economy*, 128(6), pp. 2188–2244.

Aghion, P., Hepburn, C., Teytelboym, A. and Zenghelis, D. (2019), "Path dependence, innovation and the economics of climate change." *Handbook on Green Growth*. Edward Elgar Publishing.

EIB (2018), *Investment Report 2018/2019: Retooling Europe's economy*. Luxembourg: European Investment Bank.

EIB (2021), *Digitalisation in Europe 2020-2021: Evidence from the EIB Investment Survey*. Luxembourg: European Investment Bank.

EIB (2022), *Investment Report 2021/2022: Recovery as a springboard for change*, Luxembourg: European Investment Bank.

EPO (2017), *Patents and the Fourth Industrial Revolution: The Inventions behind Digital Transformation*, Munich: European Patent Office.

European Commission (2019), The European Green deal. COM (2019) 640 final.

GeSI (2019), *Digital with purpose: Delivering a smarter 2030*, The Global e-Sustainability Initiative (GeSI) and Deloitte.

Haščič, I., Migotto, M. (2015), *Measuring environmental innovation using patent data*.

IEA (2021), *About CCUS*. IEA, Paris.

IPCC (2021), 'Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change', Masson-Delmotte, V., P. Zhai, A. Pirani, S. L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M. I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J. B. R. Matthews, T. K. Maycock, T. Waterfield, O. Yelekçi, R. Yu and B. Zhou (eds.), Cambridge, Cambridge University Press.

Lacy, P., Rutqvist, J. (2015), *Waste to Wealth: The Circular Economy Advantage*. London: Palgrave Macmillan.

OECD (2021), *Training in Enterprises: New Evidence from 100 Case Studies, Getting Skills Right*, OECD Publishing, Paris.

CHAPTER 14

INNOVATION POLICY FOR A COMPLEX WORLD

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Summary

This chapter examines theoretically and empirically the spatial concentration of innovation in EU regional ecosystems. It proposes a detailed geography of patent distribution in several strategic areas and key technologies such as artificial intelligence (AI), blockchain, quantum computing, batteries, hydrogen, mRNA and oncology diagnostics and treatments, and looks at the complementarities across EU regions. It uses an economic complexity approach and regional network analysis to assess new opportunities for collaboration across EU regions and optimise knowledge sharing to increase the competitiveness of the EU in strategic areas and some key technologies.

1. Introduction

New technologies are invented by a few but change the life of everyone. The development of mRNA vaccines is halting COVID-19 deaths and hospitalisations. Intelligent machines drive cars and read lung scans. They can also predict what we will want to listen to, watch or buy next better than our spouse or lifelong friends. Developing controlled nuclear fusion could solve our energy needs. As Brynjolfsson and McAfee (2014) put it, technological change has bent the curve of human history like nothing else before. But who builds the technologies that get to change everyone's lives? Who decides on the core values and ethical considerations that get embedded into new products? It turns out that one of the most striking features of today's complex world is that innovation is increasingly consumed **globally** while increasingly produced **locally**.

So where does innovation come from? Large cities, mainly. Tokyo, Seoul, San Francisco, Paris and Osaka alone account for more than 20% of all new inventions granted by the European Patent Office (Paunov et al., 2019). This is a staggering number. We know from economic geography and innovation studies that urban environments make it possible to share costly infrastructures, match specialised professionals with cutting-edge organisations and provide multiple learning channels (Duranton and Puga, 2004). There is little doubt that – more than other economic activities – innovation thrives with proximity (Boschma, 2005). But as society evolves and we keep pushing knowledge frontiers, we start noticing a surprising pattern. The most transformative of all scientific and technological fields, such as biotech and IT, are also the most spatially concentrated (Balland et al., 2020).

Although a lot has been written about the spatial concentration of innovation, a large piece of the puzzle is still missing in understanding the big picture and adopting the research and innovation policy we need in today's hyperconnected world. I adopt complex systems thinking to put forward the idea that the massive dual spatial footprint we observe is a reflection of structural features of our world. The main idea of this chapter is that when the world becomes more complex, knowledge consumption becomes more global and knowledge production becomes more local. By complexity, I mean that more and more economic actors are becoming interdependent. This, in turn, creates structures that hide fundamental properties that shape a wide range of socio-economic outcomes (Hidalgo, 2021; Balland et al., 2022).

Linking increasing complexity and spatial concentration has three major implications for research and innovation policy. First, the reality of knowledge concentration requires putting regions and cities at the heart of the innovation strategy of large countries and economic zones. Second, the increasingly global nature of knowledge consumption means that regions compete based on the global value of their products. There is no room for second-best. France and Germany cannot compete with China and the USA, but Europe can. The European system of innovation is a knowledge network of regions. We need to implement an innovation policy that is coherent with this reality and focus on stimulating links between regions to scale high-quality products and accelerate leadership towards climate neutrality and the digital transition. A third implication of this complex world for innovation policy is that it is becoming impossible for political leaders and policymakers to fully understand new technological landscapes and to systematically assess which regional ecosystems are the most valuable for specific technologies. We need new tools. I will introduce how graph-based machine learning (GBML) can complement human intelligence to design sound policy in a complex world.

In section 2, I will discuss the theoretical foundation of why innovation concentrates in a complex world. In section 3, I will provide empirical evidence on the spatial concentration of innovation in EU regional ecosystems. Section 4 will focus on how to leverage regional ecosystems with human and artificial intelligence. Section 5 will show how this recommender system can be used to assess potential new opportunities in key technologies such as AI, blockchain, quantum computing, batteries, hydrogen, mRNA and oncology diagnostics and treatments. Section 6 will conclude and summarise key implications for research and innovation policy.

2. Why a more complex world accelerates the concentration of innovation

If you had asked prominent economists, policy-makers or business executives at the dawn of the internet, few would have predicted the merciless monopoly of digital giants such as Google, Amazon, Netflix, Alibaba or Tencent. Digital technologies were supposed to flatten the world. Everyone, everywhere, would get a chance to collaborate and create technologies consumed on the other side of the planet. This vision turned out to be dramatically wrong. Today's reality is that innovation is increasingly consumed globally while at the same time increasingly produced locally. Most of the rich Western world consumes Gmail or Netflix products on a daily basis, but the AI that powers their technology only comes from tiny pockets within Silicon Valley, Seattle or Boston. Geography matters less and less on the demand side but more and more on the supply side. This is the worst-case scenario for spatial inequality[1]. As the global consumer base widens, it fuels the growth of a few local peaks of Richard Florida's spiky world. The wider the base, the higher the peaks. Paradoxically, a more global world has also much more marked regional features (Storper, 1997).

Why does spatial inequality emerge as a result of the increasing complexity of our world? Let us first examine global demand. Digital technologies and falling transportation costs of physical goods allow products to be widely distributed. That means that it matters less and less where consumers are located – global corporations can access everyone's wallets. Global competition is emerging in more and more industries. This is completely different from non-tradable industries such as the hairdressing business. A hairdresser in Kraków does not compete with a hairdresser in Porto, even it provides a much better and cheaper service. But customers in a global, interconnected world do not care about the second best because they can access all providers equally. Email services, for instance, do compete globally. Gmail has 1.5 billion active users worldwide, Outlook about 400 million, Yahoo, 200 million. This is an incredibly skewed distribution, where the winner takes all and the rest eat the crumbs.

So the fact that our world is incredibly interconnected allows for the possibility for the few winners to take it all. Things get even worse when the quality of the product depends on data collection. A small initial comparative advantage can quickly compound into an absolute monopoly. Slightly better initial recommendations of an AI system will attract more users. More users will automatically lead to more data for the digital platform. What comes next is that more data will lead to better predictions and therefore more users, and that this self-reinforcing feedback loop will not stop until a specific segment of the digital market is almost entirely absorbed by a handful of global giant organisations (Lee, 2018; Tucker, 2019; Catalini and Gans, 2020; Aral, 2021). Google has a monopoly of website recommendations in the West and Baidu in China; Amazon in product recommendations in the West; Alibaba in China. The logic is the same for other digital products[2].

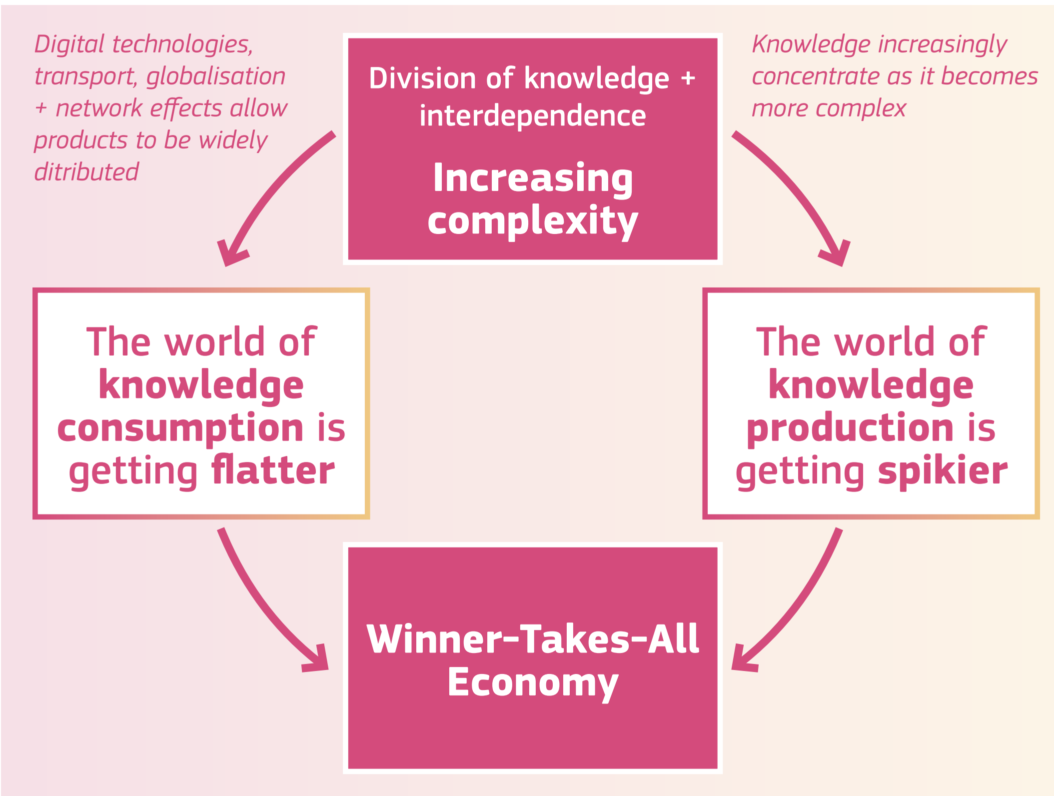
1 Spatial inequality has been documented to be on the rise across the world and to fuel populism and social unrest (Rodríguez-Pose, 2018). More complex and interdependent economic structures create the leverage conditions that condition the rise of inequality within and between regions.

2 It is a feature of Web 2.0 and is predicted to be disrupted by blockchain technologies, decentralisation and the evolution towards Web 3.0.

So far, we have discussed why the structural features of our world create the possibility for superstars entrepreneurs, products and corporations to emerge. It would not be too much of a problem if these winners of the global economy were also distributed randomly in the world. The problem is that they also concentrate in a few places. Digital goods are highly complex activities that concentrate in large cities, the knowledge hubs of the global economy (Balland et al., 2020). Complex products require a deeper division of knowledge, which forces individuals to narrow down their expertise and specialise (Jones, 2009). In fact, there is a limit to how much knowledge can be stored in someone's head (Hidalgo, 2015). This division of knowledge creates high coordination costs since specialised knowledge alone is useless. It needs to be connected back to other specialised individuals, which is why we have witnessed an increasing size of teams in science and innovation (Wuchty et al., 2007). Cities – in particular, the largest ones – help to solve the coordination problems created by the division of knowledge by creating multiple mixing and matching opportunities.

The rise of the winner-takes-all economy results in increasing complexity, a more global world of knowledge consumption and a more local world of knowledge production, as summarised in Figure 1. The magnitude of this monopolistic structure in strategic products and technologies shapes the spatial nature of innovation, which we will document in the next section. These patterns call for new principles of innovation policy and new tools.

Figure 14-1: The rise of the winner-takes-all economy



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Stats.: https://ec.europa.eu/assets/rtd/srip/2022/figure-14-1.xlsx

3. Regions are the engines of the European innovation system

The most accepted approach to systematically assessing the spatial distribution of new technologies is to analyse patent documents. Even though patented inventions do not capture all forms of invention and knowledge production, they contain unique information that has been extensively used in innovation studies[3] (Jaffe et al., 1993; Audretsch and Feldman, 1996; Hall et al., 2001; Thompson and Fox-Kean, 2005). In exchange for the codification of and openness in how technology is produced, patent offices over the world grant the right to exclude others from the commercial exploitation of the invention. This allows the systematic documentation of new technologies that no other form of data allows.

Two key pieces of information are available in patent documents to map innovation ecosystems accurately and systematically and to further inform innovation policy: what is invented and where it comes from. Both pieces of information are available at a very fine-grained resolution. The place of residence of inventors gives the detailed geography of inventions, while each patent is meticulously classified within 250 000 technological categories (international patent classification, IPC). Combining these two key pieces of information allows us to map the geography of innovation in Europe precisely. In this chapter, I use the OECD REGPAT 2021 database (Maraut et al., 2008). The REGPAT dataset provides detailed information on patents filed at the European Patent Office (EPO) and at the World Intellectual Property Organization (WIPO) since 1978.

What does the geography of innovation look like in Europe? Figure 2[4] simply maps the number of patents per capita in information and communication technologies during the period 2014-2018[5]. What is clear from this map is the strong evidence of spatial concentration of inventive activities, as also extensively shown in part I of this report (Section 2.2 – Zoom in – Regional analysis). The European information and communications technology (ICT) innovation system is formed by leading regions Stockholm, South Sweden, Helsinki-Uusimaa, Mittelfranken, Oberbayern, North Brabant, Brittany and Île de France. Île de France, Oberbayern, Stockholm, Mittelfranken and Brittany are also the top five regions in terms of the absolute number of ICT patents, and together account for no less than 30% of the ICT patents of the EU-27 regions. These leading regions are key to establishing the global sovereignty of EU technologies. But what is also fascinating in this map is that country borders are almost impossible to distinguish. European regions, not countries, are where innovation truly concentrates and therefore should be the focus of innovation policy.

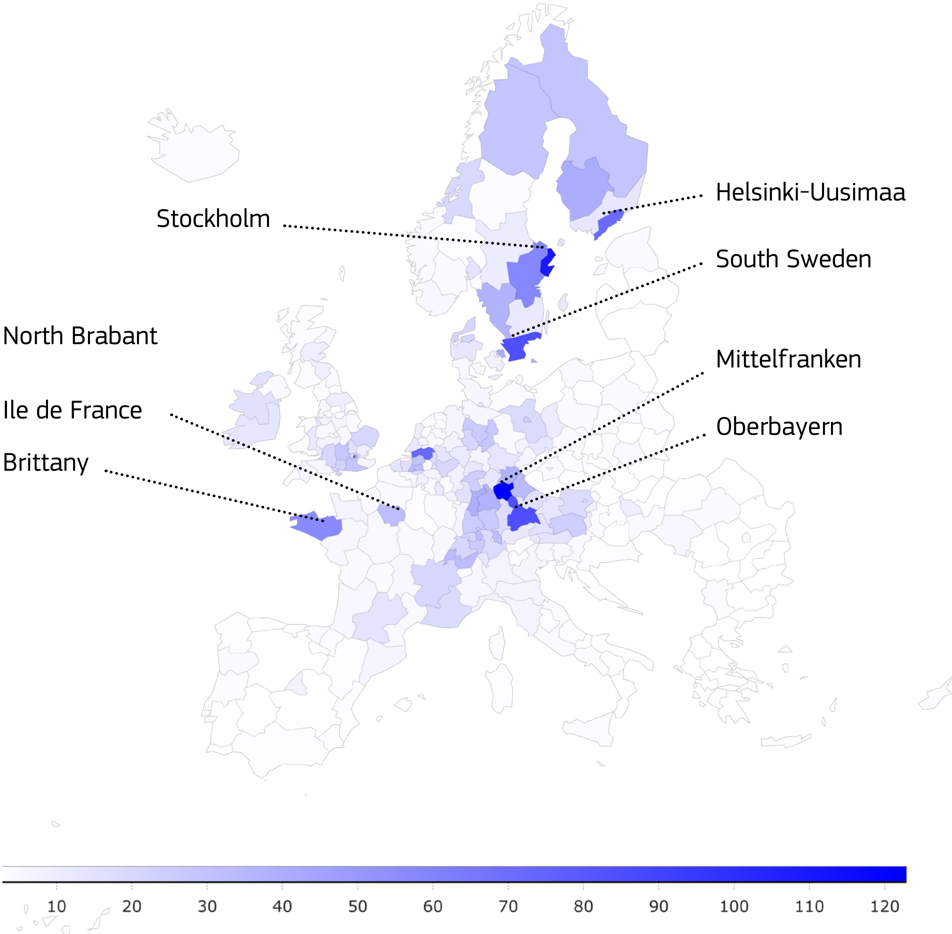
This concentration pattern becomes even stronger when we unpack the level of complexity of technologies. This distinction is not trivial because complex technologies are the ones that allow for the most leverage of economic structures and therefore the ones that are the most critical for future economic growth (Hidalgo and Hausmann, 2009; Hidalgo, 2021; Balland et al., 2022). As mentioned earlier, complexity refers to the division of knowledge behind the creation of a specific technology.

3 The geography of innovation can also be analysed using participation in R&D projects, venture-capital deals (Crunchbase, DealRoom) or GitHub repositories for instance.

4 An interactive version of this map is available here: https://www.paballand.com/asg/srip/map-ict-pc.html

5 This map uses data from Balland and Boschma (2021).

Figure 14-2: **ICT regional ecosystems in Europe**



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Stats.: https://ec.europa.eu/assets/rtd/srip/2022/figure-14-2.xlsx

A technology that a human can invent entirely by herself is, by our definition, simple. Now, the more you build on others' knowledge, skills and inputs, the more complex the technology is. A technology that involves many actors interlinked in very specific ways is more complex. There are many ways to measure complexity (Fleming and Sorenson, 2001; Hidalgo, 2021) but in this paper, we use the standard eigenvector reformulation initially proposed by Hidalgo and Hausmann (2009) for traded products and recently adapted for patent data by Balland and Rigby (2017). This method is purely outcome-based. It brings together the diversity of regions and the ubiquity of technologies they produce to identify the technologies that a lot of regions would like to produce but very few can.

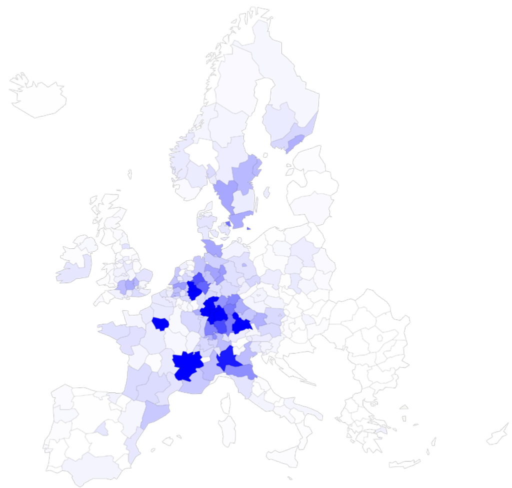
Figure 3 maps the geography of complex and non-complex patents in European regions from 2015 to 2020[6]. On the left panel, we can see the distribution of the least complex patents[7] (bottom 25 %) and on the right, the most com-

6 For an extensive analysis of the geography of knowledge complexity in Europe, see Pintar and Scherngell (2021)

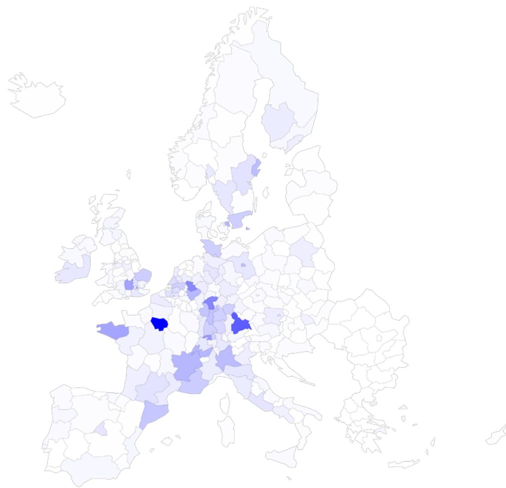
7 An interactive version of this map is available here: https://www.paballand.com/asg/srip/bottom25.html

Figure 14-3: The geography of complex patents in Europe

Bottom 25 % complex patents



Top 25 % complex patents



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plex ones[8] (top 25 %). We can see two very different geographies. Complex patents are very highly concentrated while the least complex ones are much more dispersed across European regions. The regions that have a disproportionate number of complex patents are mainly the capital regions such as Île de France, Inner London, Stockholm or Madrid.

To systematically document the unequal distribution of technologies we turn to a simple index of spatial concentration: the Gini coefficient. The Gini coefficient is defined as a ratio of two surfaces derived from the Lorenz curve and ranges from 0 (perfect spatial equality where every region produces the same number of patents) to 1 (perfect spatial inequality where one region produces all patents).

In Figure 4, I analyse, for 2015-2020, the spatial inequality behind the production of 35 core technologies[9] as originally defined by Schmoch (2008), together with seven key technologies for European technological sovereignty: AI, blockchain, quantum computing, batteries, hydrogen, mRNA and Oncology[10].

8 An interactive version of this map is available here: https://www.paballand.com/asg/srip/top25.html

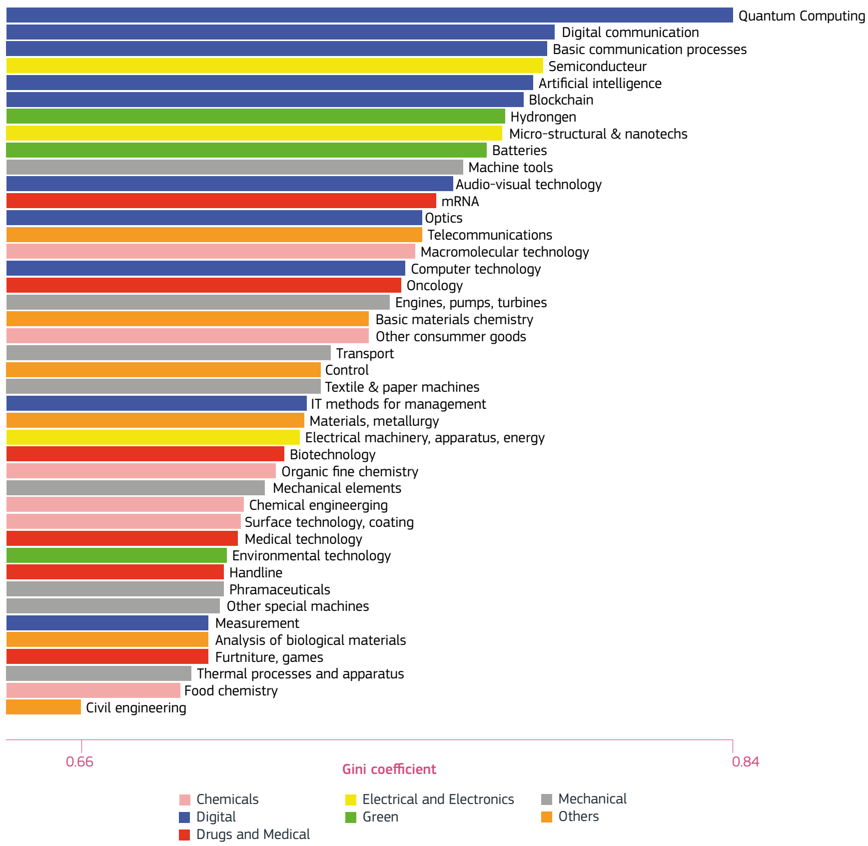
9 The analysis of biological materials; audio-visual technology; basic communication processes; basic materials chemistry; biotechnology; chemical engineering; civil engineering; computer technology; controls; digital communications; electrical machinery, apparatus, energy; engines, pumps, turbines; environmental technology; food chemistry; furniture, games; handling; IT methods for management; machine tools; macromolecular chemistry, polymers; materials, metallurgy; measurement; mechanical elements; medical technology; micro-structural and nanotechnology; optics; organic fine chemistry; other consumer goods; other special machines; pharmaceuticals; semiconductors; surface technology, coatings; telecommunications; textile and paper machines; thermal processes and apparatus; transport. These technologies are defined from the updated Cooperative Patent Classification (CPC) classification proposed in Schmoch (2008).

10 The technologies are identified from text mining patent documents and the CPC classification, following the method of Balland and Boschma (2021).

The five most concentrated fields are quantum computing, digital communication, basic communication processes, semiconductors and AI. These are also highly complex fields that are associated with high talent pools and capital investments. The five most spatially dispersed fields, however, are less knowledge-intensive activities: civil engineering, food chemistry, thermal processes and apparatus, furniture and games, and analysis of biological materials. Again, from this exercise, it is clear that the most complex fields are also the most spatially concentrated.

Another fundamental way to document the spatial distribution of knowledge is not to look at regions in isolation from each other but to analyse the European interregional system of innovation. In Figure 5, we plot the co-inventor ties between regions[11], for all technologies. The results are striking. When looking at collaborations, country borders become extremely marked. The top 10 connections of Île de France – the EU regions with the most internal collaborations – are all other French regions.

Figure 14-4: Spatial concentration of core technologies



Science, Research and Innovation Performance of the EU 2022

Stats.: link

11 In the network presented in Figure 4, we only display links between regions (n=74) that have more than 10 000 internal links. This is purely for visualisation purposes. We also use a maximum spanning-tree algorithm to map the backbone of the network and to avoid isolated nodes. Some primary links are therefore removed for visualisation purposes. The results are qualitatively similar when plotting the whole network of European regions. An interactive version of this map is available here: https://ec.europa.eu/assets/rtd/srip/2022/figure-14-4.xlsx

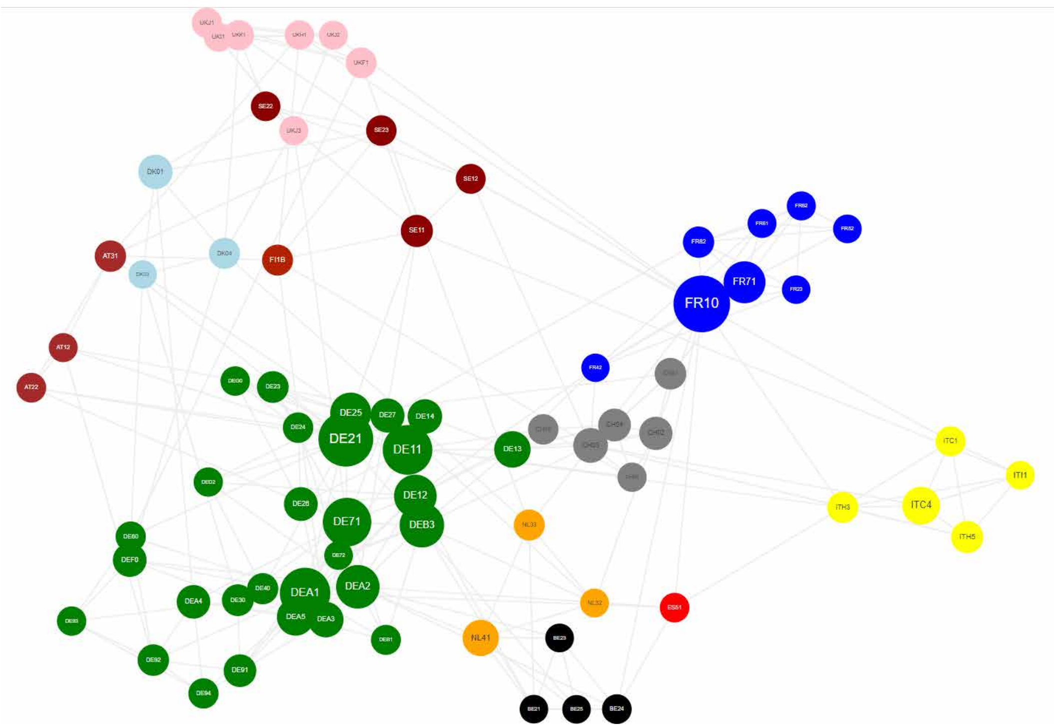
The same goes for Upper Bavaria and other EU regions. European regions disproportionally favour same-country collaborations over pan-European ones. Based on the maps presented in Figures 2 and 3, we would expect the top EU regions to be strongly connected. This fact that they are not signals a system failure in the innovation systems that justifies higher-policy-level intervention to scale up EU technologies and achieve global leadership in the twin transition.

We have learned two key facts about the geography of innovation in Europe. First, technologies – especially the most complex ones – are heavily concentrated in a few regional ecosystems. It is essential to take into account this real-world pattern and to design an EU-wide place-based[12] innovation policy. Second, the EU regional innovation system does not reflect this geography when it comes to interregional collaborations.

This gap signals a poor knowledge-capability matching that urgently needs to be reduced with the right network-based innovation policy tools. In the next section, we turn to the use of modern graph-based machine learning tools to:

- identify promising knowledge ecosystems;
- identify the most valuable interregional connections.

Figure 14-5: The EU regional system of innovation



Stats.: https://ec.europa.eu/assets/rtd/srip/2022/figure-14-5.xlsx

12 Place-based policy is often meant as policy that helps lagging regions to catch up (Barca et al., 2009). Here, we mean place-based innovation policy in the sense of policy that leverages regional ecosystems to generate EU global leadership.

4. Leveraging regional ecosystems with human and artificial intelligence

A large part of successful innovation policy at the scale of large integrated markets such as Europe, the USA or China comes down to simultaneously betting on the right technologies and the right places. Prioritising investments is key to accelerating global leadership towards climate neutrality and digital transitions while developing EU sovereignty in key technologies. Shall we mainly fund AI? Blockchain? Nuclear power? Solar energy? And how much should go to each technology? Once the overall plan is defined at the level of large countries or economic zones (EU, USA, China) the next important step is to define who receives the funding (regions and cities). This is also critical to enabling diversification of regions and stimulating their long-term economic development (Boschma, 2018; Hidalgo et al., 2018).

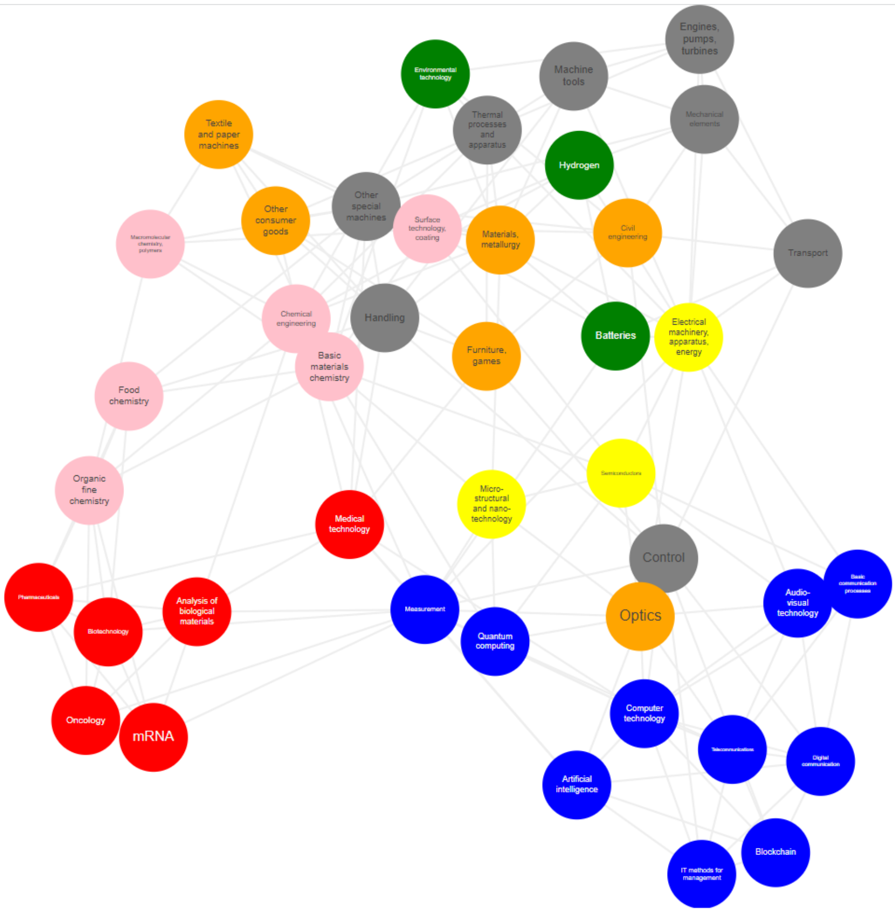
But simultaneously betting on the right technologies and the right places is an increasingly difficult exercise. It was already challenging in a less globalised world characterised by slower technological change but today, there are too many new complex technologies and global knowledge ecosystems to assess intuitively what the optimal investment really is (Balland et al., 2019). If the goal is to achieve EU leadership in AI for instance, is it wiser to focus investments on the Île de France, Bavaria and Budapest ecosystems or Milan, Bucharest and Eindhoven? These choices matter tremendously. Domain experts provide very valuable knowledge but cannot have equal knowledge of all new technologies and their geographies. It is getting harder and harder to flag risky strategies and identify hidden gems. We need better tools.

I argue that modern R&I policymaking needs to combine human and artificial intelligence to deliver more optimal public investments. The foundational principles of such AI tools already exist in GBML. Collaborative filtering, in particular, has shown that there is much more predictive power in economic and social structures than in demographic variables. To put it simply, gender, height, country of origin and other individual-level variables are poor predictors of music tastes or purchasing patterns. But it is possible to automate predictions (filtering) by also analysing preferences from many other users (collaborating).

Similar algorithmic principles that govern Amazon, Netflix or Spotify prediction machines can also be applied to the prioritisation of public investment decisions in research and innovation policy. These tools are increasingly applied in the context of the smart specialisation strategy and green policy initiatives (Balland et al., 2019; Balland et al., 2021; Deegan et al., 2021; Mealy and Teytelboym, 2020; Uyarra et al., 2020; Montresor and Quatraro, 2020; Hassink and Gong, 2019) by building on decades-long academic literature on economic complexity and economic geography. One of the key findings of this literature is that regional diversification happens through the principle of relatedness (Hidalgo et al., 2007; Hidalgo et al., 2018). Regions develop new products and technologies by recombining pre-existing available capabilities. Mapping existing capabilities in a region allow estimating the distance with any new domain, measured by the concept of relatedness density.

The particular way technologies are connected to each other indicates how easy it is for a region, country or individual to move from one to the other. It represents hidden constraints that shape our decisions and opportunities. Figure 6[13] is a graph-based representation of how the 42 technologies presented in section 3 are related to each other from 2015 to 2020. Previous research has mapped connections between products (Hidalgo et al., 2007), scientific fields (Boschma et al., 2014) or job categories (Farinha et al., 2019). Here, we use a recombination of subtechnologies on the same patents to produce this graph. We can see how the digital technologies (blue) of blockchain, AI or quantum computing cluster together, while health-related technologies (red) such as mRNA or oncology diagnostics and treatments are grouped in a different quadrant of this space. A fine-grained resolution of this technology space (we can go up to 250 000 technologies) allows mapping of the regional ecosystems that are the most promising for specific technologies.

Figure 14-6: The technology space



Stats.: https://ec.europa.eu/assets/rtd/srip/2022/figure-14-6.xlsx

13 An interactive version of this map is available here: https://www.paballand.com/asg/srip/tech-space.html

By mapping links between technologies and the current knowledge structure of EU regional ecosystems, it becomes possible to compute relatedness density and predict the growth potential of new technologies. This is a huge breakthrough because it means that we do not need a place to produce knowledge to actually know if it can produce knowledge in the future. Relatedness density indicates – for any domain – the shares of related technologies that are present in a region. To illustrate this principle with a simplified example, let us say that 10 technologies are related to AI and eight of these technologies can be found in Paris. The relatedness density between AI and Paris is 8/10 = 80%. Regions with the highest relatedness density are the strongest candidates for prioritising funding.

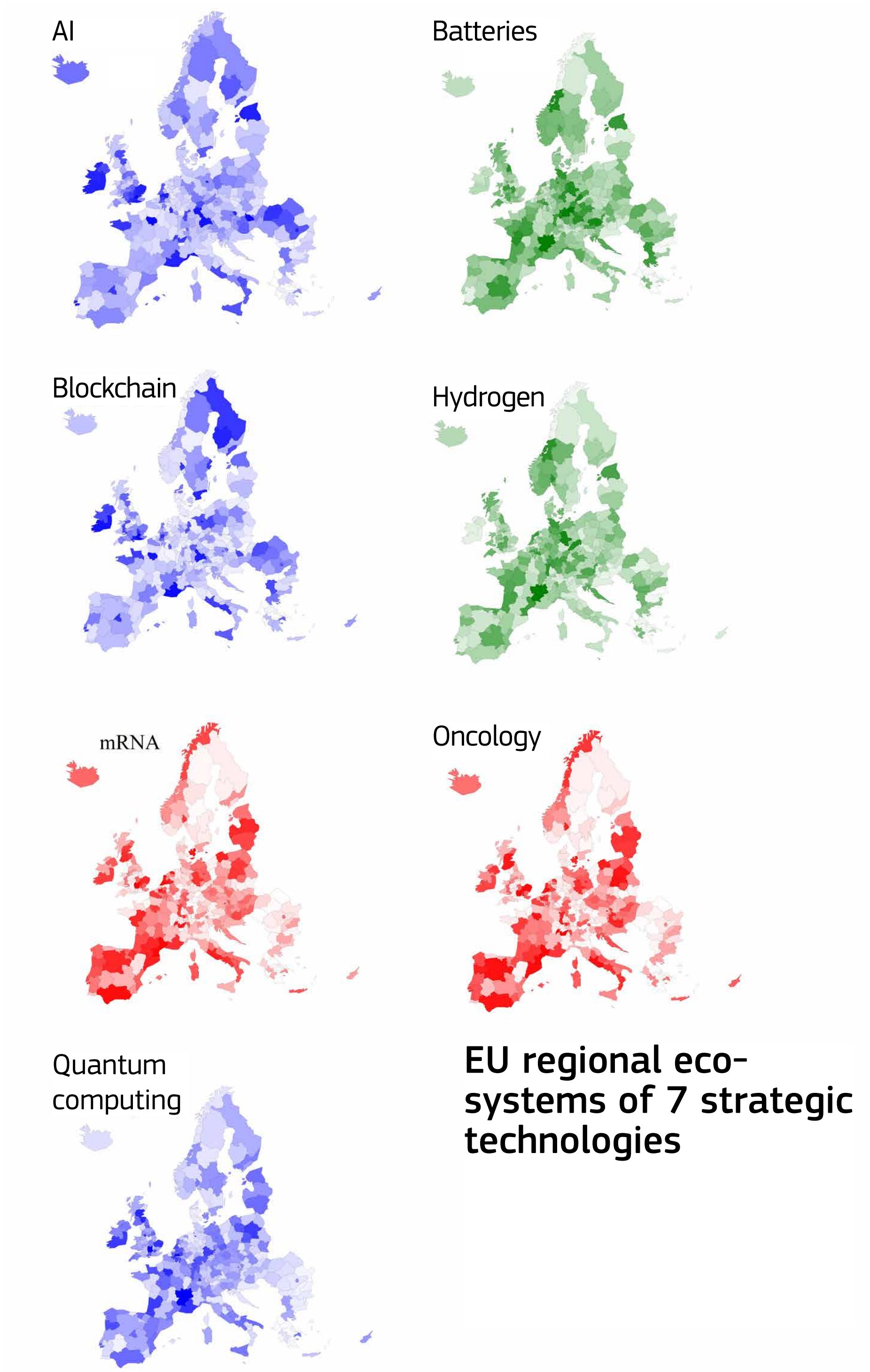
Figure 7 presents relatedness density maps[14] that indicate which EU regions are in the best position to lead technological change in seven key technologies. We can see that each technology is characterised by a very specific geography. Île de France, Oberbayern and London have core technologies related to AI but when it comes to batteries, Rhone-Alpes, Stuttgart or Trondelag (Norway) are better positioned. mRNA connects most to technologies found in the capital region of Denmark, in Berkshire, Buckinghamshire and Oxfordshire or in Languedoc-Roussillon.

By plotting relatedness density against a regional variable, it is possible to introduce more nuanced and realistic trade-offs that are fundamental to real-world policymaking. Relatedness density is a region-technology-level variable, so a region can have a high level of relatedness density around a given technology (AI), but very low around another one (biotech). The regional variable would be, by definition, fixed across regions. For illustration purposes, we will discuss regional complexity, which is a predictor of long-run regional development, but it could also be GDP or patents per capita.

Figure 8 presents a framework that indicates the position of all EU regions in terms of their relatedness density around a specific technology (let us say AI, along the x-axis) and the overall regional complexity of the region (y-axis). On the top-right quadrant (**excellence policy**) we have world-class regions (complex) that are also in the best position to become leaders in AI. These are safe bets, but they come with the potential drawback of making strong regions even stronger. The bottom-right corner (**inclusive policy**) shows regions that might not come as quickly to mind but that have strong potential in this technology. Betting on these regions comes with the added benefit of reducing disparities. The two other quadrants do not make as much sense from a structural approach.

14 All relatedness density maps are available as interactive HTML files: https://www.paballand.com/asg/srip/maps/artificial-intelligence.html
https://www.paballand.com/asg/srip/maps/batteries.htmlhttps://www.paballand.com/asg/srip/maps/blockchain.html
https://www.paballand.com/asg/srip/maps/hydrogen.html
https://www.paballand.com/asg/srip/maps/mrna.html
https://www.paballand.com/asg/srip/maps/oncology.html
https://www.paballand.com/asg/srip/maps/quantum-computing.html

Figure 14-7: Relatedness density maps



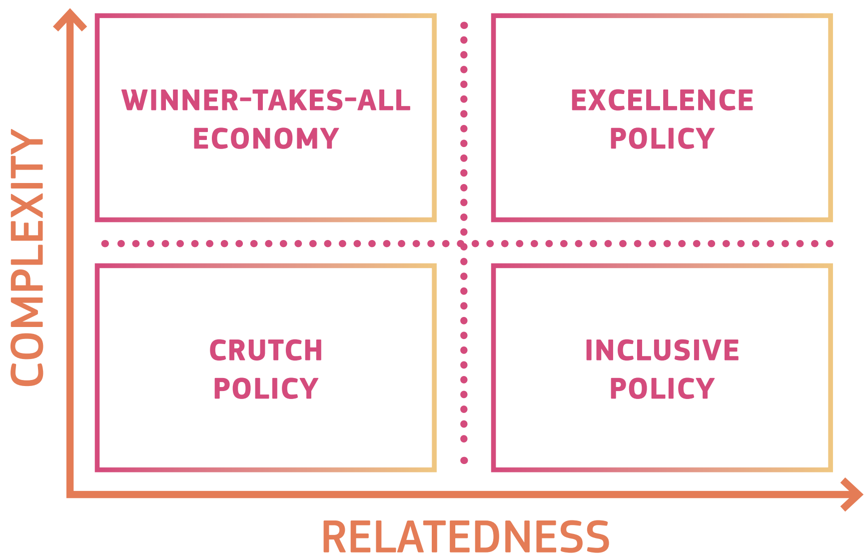
Stats.: https://ec.europa.eu/assets/rtd/srip/2022/figure-14-7.xlsx

The top-left (**winner-takes-all policy)** indicates regions that are already very strong (overall) and do not have a specific edge in AI. Talent, regional brand, pre-existing capital or infrastructure can explain such an investment. The bottom-left (**crutch policy**) is also to be avoided as it is very unlikely that the support can ever kick-start organic growth in these regions. It does not mean that these regions should be left behind. But from an innovation policy perspective, these regions should focus on technologies in which they have related capabilities.

A carefully designed R&I policy should be technology-specific and empower relevant knowledge ecosystems. It is also important to stimulate interregional linkages. Links that are the most impactful for regional leadership and innovation are the ones that build on complementary assets (Balland and Boschma, 2021). And as shown in section 3, European regions seem to disproportionally favour within-country collaboration. To stimulate pan-European collaboration, we need a strong innovation policy framework that brings European regions together.

Balland and Boschma's (2021) measure analyses gaps and similarities between technology spaces of all EU regions. It is always region-tech-region specific (three-way). With this method, it is possible to assess the complementarity potential of a given region with any other region in a given technology. Let us, for instance, evaluate the complementarity potentials of EU regions with the Occitanie region in the field of AI (as indicated in Figure 9[15]). To put it simply, let us say that AI is related to 100 other technologies (in a more fine-grained version of the overall technology space presented in Figure 6). Occitanie has expertise in 30 out of these 100 technologies, leading to a level of relatedness density between Budapest and

Figure 14-8: **Prioritising investments in regional ecosystems**



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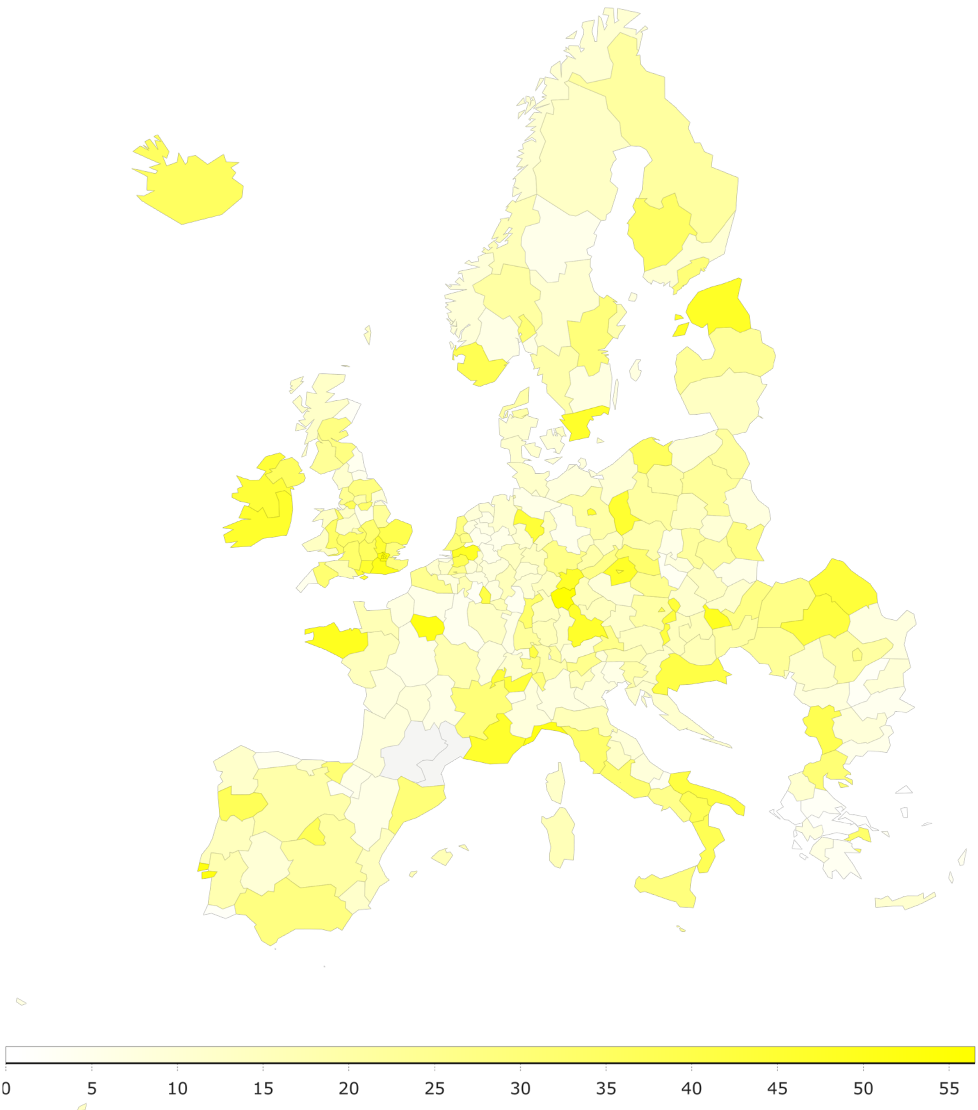
Stats.: https://ec.europa.eu/assets/rtd/srip/2022/figure-14-8.xlsx

15 An interactive version of this map is available here: https://www.paballand.com/asg/srip/ai-occitanie.html

AI of 50% (as presented in Figure 7 and in the x-axis of Figure 8). Analysing the portfolio of other EU regions reveals that Budapest has expertise in 49 other technologies that are related to AI but that Occitanie does not have expertise in. Linking to Budapest, Occitanie could compensate for the lack of regional knowledge, and relatedness density would go up by 49%. This 49% is the level of complementarity between Occitanie and Budapest in AI. Please note that it would change for biotech or any other technologies and is also not symmetric. If Occitanie only has technology that Budapest already has, then the complementarity score between Budapest and Occitanie in AI would be exactly 0%.

Figure 14-9: Complementarity maps between Occitanie and other EU regions in AI



Stats.: https://ec.europa.eu/assets/rtd/srip/2022/figure-14-9.xlsx

6. Conclusion

The overarching idea of this chapter is that new technologies are extremely concentrated in space. I argue that this spatial concentration is increasing over time as a result of the increasing complexity and interconnectivity of our economic system. I discuss the theoretical mechanisms but also empirically demonstrate that this is especially true for the most transformative technologies, such as AI, blockchain or advanced clean technologies. A few regional knowledge ecosystems are responsible for most innovations that shake the world and impact the lives of all citizens. The most important implication of this real-world pattern is that – more than ever – we need an ambitious innovation policy that truly leverages the spatial dimension of innovation.

To develop such a region-based innovation policy we need tools. I also argue that today's science and technology world is far too complex for policymakers and key stakeholders at the EU, regional or national level to systematically map knowledge ecosystems and the links between them. GBML, the technology behind the recommendation systems of Amazon, Netflix and Spotify, can be used to support innovation policy and public-investment decisions. I show how GBML can map current structures, predict future development paths and also predict best matches between regions based on systemic complementarity analyses.

Beyond understanding key principles and patterns of the geography of innovation, we also need new policy frameworks and instruments. We need to support local governments in setting up ambitious science and technology visions, orchestrating local ecosystems, attracting external players and connecting the dots between local stakeholders. The type of policy instruments chosen could connect to the current smart specialisation policy of DG REGIO. This makes a lot of sense since the seminal smart specialisation concepts outlined by Foray, David and Hall (2009) were developed as an innovation policy and discussed extensively within DG RTD. Today, the smart specialisation strategy is a place-based policy (Barca et al., 2012) in the sense of reducing EU regional disparities by supporting regional change. This is an excellent initiative that is becoming increasingly armed with advanced methodological tools. We need similar instruments with a very different goal. We need a place-based innovation policy that has the clear objective of pushing further overall EU technological sovereignty by betting on the regional ecosystems that are the fittest to achieve global leadership. Regions – not projects – could therefore receive funding based on an overall excellence- and knowledge-matching strategy. It would all be about prioritising technologies to invest in and outlining an execution plan on how to make it happen.

But to truly develop EU sovereignty in strategic technologies, a higher level of leadership is needed. The consequence of the global consumption of knowledge is that we need scale to develop tech champions, especially in the digital sector. The EU has all it takes to compete with China and the USA, but France or Germany cannot go alone. The EU needs to be the captain, setting up overall innovation strategy and building on a system of regions to make it work. But what is clear from the analysis of interregional linkages presented in this paper is that the EU system of innovation is far from being optimally structured. There are an excessive number of within-country collaborations and we are far from a true common innovation area. While one would expect the larger regions or those with the most complementary structures to be the most connected (as is the case in the USA and China), this strong country-border effect considerably harms EU innovation potential.

To thrive in the 21st century, we need strong EU leadership in priority-setting and coordination efforts. Attracting global talent and granting EU-wide special visas, for instance, would not only be a way to boost innovation but also to break a shared historical context that prevents cross-country connections. More directly, we need instruments that build a true European community by encouraging mobility (in the spirit of the Erasmus programme and the framework programmes). What we need is a true Airbus moment, where the division of knowledge at the level of EU regions allows us to scale and develop globally competitive complex products.

References

Aral, S. (2021), *The Hype Machine: How Social Media Disrupts Our Elections, Our Economy, and Our Health--and How We Must Adapt Currency.*

Audretsch, D. B., Feldman, M. P. (1996), 'R&D spillovers and the geography of innovation and production', *The American economic review*, 86(3), pp. 630-640.

Balland, P. A., Boschma, R. (2021), 'Complementary interregional linkages and Smart Specialisation: an empirical study on European regions', *Regional Studies*, 55(6), pp. 1059-1070.

Balland, P. A., Boschma, R., Crespo, J., Rigby, D. L. (2019), 'Smart specialization policy in the European Union: relatedness, knowledge complexity and regional diversification', *Regional Studies*, 53(9), pp. 1252-1268.

Balland, P. A., Jara-Figueroa, C., Petralia, S. G., Steijn, M. P., Rigby, D. L., Hidalgo, C. A. (2020), 'Complex economic activities concentrate in large cities', *Nature Human Behaviour*, 4(3), pp. 248-254.

Balland, P.A., Broekel, T., Diodato, D., Giuliani, E., Hausmann, R., O'Cleary, N., Rigby, D. (2022), 'The new paradigm of economic complexity', *Research Policy*, forthcoming.

Barca, F., McCann, P., Rodríguez Pose, A. (2012), 'The case for regional development intervention: place based versus place neutral approaches', *Journal of regional science*, 52(1), pp. 134-152.

Boschma, R. (2005). Proximity and innovation: a critical assessment. *Regional studies*, 39(1), pp. 61-74.

Boschma, R. (2017), 'Relatedness as driver of regional diversification: A research agenda', *Regional Studies*, 51(3), pp. 351-364.

Boschma, R., Heimeriks, G., Balland, P. A. (2014), Scientific knowledge dynamics and relatedness in biotech cities', *Research policy*, 43(1), pp. 107-114.

Brynjolfsson, E., McAfee A., (2014), *The second machine age: Work, progress, and prosperity in a time of brilliant technologies*, WW Norton & Company.

Catalini, C., Gans, J. S. (2020), 'Some simple economics of the blockchain', *Communications of the ACM*, 63(7), pp. 80-90.

Deegan, J., Broekel, T., Fitjar, R. D. (2021), 'Searching through the Haystack: The relatedness and complexity of priorities in smart specialization strategies', *Economic Geography*, 97(5), pp. 497-520.

Duranton, G., Puga, D. (2004), 'Micro-foundations of urban agglomeration economies', *Handbook of regional and urban economics*, Vol. 4, pp. 2063-2117.

Farinha, T., Balland, P. A., Morrison, A., Boschma, R. (2019), 'What drives the geography of jobs in the US? Unpacking relatedness', *Industry and Innovation*, 26(9), pp. 988-1022.

Fleming, L., Sorenson, O. (2001), 'Technology as a complex adaptive system: evidence from patent data', *Research policy*, 30(7), pp. 1019-1039.

Foray, D., David, P. A., & Hall, B. (2009). Smart specialisation–the concept. Knowledge economists policy brief, 9(85), pp. 100.

Hall, B. H., Jaffe, A. B., & Trajtenberg, M. (2001). The NBER patent citation data file: Lessons, insights and methodological tools.

Hassink, R., & Gong, H. (2019). Six critical questions about smart specialization. European Planning Studies, 27(10), pp. 2049-2065.

Hidalgo, C. (2015), *Why information grows: The evolution of order, from atoms to economies*, Basic Books.

Hidalgo, C. A. (2021), 'Economic complexity theory and applications', *Nature Reviews Physics*, 3(2), pp. 92-113.

Hidalgo, C. A., Balland, P. A., Boschma, R., Delgado, M., Feldman, M., Frenken, K., ... & Zhu, S. (2018), 'The principle of relatedness. In International conference on complex systems', pp. 451-457.

Hidalgo, C. A., Klinger, B., Barabási, A. L., Hausmann, R. (2007), 'The product space conditions the development of nations', *Science*, 317(5837), pp. 482-487.

Jaffe, A. B., Trajtenberg, M., Henderson, R. (1993), 'Geographic localization of knowledge spillovers as evidenced by patent citations', *the Quarterly journal of Economics*, 108(3), pp. 577-598.

Jones, B. F. (2009), 'The burden of knowledge and the "death of the renaissance man": Is innovation getting harder?', *The Review of Economic Studies*, 76(1), pp. 283-317.

Lee, K. F. (2018), *AI superpowers: China, Silicon Valley, and the new world order*, Houghton Mifflin Harcourt.

Maraut, S., Dernis, H., Webb, C., Spiezia, V., Guellec, D. (2008), *The OECD REGPAT database: a presentation*.

Mealy, P., Teytelboym, A. (2020), 'Economic complexity and the green economy', *Research Policy*, 103948.

Montresor, S., Quatraro, F. (2020), 'Green technologies and Smart Specialisation Strategies: a European patent-based analysis of the intertwining of technological relatedness and key enabling technologies', *Regional Studies*, 54(10), pp. 1354-1365.

Paunov, C., Guellec, D., El-Mallakh, N., Planes-Satorra, S., Nüse, L. (2019), *On the concentration of innovation in top cities in the digital age.*

Pintar, N., Scherngell, T. (2021), 'The complex nature of regional knowledge production: Evidence on European regions', *Research Policy*, 104170.

Rodríguez-Pose, A. (2018), 'The revenge of the places that don't matter (and what to do about it)', *Cambridge journal of regions, economy and society*, 11(1), pp. 189-209.

Schmoch, U. (2008), *Concept of a technology classification for country comparisons. Final report to the world intellectual property organisation*, WIPO.

Storper, M. (1997), *The regional world: territorial development in a global economy*, Guilford press.

Thompson, P., Fox-Kean, M. (2005), 'Patent citations and the geography of knowledge spillovers: A reassessment', *American Economic Review*, 95(1), pp. 450-460.

Tucker, C. (2019), 'Digital data, platforms and the usual [antitrust] suspects: Network effects, switching costs, essential facility', *Review of Industrial Organization*, 54(4), pp. 683-694.

Uyarra, E., Zabala-Iturriagagoitia, J. M., Flanagan, K., Magro, E. (2020), 'Public procurement, innovation and industrial policy: Rationales, roles, capabilities and implementation', *Research Policy*, 49(1).

Wuchty, S., Jones, B. F., Uzzi, B. (2007), 'The increasing dominance of teams in production of knowledge', Science, 316(5827), pp. 1036-1039.

CHAPTER 15

FROM LAB TO MARKET: EVIDENCE FROM PRODUCT DATA

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Summary

Evaluating the extent to which scientific research findings reach the market has proven to be a challenging task for scholars and policy analysts alike. Attempts have been confined to case studies of successfully commercialised research and large-scale studies of scientific publications cited in patents (as proxies for successful innovations). However, many patents are never commercialised. Besides, consumers do not buy patents, but products that embed these patents. This chapter provides proof of concept of a method that enables tracking of ideas as they progress from the lab to the market, focusing on scientific findings from Europe. The method exploits novel data on patent-protected products and links these patents to scientific articles. It then derives several stylised facts about, among others, the gestation lags of science. On average, today's investments in science will reach the market in about 20-25 years, with surprisingly little difference across scientific fields. The method appears to be a promising one to perform research evaluations of various kinds.

1. Introduction

Europe, which hosts strong higher education institutions and scientists, has a well-performing science system overall (European Commission, 2020; Schiermeier, 2019; OECD, 2017). However, the value of Europe's science base only materialises once science reaches the market, a sine-qua-non condition for generating welfare improvements and economic benefits. Turning science into innovation is a particularly challenging task, and policymakers (and, to a certain extent, administrators at higher education institutions and public research organisations) have been struggling to provide the environment that maximises the appropriation of science.

Leaving aside the difficulty of organising private (and public) markets to achieve this aim, policy analysts lack data, metrics and methods to guide them. It is notably complex to assess the impact of public funding on the production of science and, *a fortiori*, on innovation. The outcomes ('innovations') are hard to measure, and the lags between science and innovation are long and heterogeneous. Furthermore, establishing the 'but for' baseline (so-called counterfactual outcome) is notoriously difficult – concretely, establishing the innovation output we would have had without a specific policy intervention. As a result, scholarly research has focused on documenting case studies (Bastianin et al., 2021) or evaluating specific funding programs (Li and Agha, 2015; Azoulay et al., 2019).

One key piece of information that scholars and analysts have been missing so far at large scale concerns how science translates into actual products. Getting such data is critical to improving our understanding of the innovation ecosystem and, ultimately, to devising the appropriate policy tools and incentive schemes. Some recent research has analysed the extent to which scientific publications by universities reach industry by systematically tracking publications that are cited in patent documents

(Jefferson et al., 2018). However, the mere fact that a patent cites a scientific publication does not offer evidence of real-world impact. Indeed, not all patents are commercialised, and a large majority of patents are 'worthless' (Lemley and Shapiro, 2005; Moore, 2005). Besides, consumers do not buy patents – they buy products that embed these patents.

The present chapter attempts to trace ideas as they progress from the lab to the market by identifying the science behind a set of high-tech goods. It observes the science on which more than 6 000 high-tech goods build by exploiting a novel approach that has never been deployed at scale. The approach involves searching the web for patent marks, indicating which patents protect a firm's products. Therefore the analysis also serves as a feasibility study that opens the door to more fine-grained analyses of the determinants of science's market reach.

The chapter uses the data to derive several stylised facts about the market reach of scientific findings from the European continent (EU, UK and Switzerland). The most notable finding is that the gestation lags from the lab to the consumer are long. On average, today's investments in science will reach the market in about 20-25 years, with surprisingly little difference in gestation lags across scientific fields. These gestation lags typically exceed the policy timeframe and, therefore, pose a challenge to policy design and evaluation.

The rest of the chapter is organised as follows. Section 2 presents the data for the analysis. Section 3 derives some stylised facts from the data. Section 4 concludes by discussing the policy implications of the findings.

2. Data

The data for the present analysis relies on two primary sources of information: one that links products to patents and another that links patents to scientific papers. Data on product-patent links come from a novel research project, called IPRoduct – a contraction of the terms 'intellectual property right' (IPR) and 'product'[1]. IPRoduct scouts the web in search of associations between patents and products by exploiting information contained in virtual patent marking (VPM) webpages. VPM is the online provision of constructive notice to the public that an article is patented. It is the modern equivalent of physical marking, whereby patent numbers were physically printed on products. The marking statute is an old provision in US patent law, codified under Section 287(a) of Title 35 of the US Code. In 2011, the Leahy-Smith America Invents Act (AIA) added a new method of marking to the statute, allowing patentees to affix the word 'patent' or 'pat.' on the article along with a URL of a webpage that associates the patented article with the patent number(s). de Rassenfosse (2018) and de Rassenfosse and Higham (2020) provide detailed explanations of innovative firms' incentives to adopt patent marking. More information on the project is available at www.iproduct.io.

There is no VPM provision in the patent laws of European countries. VPM documents relate to US legislation and hence cover products sold in the USA. However, they offer a rich source of information for studying the reach of European science into the market for two reasons. First, the IPRoduct database includes data on European firms selling in the USA, as Figure 15-1 exemplifies with the VPM webpage of Philips, the Dutch multinational conglomerate company. Innovative European firms that sell patent-protected products in the USA have the same incentives as US firms to virtually mark their products. Second, scientific knowledge is well known to spill across international borders (e.g. Lee, 2006; Hassan and Haddawy, 2013; Tang and Hu, 2013). US firms exploit science produced not only in the USA but also in Europe. Hence, the IPRoduct database allows us to study the reach of European science. Having noted this aspect of the data, the reader should bear in mind that focusing on products sold in the USA filters out products sold only in Europe and science that non-EU firms never picked up.

Data on patent-paper links come from Marx and Fuegi (2020) and Lens.org. Both databases source the raw data by parsing the full text of patent documents in search of citations to scientific papers. A link between patent A and paper B arises when patent A cites scientific paper B (either on the front page or the body of the text). A number of recent research studies have used such data to assess the reliance on science by patent assignees and inventors (e.g. Ahmadpoor and Jones, 2017; Arora, Belenzon and Sheer, 2021; Fleming et al., 2019).

The majority of patent-protected products in the IPRoduct dataset do not rely on science (or, more precisely, have patents that do not make a direct reference to scientific papers). We find that about 37% of products in IPRoduct rely on science, totalling 6443 products. These products are covered by 8 702 unique US patents (with some protecting more than one product). Five patents protect these products on average. However, the distribution of the number of patents protecting products is highly skewed, with a median of 2 patents and a maximum of 807 patents (and an interquartile range of 3 patents). Patents in the sample collectively cite 42473 unique scientific papers (with some papers being cited by more than one patent).

1 The project is conducted at the Ecole Polytechnique Fédérale de Lausanne, Switzerland. It was started as a pilot funded by the US National Science Foundation (NSF).

FIGURE 15-1: Philips' patent marking webpage

PHILIPS

Consumer products | Professional healthcare | **About us**

Who we are | News | Innovation | ESG | Investors | Careers | Suppliers

About us > Innovation > About IP&S > Contact and support > Patent marking

Patent marking

In accordance with Section 287(a) of Title 35 of the United States Code, Koninklijke Philips N.V. and its affiliates hereby give notice to the public that the following products are covered by the patents identified below. The products may also be covered by other U.S. patents or pending applications.

Product Name	US Patent(s)
AngioSculpt Scoring Balloon Catheter	7686824
ComboMap System	6,265,792 6,585,660
ComboWire Wire	8231537
CORE Console	6,200,268 6,381,350 7,134,994 7,215,802 7,359,554 8,029,447 8,289,284 8,449,465 8,531,428 8,556,820 8,562,537 8,636,659 9,026,384 9,314,226 9,339,348 9,364,153 9,392,979 9,469,438 9,775,524 9,974,443

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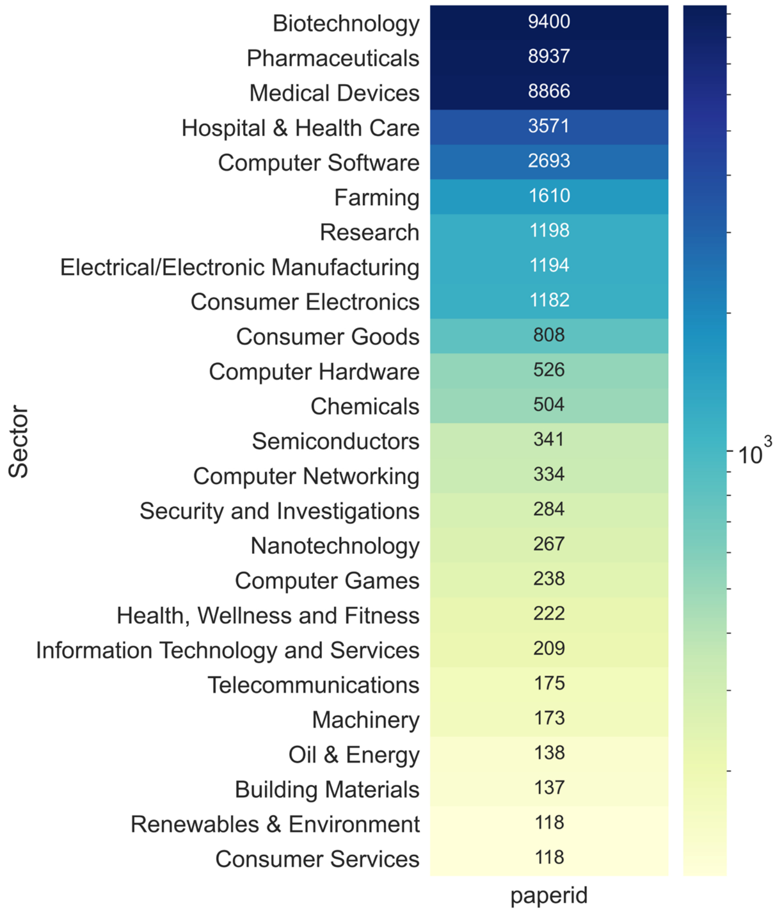
Notes: Taken from <https://www.philips.com/a-w/about/innovation/ips/contact-and-support/patent-marking.html>, last accessed 13 September 2021.
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-15-1.xlsx

Figure 15-2 presents the count of scientific papers by the sector of activity associated with the high-tech goods. The vast majority of papers were published between 1980 and 2010 (see Figure 15-4). There is a predominance of publications covering health-related products, but the sample covers a wide range of sectors, including farming, consumer electronics and building materials. The following figure also provides a breakdown by field of science. It shows that biotechnology products, computer software and farming rely primarily on publications in natural sciences. In contrast, pharmaceuticals and medical devices rely primarily on publications in medical and health sciences. Publications in engineering and technology are most prevalent in consumer electronics.

Having assembled the data, the following section turns to analysing them.

FIGURE 15-2: Distribution of scientific publications by sector of activity



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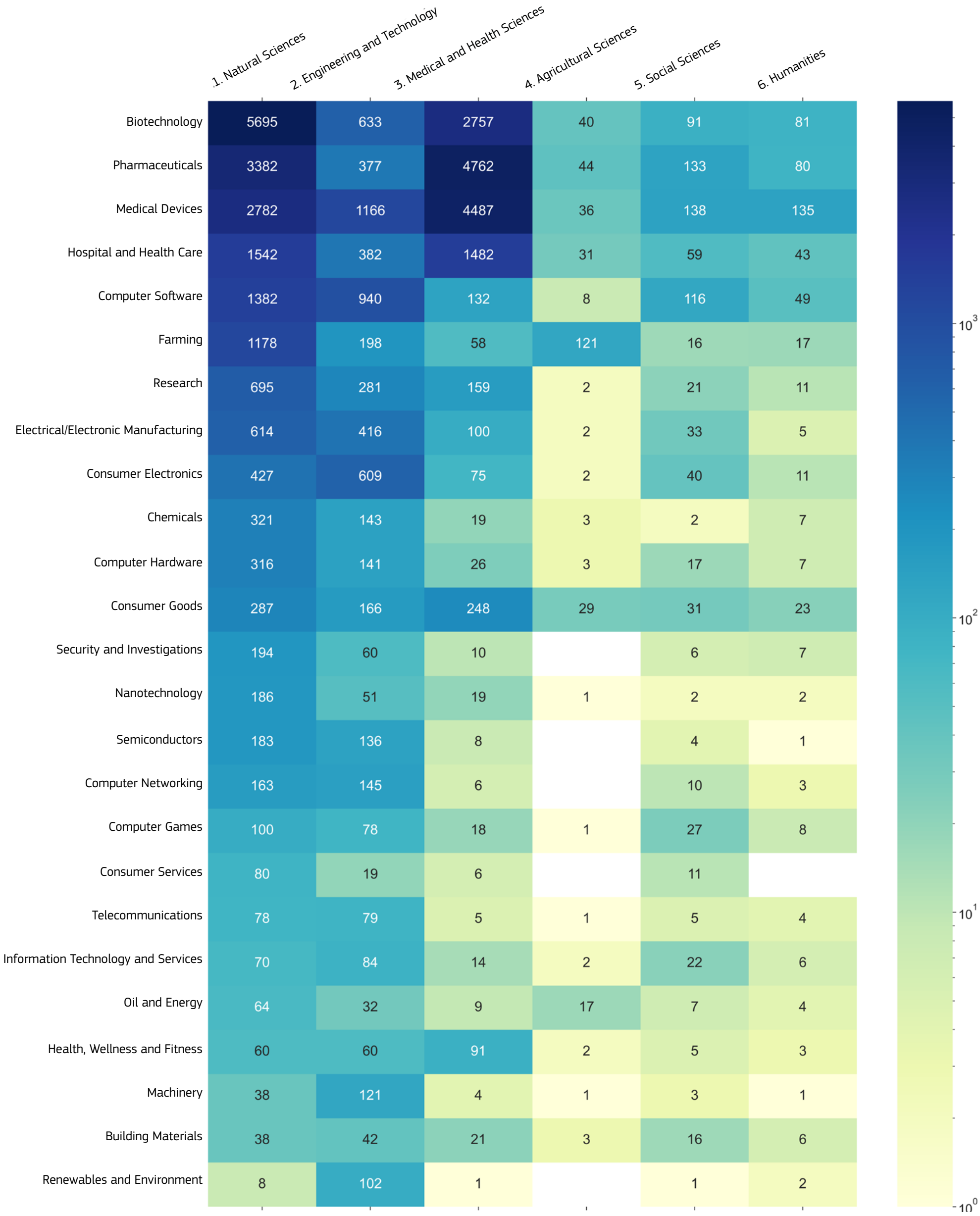
Notes: Count of unique scientific publications cited by patents protecting the high-tech goods in the sample by sector of activity. High-tech goods are classified according to the LinkedIn sector of activity to which the commercialising company belongs. Sectors with more than 100 publications are reported.

Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-15-2.xlsx

FIGURE 15-3: Distribution of scientific publications by sector of activity and field of science



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Notes: Count of unique scientific publications cited by patents protecting the high-tech goods in the sample by sector of activity and field of science. High-tech goods are classified according to the LinkedIn sector of activity to which the commercialising company belongs. The allocation into fields relies on OECD's field of science and technology classification (OECD, 2007).
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-15-3.xlsx

3. Stylised Facts

Science and technology gestation lags

The data inform us about the time it takes for science and technology to reach consumers. We call these time lags the 'gestation lags,' although we note that the literature sometimes uses the term 'application lags' (e.g. Kafouros and Wang, 2008). For convenience, we refer to 'science' when discussing scientific papers and 'technology' when referring to patent documents.

Figure 15-4 depicts the distribution of the publication years of scientific papers behind today's products and the distribution of the filing years of patents protecting these products. For the most part, science that led to today's products was published during the 1990s, with the median being in the mid-1990s. In other words, it takes about 25 years for scientific findings to reach the market. Notice that a significant number of scientific papers were published in the 1980s and earlier, providing evidence that the science base has a long-lasting effect.

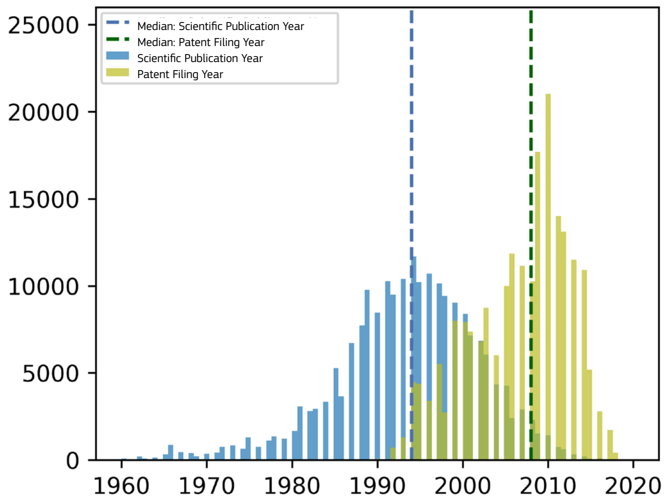
Today's products embed technology developed more than 10 years ago, based on patent filing dates. Previous research has established that the lags between R&D investments and patent filing are very short, about 1 year on average (de Rassenfosse and Jaffe, 2018), implying that today's products exploit R&D activities performed in the mid-to-late 2000s. Note, however, that we do not observe when these products appeared on the market. All we know is that these products are still available today. Should these products have been released on average 3 years ago (which is a reasonable assumption), it would take less than 10 years for R&D investments to start generating economic returns.

Despite the uncertainty about product release dates, the R&D gestation lags reported herein are relatively long compared to previous estimates. Examining the lag between R&D investments and their impact on the profits of US firms, Ravenscraft and Scherer (1982) estimated that it is about 4 years. In a similar analysis, Lev and Sougiannis (1996) found that the benefits of R&D are usually maximised in 2 or 3 years. Esposti and Pierani (2003) calibrated a model of knowledge-capital formation and came up with a gestation lag of 6 years for public R&D investment in Italian agriculture. The contrast with the literature on productivity growth is most striking, which generally assumes that R&D investment becomes productive as soon as, or soon after, it is put in place. For instance, Corrado, Hulten and Sichel (2009) consider that R&D investments instantaneously translate into productivity growth, whereas Li and Hall (2020) assume a 2-year lag. Our data challenge this assumption[2].

An apparent difference between the distributions of papers and patents is the fatter tail for scientific papers, suggesting that old science contributes to today's products, but old technology does not.

2 One potential explanation of the difference in R&D gestation lags is that we focus exclusively on commercialised products whereas models that infer gestation lags from statistical models also include process innovations, which are implemented internally by the firm (presumably at a fast rate). Another, possibly concurrent, reason is that we observe the correspondence between patents and products with high precision whereas models that infer lags from statistical models are necessarily imprecise.

FIGURE 15-4: Distribution of the publication years of science and technology contained in today's products



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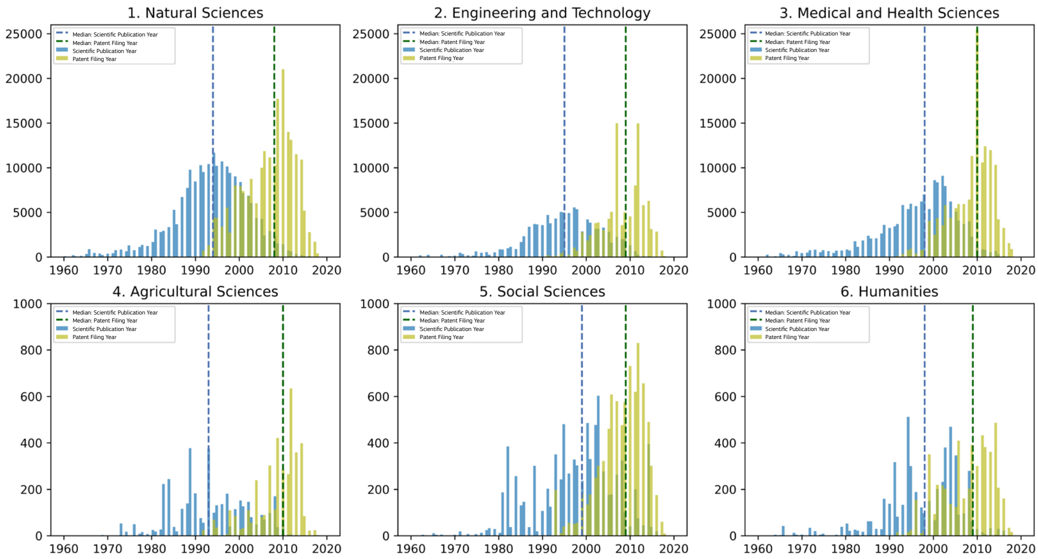
Notes: An observation corresponds to a product-patent-paper triad.
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-15-4.xlsx

There may be some truth to this claim, but the observed phenomenon is partly an artifact of the data. Since patent rights expire a maximum of 20 years after the filing date, high-tech goods inevitably lose patent protection even if these goods are still on the market. VPM web-pages cover active patent rights, which potentially truncate the left tail of the distribution.

Figure 15-5 provides a breakdown of the gestation lags by main research field. The technology distributions look surprisingly similar across fields, with the median filing year being systematically just below 2010. The difference across fields is more pronounced for science than for technology, with gestation lags being longest for agricultural sciences and natural sciences (median in the mid-1990s) and shortest for social sciences and humanities (SSH) (median in the late 1990s). However, there is overall little heterogeneity across fields.

The literature often points to the long gestation lags for products relying on medical and health sciences (e.g. Dranove and Meltzer, 1994; Lexchin, 2021), with some drugs and medical devices having to go through lengthy regulatory approvals. However, when considering a broad set of products in this area, and not just approved drugs, the data suggest that the lags from the lab to the market are not significantly different from those in other fields on average.

FIGURE 15-5: Distribution of the publication years of science and technology contained in today's products, by field of science



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Notes: The allocation into fields relies on OECD's field of science and technology classification (OECD, 2007). Allocation based on scientific papers. An observation corresponds to a product-patent-paper triad.

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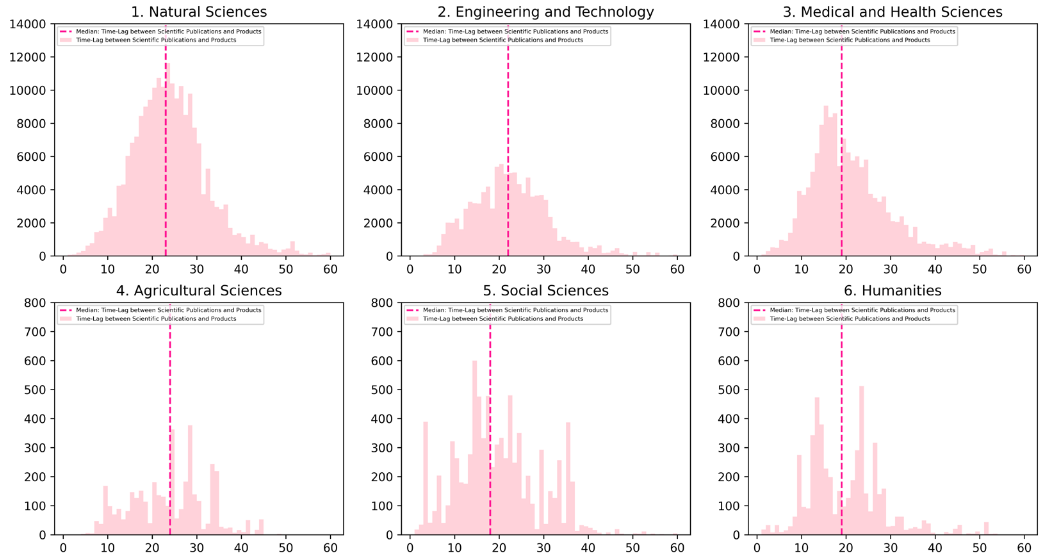
FIGURE 15-6: Distribution of science gestation lags by field



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Notes: The allocation into fields relies on OECD's field of science and technology classification (OECD, 2007). Allocation based on scientific papers. An observation corresponds to a product-patent-paper triad.

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The figure 15-6 presents an alternative view of the lags. It depicts the number of years elapsed between the scientific publication and the product commercialisation dates (assumed to be 2017 for most products)[3]. In medical and health sciences, the average lag is about 19 years, and the mode is at about 15 years – shorter than in natural sciences and in engineering and technology.

Institutional perspective

Among scientific papers for which we were able to retrieve metadata, 56 % are published by authors from institutions in the USA (possibly involving authors from other countries but none from Europe), 23 % are published by authors from Europe (including the United Kingdom and Switzerland, and possibly involving authors from other countries but none from the USA), 3 % are published by authors from both blocs, and the remaining 18 % are published by authors from other countries[4].

3 We have chosen the year 2017 based on manual inspection of a handful of products in the sample. When a patent was filed after 2017, we set the product commercialisation date to one year after the patent filing date.

4 We could retrieve data such as DOI and authors' affiliations for 13 022 of these papers.

There is no point in interpreting the difference in the number of papers between the USA and Europe because sample composition affects these differences (remember that VPM is a provision in US patent law). However, heterogeneity within Europe is worth commenting on. We have manually cleaned the affiliation data for the top 50 European universities (belonging either to the EU-27, Switzerland or the UK) listed in the Quacquarelli Symonds QS World University Rankings[5].

Figure 15-7 provides a breakdown of the contribution of universities' scientific output to the development of high-tech goods. Universities in the UK dominate the list, with three UK universities on the podium and six universities in the top 10. Given the long gestation lags documented in the previous section, the data do not tell us much about universities' current performances. Therefore, we should not use the data presented therein to assess the performance of individual universities. However, they show the Anglo-Saxon model's dominance concerning technology transfer (e.g. Cooke, 2001; Casper and Karamanos, 2003; Searle et al., 2003). An additional explanation for the dominance of UK universities is the strong economic ties and cultural proximity with the USA.

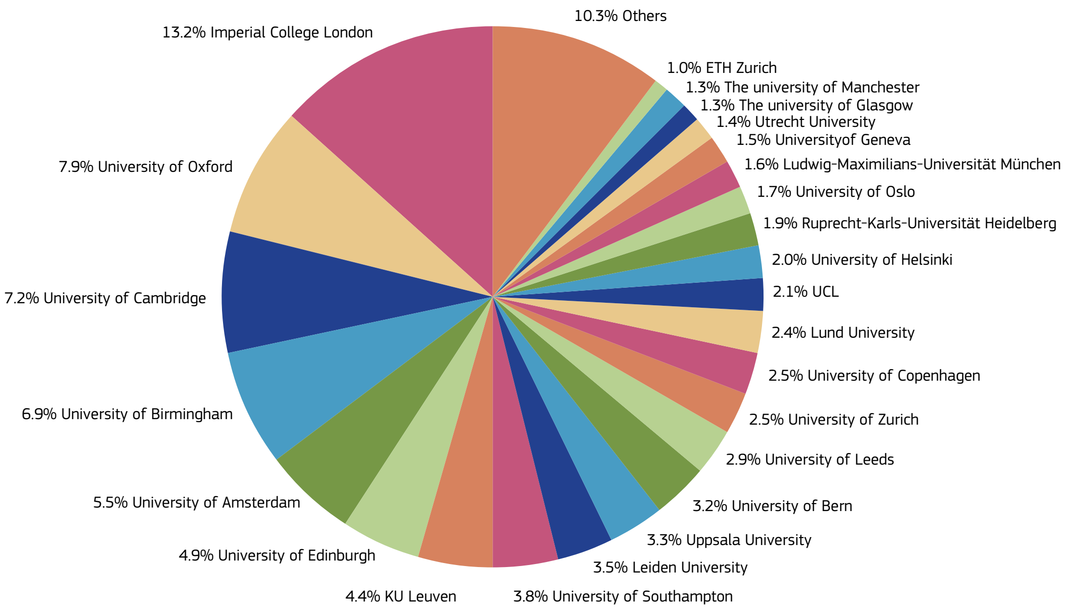
However, the data also indicate the strong performance of the 'Scandinavian model' (e.g. Benneworth et al., 2009; Bengtsson, 2017), with four universities in the top 50 for a population of about 21 million inhabitants among Norway, Sweden and Denmark.

Table 1 shows the distribution by field of cited papers for universities in the top ten. Performing an in-depth statistical analysis of the factors that drive universities' market reach is out of the scope of the present paper. Nevertheless, the table also reports the size of the universities, as proxied by the number of academic staff[6]. Two main findings emerge from the table. First, although university size seems to correlate with universities' position in the list, it is certainly not the only driver. In terms of the number of academic staff, the first-listed institution (Imperial College London) is three-fifths the size of the second-listed institution (University of Oxford), and the largest institution in the table (K.U. Leuven) is followed by one of the smallest (University of Southampton). However, we note that the last three universities listed are also the smallest, giving some credit to the hypothesis that size matters.

5 The top 50 universities are, in that order, University of Oxford (UK), ETH Zurich (CH), University of Cambridge (UK), Imperial College London (UK), UCL (UK), EPFL (CH), The University of Edinburgh (UK), The University of Manchester (UK), King's College London (UK), LSE (UK), Technical University of Munich (DE), Université PSL (FR), Delft University of Technology (NL), University of Bristol (UK), University of Amsterdam (NL), Ecole Polytechnique (FR), The University of Warwick (UK), Ludwig-Maximilians-Universität München (DE), Ruprecht-Karls-Universität Heidelberg (DE), University of Zurich (CH), Lomonosov Moscow State University (RU), University of Copenhagen (DK), University of Glasgow (UK), Sorbonne University (FR), KU Leuven (BE), Durham University (UK), University of Birmingham (UK), University of Southampton (UK), University of Leeds (UK), The University of Sheffield (UK), University of St Andrews (UK), Lund University (SE), KTH Royal Institute of Technology (SE), University of Nottingham (UK), Trinity College Dublin, The University of Dublin (IE), Technical University of Denmark (DK), University of Helsinki (FI), University of Geneva (CH), University of Oslo (NO), University of Bern (CH), Queen Mary University of London (UK), Wageningen University (NL), Humboldt Universität zu Berlin (DE), Eindhoven University of Technology (NL), Utrecht University (NL), Uppsala University (SE), Aalto University (FI), Leiden University (NL), University of Groningen (NL), and Freie Universitaet Berlin (DE).

6 Note that the data on academic staff correspond to the year 2016. These data change slowly over time and give us an indication of the relative size of institutions. Given the long gestation lags, more recent numbers are not relevant for the purpose of the present analysis.

FIGURE 15-7: Distribution of cited papers by originating university



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Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-15-7.xlsx

Second, it is remarkable to observe the substantial heterogeneity across universities. Overall, medical and health sciences form the most prominent category. However, this result partly reflects a sample-composition effect, as high-tech goods in the sample include many pharmaceuticals and medical devices (see Figure 15-3). Medical and health sciences accounts for more than 80% of all cited publications by the University of Birmingham, Imperial College London, KU Leuven and the University of Amsterdam. By contrast, natural sciences account for more than 80% of the cited publications by the University of Edinburgh and the University of Oxford. Other universities have a more balanced profile, including the University of Southampton and the University of Leiden, with close to 20% of publications in engineering and technology. Of course, this table tells us nothing about how 'relevant' a given field is in a given university. For instance, consider that university U has more than 20% of publications cited by patents protecting products in field F. However, these publications account for a mere 5% of U's total number of scientific publications. In that case, field F is very relevant in comparison to the other fields.

Figuure 15-8: Distribution of cited papers by field

University	Academic staff (FTE)	Field of publication		
		Natural sciences	Engineering & technology	Medical & health sciences
Imperial College	3 900	7%	1%	92%
U. of Oxford	6 390	82%	1%	16%
U. of Cambridge	5 590	18%	3%	78%
U. of Birmingham	3 040	4%	0%	95%
U. of Amsterdam	2 779	9%	4%	86%
U. of Edinburgh	4 215	92%	1%	3%
K.U. Leuven	7 094	6%	3%	90%
U. of Southampton	2 730	35%	17%	48%
Leiden U.	2 303	17%	19%	64%
Uppsala U.	2 970	36%	5%	59%

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Notes: Data on academic staff sourced from the European Tertiary Education Register (ETER) for 2016 (most recent year available). Only the three largest fields reported (agricultural sciences, social sciences, and humanities not reported).
Stat. link: https://ec.europa.eu/assets/rtd/srip/2022/figure-15-8.xlsx

4. Policy discussion

This chapter provides proof of concept of a method that enables tracking of ideas as they progress from the lab to the consumer. Scholars and policy analysts, who have lacked such data in the past, can use the method to study factors that facilitate technology transfer (at the university level or the level of the regional or national higher education systems, see Williams et al., 2013). Having applied the method to study the reach of European science into the market, the empirical analysis has uncovered five main findings that have policy implications.

First, the gestation lags from the lab to the consumer are long. On average, today's investments in science will reach the market in about 20-25 years. While experts are familiar with such lags in products exploiting medical and health sciences, the figure is remarkably stable across scientific fields. These long lags exceed the typical policy timeframe and, consequently, pose an immediate challenge to policy evaluation.

Second, the science base has a long-lasting effect, with some papers published in the 1980s and earlier still contributing to today's technological progress. Although this finding does not come as a surprise, it is a helpful reminder that the opposite also holds: reducing the knowledge base today has long-lasting consequences.

Third, all fields of science contribute to commercial products, including SSH. However, translation (of the sort we can observe in our data) occurs primarily in natural sciences and medical and health sciences. Scientific papers in engineering and technology represent the third-largest group. We caution against using this finding to conclude that SSH research has no real-world impact. Our method tracks science embedded in products, which is not a typical outcome for SSH research. For SSH, this research requires alternative evaluation methods that consider their social and political impacts (Reale et al., 2018; Pedersen et al., 2020).

Fourth, universities exhibit very heterogeneous profiles regarding the fields of science that are being translated. Whereas some universities are very strong in one field, others have a more balanced profile. This finding suggests that there is no dominant discipline when it comes to research impact. Note that, given the incomplete data on which the analysis builds, the list of universities should not be taken as a ranking especially not a ranking of the current performance of universities given the long gestation lags uncovered above. Although there is merit in benchmarking universities by exploiting such data in the future, a careful analysis that accounts for various statistical and data collection pitfalls is warranted.

Fifth, turning to country-level 'performances' on the European continent, the UK university system seems to contribute the most to high-tech goods, probably driven by the biotechnology revolution (see, e.g., Searle et al., 2003). Interestingly, Scandinavian countries are punching above their weight, with four universities in the top 50. It would be worth investigating the reasons behind this phenomenon in follow-on research.

More generally, this chapter has illustrated that data for Europe are patchier than for the USA. However, this does not need to be the case. To help us collect data, the inclusion of virtual marking provisions in the patent laws of European countries would be particularly helpful. To improve further the data infrastructure of EU science policy, systematically tracing linkages from scientific papers to European patents – and making the data openly available – seems a natural first step.

References

Ahmadpoor, M., Jones, B. F. (2017), 'The dual frontier: Patented inventions and prior scientific advance', *Science*, 357(6351), pp. 583–587.

Azoulay, P., Graff Zivin, J., Li, D., Sampat, B. (2019), 'Public R&D investments and private-sector patenting: evidence from NIH funding rules', *The Review of Economic Studies*, 86(1), pp. 117–152.

Bastianin, A., Castelnovo, P., Florio, M., Giunta, A. (2021), 'Big science and innovation: gestation lag from procurement to patents for CERN suppliers' *The Journal of Technology Transfer*, in press.

Bengtsson, L. (2017), 'A comparison of university technology transfer offices' commercialization strategies in the Scandinavian countries', *Science and Public Policy*, 44(4), pp. 565–577.

Benneworth, P., Coenen, L., Moodysson, J., Asheim, B. (2009), 'Exploring the multiple roles of Lund University in strengthening Scania's regional innovation system: Towards institutional learning?', *European Planning Studies*, 17(11), pp. 1645–1664.

Casper, S., Karamanos, A. (2003), 'Commercializing science in Europe: the Cambridge biotechnology cluster', *European Planning Studies*, 11(7), pp. 805–822.

Cooke, P. (2001), 'Biotechnology clusters in the U.K.: Lessons from localisation in the commercialisation of science', *Small Business Economics*, 17(1), pp. 43–59.

Corrado, C., Hulten, C., Sichel, D. (2009), 'Intangible capital and US economic growth', *Review of Income and Wealth*, 55(3), pp. 661–685.

de Rassenfosse, G. (2018), *Notice failure revisited: Evidence on the use of virtual patent marking*, National Bureau of Economic Research Working Paper No. 24288

de Rassenfosse, G., Jaffe, A. B. (2018), 'Econometric evidence on the depreciation of innovations', *European Economic Review*, 101, pp. 625–642.

de Rassenfosse, G., Higham, K. (2020), 'Wanted: a standard for virtual patent marking', *Journal of Intellectual Property Law & Practice*, 15(7), pp. 544–553.

Dranove, D., Meltzer, D. (1994), 'Do important drugs reach the market sooner?', *The RAND Journal of Economics*, 25(3), pp. 402-423.

Esposti, R., Pierani, P. (2003), 'Building the knowledge stock: Lags, depreciation, and uncertainty in R&D investment and link with productivity growth', *Journal of Productivity Analysis*, 19(1), pp. 33–58.

European Commission (2020), *The 2020 E.U. Industrial R&D Investment Scoreboard*. Publications Office of the European Union.

Fleming, L., Greene, H., Li, G., Marx, M., Yao, D. (2019), 'Government-funded research increasingly fuels innovation', *Science*, 364(6446), pp. 1139–1141.

Hassan, S. U., Haddawy, P. (2013), 'Measuring international knowledge flows and scholarly impact of scientific research', *Scientometrics*, 94(1), pp. 163–179.

Jefferson, O. A., Jaffe, A., Ashton, D., Warren, B., Koellhofer, D., Dulleck, U., Ballagh, A., Moe, J., DiCuccio, M., Bilder, G., Dolby, K., Jefferson, R. A. (2018), Mapping the global influence of published research on industry and innovation, *Nature Biotechnology*, 36(1), pp. 31–39.

Kafouros, M. I., Wang, C. (2008), 'The role of time in assessing the economic effects of R&D', *Industry and Innovation*, 15(3), pp. 233–251.

Lee, G. (2006), 'The effectiveness of international knowledge spillover channels', *European Economic Review*, 50(8), pp. 2075–2088.

Lemley, M. A., Shapiro, C. (2005), 'Probabilistic patents', *Journal of Economic Perspectives*, 19(2), pp. 75–98.

Lev, B., Sougiannis, T. (1996), 'The capitalization, amortization, and value-relevance of R&D', *Journal of Accounting and Economics*, 21(1), pp. 107–138.

Lexchin, J. (2021), 'Development time and patent extension for prescription drugs in Canada: A cohort study', *International Journal of Health Policy and Management*, 10(8), pp. 495–499.

Li, D., Agha, L. (2015), 'Big names or big ideas: Do peer-review panels select the best science proposals?', *Science* 348(6233), pp. 434–438.

Li, W., Hall, B. H. (2020), 'Depreciation of business R&D capital', *Review of Income and Wealth*, 66(1), pp. 161–180.

Marx, M., Fuegi, A. (2020), 'Reliance on science: Worldwide front-page patent citations to scientific articles', *Strategic Management Journal*, 41(9), pp. 1572–1594.

Moore, K. A. (2005), 'Worthless patents', *Berkeley Technology Law Journal,* 20, pp. 1521.

OECD (2007), *Revised field of science and technology classification in the Frascati manual*, DSTI-STP-NESTI document number 19.

OECD (2017), OECD *Science, Technology and Industry Scoreboard* 2017.

Pedersen, D. B., Grønvad, J. F., Hvidtfeldt, R. (2020), 'Methods for mapping the impact of social sciences and humanities – A literature review', *Research Evaluation,* 29(1), pp. 4–21.

Reale, E., Avramov, D., Canhial, K., et al. (2018), 'A review of literature on evaluating the scientific, social and political impact of social sciences and humanities research', *Research Evaluation*, 27(4), pp. 298–308.

Schiermeier, Q. (2019), 'Europe is a top destination for many researchers', *Nature* 569(7758), pp. 589–592.

Searle, S., Graves, B., Towler, C. (2003), 'Commercializing biotechnology in the U.K', *Bioentrepreneur.*

Tang, L., Hu, G. (2013), 'Tracing the footprint of knowledge spillover: Evidence from US-China collaboration in nanotechnology', *Journal of the American Society for Information Science and Technology*, 64(9), pp. 1791–1801.

Ravenscraft, D., & Scherer, F. M. (1982). The lag structure of returns to research and development. *Applied Economics,* 14(6), pp. 603–620.

Williams, R., de Rassenfosse, G., Jensen, P., Marginson, S. (2013), 'The determinants of quality national higher education systems', *Journal of Higher Education Policy and Management*, 35(6), pp. 599–611.

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