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SCIENCE, RESEARCH AND INNOVATION PERFORMANCE OF THE EU 2024

A competitive Europe for a sustainable future

Research and Innovation

Science, research and innovation performance of the EU – 2024 - A competitive Europe for a sustainable future
European Commission
Directorate-General for Research and Innovation
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Contact Alexandr Hobza, Chief Economist and Head of Unit G1
Julien Ravet, Coordinator of the Science, Research and Innovation Performance of the EU 2024 Report, Unit G1
Email RTD-ECONOMIC-ANALYSIS@ec.europa.eu, Alexandr.HOBZA@ec.europa.eu, Julien.RAVET@ec.europa.eu
RTD-PUBLICATIONS@ec.europa.eu

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Science, research and innovation performance of the EU 2024

A competitive Europe for a sustainable future

2024 Directorate-General for Research and Innovation

Co-creation of SRIP2024

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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).

Florence Benoit, Bianca Cavicchi, Gabriela de Saint-Denis, Valentina Di Girolamo, César Dro, Athina Karvounaraki, Alina Knobloch, Robert Kuenzel, Alessio Mitra, Océane Peiffer-Smadja, Jan-Tjibbe Steeman, Alexis Stevenson and Julien Ravet (European Commission, DG Research and Innovation) are lead authors of Part 1 of the report.

Part 2 of this report was prepared by the following experts: Dominique Foray (École Polytechnique Fédérale de Lausanne); Hanna Hottenrott (Technical University of Munich and Leibniz Centre for European Economic Research); Jakob Edler (Fraunhofer Institute ISI and University of Manchester); Dario Diodato, Lorenzo Napolitano, Emanuele Pugliese (JRC); Won Hee Cho, Chiara Criscuolo, Isabelle Desnoyers-James, Martin Reinhard and Rudy Verlhac (OECD); Julie Delanote, Péter Harasztosi, Alessia De Simone, Christoph Weiss and Marco Zeppi (EIB).

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Foreword

It is with great pleasure that I present to you the latest edition of the report on Science, Research and Innovation Performance of the EU. Europe faces numerous challenges across a complex socio-economic and geopolitical landscape. Investments in research and innovation have proven to be essential in bolstering our competitiveness and sustainability, driving progress and underpinning our ability to tackle the pressing issues of today and tomorrow. They are instrumental in supporting European businesses, creating jobs, promoting technological leadership and underpinning the green and digital transitions. Sustained investment in research and innovation is critical to protecting our planet, fostering inclusive and healthy societies, and promoting democracy.

Understanding the dynamic research and innovation environment within the European Union (EU) and beyond is crucial for shaping effective policies. Thanks to its thorough analysis of current trends, the biennial flagship report on Science, Research and Innovation Performance of the EU (SRIP) has for many years provided a critical contribution to this endeavour.

This 2024 edition of the SRIP focuses in particular on the vital role of research and innovation in meeting the EU's climate goals, advancing the circular economy, enhancing competitiveness and supporting the transition towards a more sustainable and resilient society. It examines Europe's global position with our continued prominence in science and technology and the intensifying competition from other major economies. In addition, the report highlights other challenges, such as the under-exploitation of the European innovation ecosystem and the persistent technology gaps compared to other regions. Importantly, it discusses how robust technological capabilities and the ability to seize emerging opportunities, notably in digital and green technologies, can secure and boost the EU's competitiveness.

This edition of the SRIP reveals that we must intensify our efforts in Europe to achieve the target of investing 3% of GDP in research and development and to deliver innovative solutions for our socio-economic challenges. This involves bolstering collaboration and knowledge sharing as well as reinforcing the deployment and uptake of our innovative solutions. Boosting Europe's scientific and technological capacities is essential for both current and long-term resilience and competitiveness, especially in critical technologies. This includes giving opportunities for talent and for innovative companies to prosper in Europe, building on our wide European talent base across scientific disciplines, sectors and geographies.

The report also emphasises the necessity for complementary action at the EU, national, and regional levels. We need to continue leveraging public and private sector engagement in research and innovation for the benefit of all. They are the cornerstone of Europe's future prosperity, as this report demonstrates.

Iliana Ivanova

European Commissioner for Innovation, Research, Culture, Education and Youth

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EXECUTIVE SUMMARY

How to read the SRIP 2024 report?

The 2024 edition of the Science, Research and Innovation Performance of the EU (SRIP) report builds on a wide range of data sources to offer a comprehensive and detailed overview of how Europe is performing today in terms of science, research and innovation and analyses the key determinants of this performance. The report provides an extensive coverage of topics, which illustrates the horizontal nature of research and innovation (R&I) activities in the EU landscape.

Each chapter can be read independently, catering to readers with various backgrounds and interests. Whether you are a policymaker, researcher, industry professional, academic, investor, or member of civil society, you should find sections that directly relate to your field.

Chapter 0 provides the overarching view of this edition, building on all key messages from the report to stress policy insights for EU R&I, and is a good entry point to this report before exploring more specific chapters. In particular, it highlights how the need for decisive action to make Europe more competitive, green, and fair has further intensified since the 2022 edition of this report. It details three main challenges for EU R&I today: (i) an underutilised R&I ecosystem facing several obstacles, (ii) deep and persistent R&I divides showing a stratified structure of the EU landscape, and (iii) a technological gap with respect to other regions in the world.

PART I

Part I of the report presents key analytical insights for EU R&I with focus on four specific dimensions: R&I efforts in light of EU challenges (chapter 2), EU's scientific performance (chapter 3), the local EU R&I ecosystems (chapter 4) and EU's innovative landscape (chapter 5).

Chapter 1 opens Part I with a selection of key recent trends for EU R&I on various topics covered in chapters 2 to 5.

R&I, transition and geoeconomics

The EU's R&D intensity (chapter 2.1), at 2.2% of GDP, remains below that of the US, Japan, South Korea, and China, with private R&D investment playing a significant role in explaining the gap. Governments worldwide employ different funding instruments to boost R&D investments. Within the EU, government support for private R&D decreased by 3.4% in 2020 due to reduced tax incentives, despite this instrument being increasingly used for financing private investments. Europe has taken a strong interest in Government Venture Capital (GVC), which has proven effective for increasing access to finance, but contains higher risks of crowding out private investments. Instruments to support R&D are increasingly being designed in line with a transformative policy approach that aims to drive the transition of our economy and society.

Increasing R&D investments and ensuring a strategic approach to funding are important to bridge the specialisation gap between the EU and its counterparts (chapter 2.2). The EU remains strong in green technologies, but falls behind the US and China in digital domains like the Internet of Things and AI. In sectors which are strategic to the attainment of the EU policy objectives (e.g., critical raw materials), supply chain vulnerabilities highlight the need for strategic autonomy. The risk of the EU remaining technologically dependent on other global players in these sectors raises the stakes for science diplomacy and collaborations with international partners, from which the EU can gain in terms of technological complementarity.

The need for investments in defence R&D is underscored by the current geopolitical context (chapter 2.3). The EU's defence spending surpasses Russia but remains lower than the US in nominal terms. EU defence investments prioritise the acquisition of defence equipment, focusing on technology development and production rather than foundational R&D. Fostering the synergies between EU defence and civilian R&D programmes can support the development and uptake of dual-use technologies within the EU. These technologies, serving both civilian and military purposes, could contribute to shaping the future landscape of innovation and the EU's and Member States' security.

Recent crises also highlight the importance of resilience and preparedness (chapter 2.4). The EU has shown adaptability, with 70% of citizens viewing it as a stable region in uncertain times. During crises, top R&D investors maintained investment levels, suggesting that R&I is seen as a vital component for mitigating crises, ensuring economic resilience and fostering long-term competitiveness. This requires a forward-looking strategic perspective in our R&I policies and the need to further enhance global research networks.

Scientific knowledge production

The EU has a solid research base and ranks second globally in scientific output (chapter 3.1), excelling in less technological domains, while China leads in number of top-cited publications. The EU leads in open access of scientific output, with 80 % of peer-reviewed publications openly available, and shows high shares of international collaborations (56 % of co-publications). Despite progress, gender disparities in scientific publications persist, particularly in STEM fields. To remain competitive and address societal challenges, the EU can further improve the effectiveness and performance of its public research systems. This includes supporting the responsible use of artificial intelligence and addressing persistent knowledge gaps through targeted actions.

The EU public science system features a broad range of institutions that perform moderately in rankings, in comparison with the Anglo-Saxon model that focuses on a concentration of elite institutions (chapter 3.2). Within the EU, universities and industry partners complement each other, with universities excelling in exploration and industry in development. Skilled immigration boosts R&I, but factors such as language barriers, low salaries, and strict immigration laws contribute to the EU's brain drain in contrast to more welcoming policies in the US, Canada, and Australia. A more open stance towards skilled migration can attract talent, while internationalisation policies can contribute to reducing the EU's brain drain.

The use of AI tools can make scientists and researchers more efficient and accelerate research productivity across fields, thereby helping to push forward scientific and technological advances (chapter 3.3). The use of these tools in science is increasing at a significant pace, with China taking the lead, followed by the US and the EU. R&I policy can support AI uptake through financing and the development of the right enablers to promote multi-disciplinarity. Nevertheless, the diffusion of AI in science poses important challenges related to jobs, ethics, and privacy. R&I policies can balance these risks and opportunities of AI by promoting a human-centric approach that emphasizes creativity, supports the creation of new tasks and complements existing activities.

EU R&I ecosystems

The EU faces an R&I divide (chapter 4.1), with northern and western Europe being home to innovation leaders, while moderate and emerging innovators are mostly situated in southern and eastern Europe. At regional level, some regions managed to improve their R&I performance over the last decade while others are lagging further behind. There are notable regional disparities in R&I collaborations, spending, and employment, with the industrial structure and asymmetric developments in productive specialisation contributing to this phenomenon. European funding, particularly the actions under the Framework Programme and the European Structural and Investment Funds dedicated to supporting territory development, enhancing institutional capacity and improving public administration, have a strong potential for narrowing this divide. The Recovery and Resilience Facility funding dedicated to R&I also plays a role in supporting countries with weaker innovation performance.

R&I collaborations within the EU (chapter 4.2) have increased but are still lower compared to some of its international competitors like the US. The European regional collaboration (co-patenting) network is fragmented along national lines with strong cross-border effects. Complex technologies, such as digital ones, have the highest shares of inter-country collaborations. EU Programmes such as the EU Framework Programme for R&I and Interreg, play a vital role in enhancing and steering collaboration networks while overcoming cross-border barriers and are essential for fostering a cohesive and competitive R&I landscape across the EU.

A thriving innovative Europe

In the pursuit of economic growth and competitiveness, labour productivity is pivotal. R&I plays an instrumental role in increasing EU labour productivity growth (chapter 5.1). In the goods sector, tangible assets are key to productivity, while in the service sector, software, training, and organisational capital are more influential for labour productivity.

Technological advancements and international trade are driving job polarisation by increasing demand for high-skilled labour and reducing routine, medium-skilled roles (chapter 5.2). EU employment is concentrated in manufacturing, in contrast to the concentration of US employment in health services, IT, and finance. Across the EU, high-tech sector employment has increased, but women remain underrepresented. This underrepresentation in crucial areas such as ICT and engineering, where the number of male graduates dominates, can limit workforce diversity and size. Further promoting STEM skill development and reskilling – including of underrepresented groups - provides opportunities to spur economic growth, to advance groundbreaking technologies and to avoid further exacerbation of inequalities.

To further boost productivity and competitiveness, the EU can contribute to creating an environment conducive to innovation, attracting talent, and addressing the gender gap in venture capital (VC) funding (chapter 5.3). While business dynamism has rebounded post-COVID-19, investor confidence has decreased, thereby presenting new challenges for European tech companies. VC activity has slowed after a strong performance in 2021 and the financing gap with the US persists. Nevertheless, the EU's VC market shows resilience and untapped potential, particularly in strategic net-zero technologies. Efforts can be dedicated to ensure that investments keep flowing to EU companies at the required scale.

To maintain the EU's competitive edge and sustain its path towards the Sustainable Development Goals (SDGs), scientific findings need to be converted more rapidly into commercial and social applications. The EU's innovation performance has been improving over time, but more efforts are needed to maximise R&I returns through knowledge diffusion and valorisation. To enhance and accelerate the transformation of research into practical applications, a systemic approach to knowledge diffusion, strategic intellectual asset management, and enhanced collaboration across academia, industry, and government are essential. To foster innovation activities, an adaptable regulatory framework and a proactive standardisation strategy remain key.

PART II

Chapters in **Part II of this edition** focus on the following specific topics.

Chapter 6 explores directionality in public research, focusing on guiding innovation to meet societal and industrial challenges. It contrasts research universities and government research laboratories, advocating tailored strategies for each to achieve targeted innovation outcomes. The chapter calls for a strategic reassessment to optimize directionality in innovation policy, emphasizing the adaptability of research universities and the targeted focus of government research laboratories.

Green start-ups are vital for the transition to a more environmentally friendly economy, but face various challenges, including the triple externality problem. Green start-ups carry high costs and risks associated with their entrepreneurial activity, causing the social benefits of their innovations to often exceed private returns. Chapter 7 provides a review of key insights from the stream of research on green start-ups and discusses implications for the public support of green start-ups and policy more generally.

Technology sovereignty has emerged as a critical issue in EU science, technology, and innovation policy. The EU lags behind in several technologies and relies heavily on foreign inputs of knowledge and raw materials. The specific challenges related to technological sovereignty and its link with open strategic autonomy and economic security are discussed in chapter 8.

Chapter 9 analyses the current and future outlook of green technologies in Europe to assess the need for substantial technological transformation in the pursuit of climate neutrality. By looking through the lenses of the emerging paradigm of economic complexity, it reveals a varied landscape of specialization and diversification. The chapter highlights the importance of regional cohesion and calls for tailored regional investment strategies.

Global productivity growth has slowed. Chapter 10 focusses on its causes and consequences, with a particular focus on the growing productivity gaps between companies and the challenges posed by digitalization and the green transition. It emphasizes the positive relationship between productivity, employment, and wages, and argues for policy actions to boost digital adoption, encourage innovation, and ensure inclusive growth.

Chapter 11 focuses on corporate investment in innovation and the adoption of green and digital technologies. It highlights regional differences in innovation activities and discusses factors that can support or hamper firms' investment in digital and green technologies. It finds that the EU maintains a competitive edge in climate-related investments and that it is closing the gap with the US in advanced digital technology adoption, especially in developed regions.

CHAPTER 0

A COMPETITIVE EUROPE FOR A SUSTAINABLE FUTURE – WHAT SRIP 2024 TELLS US ABOUT KEY CHALLENGES FOR EU R&I

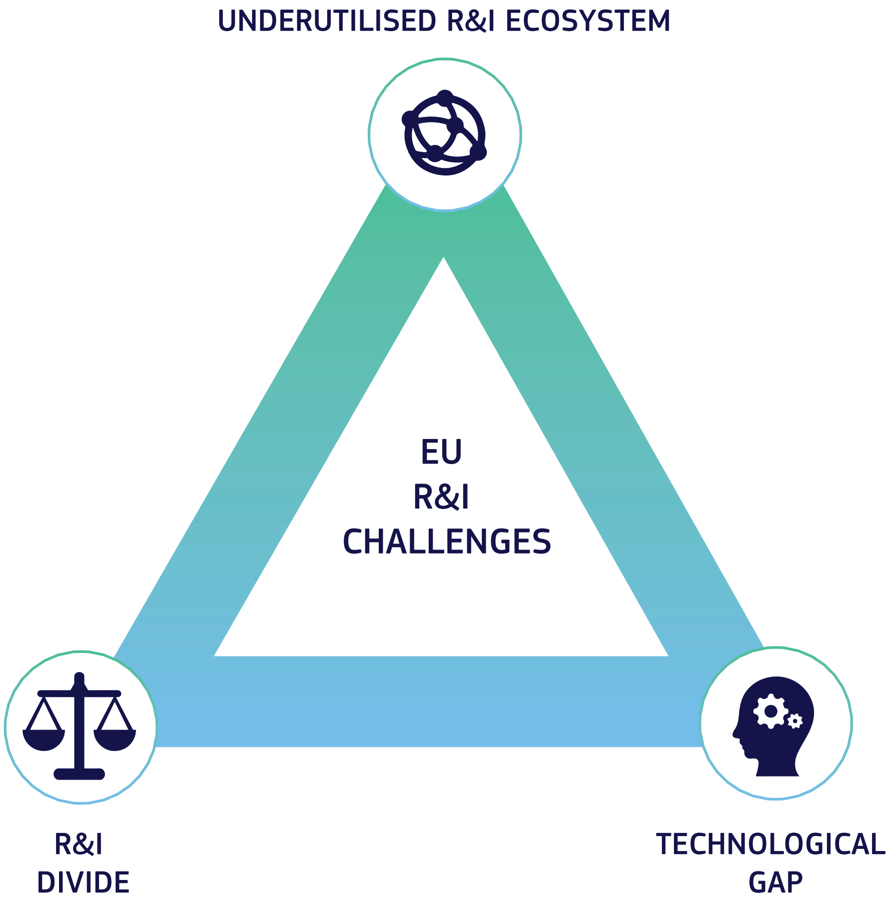
Since the 2022 edition of this report, the need for decisive action to make Europe more competitive, green and fair has further intensified. The global geopolitical situation has become more complex, and the future is ever more uncertain. Europe is often seen to be trailing the US and China in the technological race. Temperature records are being broken regularly and previously rare extreme climate events are becoming commonplace. Popular discontent is rising, some of it linked to increasing (perception of) inequality. Policies need to address these challenges and deliver on the ambitious long-term goals of the European Union (EU), while maintaining the capability to respond to emergencies in the short term. This is a tall order.

Research and innovation (R&I) is a particularly valuable instrument for finding solutions to these challenges: it is key to build ***a competitive Europe which will also shape a sustainable future***. Investing in R&I means investing in Europe's ability to handle the difficulties of the 21st century (European Commission, 2024a). It is crucial for boosting Europe's long-term competitiveness and improving living standards. And its role in supporting productivity growth and transition towards a sustainable economy will further increase with population ageing and the consequent shrinking of the labour force. It is also essential for meeting the EU's climate objectives, building a stronger circular economy and supporting the transformation of agro-food, energy and transport systems, which is needed for the green transition. Furthermore, it plays a significant role in building a fairer Europe, ensuring well-being and revamping the social contract.

But R&I is not a silver bullet. It helps to generate knowledge, technologies and skills that are crucial for tackling certain societal challenges. It makes some policy trade-offs less biting. However, it needs to be part of a comprehensive policy mix to deliver its potential benefits. Moreover, R&I does not materialise on its own and requires well-designed policies, which themselves often involve trade-offs.

Against this backdrop, the 2024 Science, Research and Innovation Performance of the EU (SRIP 2024) report offers rich analytical insights to underpin policy. The various chapters of SRIP 2024 provide a basis for discussion on R&I policies by exposing three main challenges for EU R&I today (Figure 0-1): an underutilised R&I ecosystem which faces several obstacles, deep and persistent R&I divides showing a stratified EU landscape, and a technological gap with respect to other regions. The challenges are big, ranging from the need for a long-term vision and economic integration to the need to foster an environment where inclusion and excellence in innovation coexist harmoniously. This chapter sets the stage for the in-depth examination that the individual chapters provide, highlighting the main messages.

Figure 0-1 The triangle of current R&I challenges



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

1. An underutilised R&I ecosystem – an opportunity to strengthen efforts and impact

R&I efforts[1]

Although the EU has set itself an ambitious research and development (R&D) investment target[2] of 3 % of GDP, it is struggling to achieve this objective. R&D efforts vary immensely across Member States. Moreover, R&D budgets often lack the necessary long-term stability as they might be cut when emergencies arise to address more immediate needs. The strategic direction of European R&I thus needs strengthening. Globally, the EU lags behind key peers such as the US, Japan, South Korea and, since recently, China. This gap is mainly caused by large differences in private R&D investment, which highlights the need for the EU to create better conditions for stimulating private sector engagement in R&I.

The European R&I ecosystem continues to be fragmented along national lines, which restricts the EU's ability to achieve global leadership. SRIP 2024 discusses the need for more concertation and, in some cases, harmonisation to align priorities and direct financial resources efficiently. Greater commitment to coordinating policies through tools like the European Semester or the European Research Area (ERA) will be key to achieving a well-coordinated and effective R&I ecosystem. At the same time, the implementation of structural reforms in EU Member States' national R&I systems is essential for modernisation and adaptation to a fast-changing innovation environment. The EU framework programme (FP) for R&I is a crucial EU-level instrument for creating synergies of the kind that could not be created by individual countries acting alone. It enables the development of more ambitious projects, fosters transnational collaborations, addresses EU-wide challenges, reduces redundant efforts, allows for EU-wide competition and sets unified standards (European Commission, 2024b).

A shift towards a greater adoption of transformative R&I policies has been observed. Such policies are designed to ignite transformative changes in the economy by directing R&I efforts towards greater sustainability and inclusivity. As such, formulation of these policies requires a profound understanding of the socio-economic systems and the complex interactions embedded within them. The policies are based on involvement of different stakeholders and multi-level governance. Their design must, therefore, be underpinned by a comprehensive approach which includes systems thinking, experimentation, stakeholder involvement and continuous monitoring.

Public authorities must design the mix of policy instruments to support R&I with care. Current trends show an increased use of tax incentives compared to direct subsidies, to encourage private R&I investment. Tax incentives come with a lower administrative burden, but they also bring challenges in terms of potential reductions in both efficiency and focus on societal problems, and a risk of creating tax competition. SRIP 2024 points to the role of government venture capital (GVC) in promoting innovation, particularly by making finance and human resources available. On the other hand, the risk of GVC crowding out private investment sources necessitates careful design and implementation of such measures.

1 Based on Chapters 2.1, 4.1 and 6 of the report.
2 This 3 % target was stressed in the European Council conclusions of 18.4.2024.

The 'R' in the ecosystem...[3]

The EU is a top global player in scientific research. Yet the global knowledge frontier is expanding ever more quickly, as shown by the fast growth in high-quality scientific output in countries like China and India, especially in STEM fields. This emphasises the fact that the EU must work hard to maintain its level of excellence and to enhance its scientific competitiveness globally. This requires not only the allocation of sufficient funding for science but also the promotion of international collaboration and mobility so as not to lose prominence within the global knowledge economy.

The speed of the diffusion of artificial intelligence (AI) across scientific areas brings opportunities and challenges for the EU's research environment. AI has the potential to greatly improve research productivity and push forward scientific progress, but it is essential to tackle the ethical, transparency and privacy challenges linked with this technology. Policy actions that encourage responsible use of AI, and traditional R&I tools, are necessary to maintain a balanced and human-centric approach to innovation.

The EU's research ecosystem also faces a significant challenge in terms of brain drain compared with other regions of the world. Europe's attractiveness is hindered by language barriers, rigid academic hierarchies, lower salaries and strict immigration laws in contrast to the US, Canada and Australia. Open immigration policies and internationalisation of education – as demonstrated by the Bologna and Lisbon processes – are key elements for bringing in and keeping highly skilled talent. In addition, the fact that immigrants are strongly represented among inventors and entrepreneurs underlines how crucial it is to create an environment that is inviting and inclusive for global talent.

The increasing prevalence of public-private collaborations demonstrates the important complementarities between universities and industry partners in terms of skills sets and missions. This is facilitated by open access policies, which strengthen the research ecosystem by fostering collaboration and enhancing participation of all actors, notably underrepresented actors. Notwithstanding challenges like the shifting of publication costs to authors, potential quality compromises and the creation of financial disparities within the research community, such policies help make knowledge equally accessible for all and improve research visibility. The EU's open access publication rates show a commitment to an inclusive R&I environment that promotes collaboration.

3 Based on Chapters 3.1, 3.2 and 3.3 of the report.

… and the ‘I’[4]

Translating scientific advances into innovation is key to boosting the competitiveness of the EU. Investments in R&D, software and organisational capital across multiple sectors are a critical driver of efficiency improvements in our economies, as captured in productivity metrics. A crucial precondition for the positive effects of R&I is a well-functioning innovation ecosystem which fully exploits the innovative potential of individual actors and facilitates cooperation and interaction. The EU path towards achieving this depends on proper valorisation of R&I outputs. We thus need a strategic focus that not only encourages scientific advances but also ensures and speeds up the translation of knowledge into industrial applications, solutions and innovations that reach the market, are broadly diffused in the economy and benefit society. This can be achieved, for instance, by wider use of incentives, interactive tools and models of collaboration between industry, academia, civil society and policymakers, as well as by increasing access to knowledge through efficient intellectual asset management. This will help Europe to become more competitive and boost long-term economic growth. In this respect, AI has the potential to boost knowledge valorisation and reverse the productivity slowdown that has plagued western economies in recent decades. However, for this to happen, it is crucial to implement policies that ensure AI augments, rather than replaces, human labour.

For the EU to be a leader in innovation and technology, a concerted effort is needed to create an environment which allows for innovative, ground-breaking advancements. A comprehensive approach can not only address the immediate requirements for technological progress but can also put the EU in a position to greatly influence future global innovation. But building an innovation-friendly environment and an innovation-centric culture in the EU is not just about putting money into state-of-the-art R&I; it also requires a paradigm shift towards knowledge valorisation to speed up the process of turning research results and new technologies into marketable products, as well as adequate strategic alliances, increased multi-stakeholder co-creation, regulatory frameworks, adequate skills and policy tools, openness to new ideas, risk tolerance and recognition, and incentives for entrepreneurship and innovative approaches. These are core elements in the New European Innovation Agenda. The creation of the European Innovation Council (EIC) as a catalyst for deep tech innovation also highlights the EU’s commitment to leading the next wave of breakthrough innovations.

4 Based on Chapters 5.1, 5.2, 5.3, 7, 10 and 11 of the report.

A thriving landscape of innovative firms is crucial to the innovation capacity of an economy. The cooling of venture capital (VC) investment after 2021 and the difficulties of EU tech firms in scaling up show an urgent need for policy action. This requires a multifaceted approach to encouraging investment, especially in strategic technologies – including deep tech – and clean energy, crucial for navigating the green and digital transitions, supporting start-ups and scaleups and ensuring the availability of a highly skilled workforce. This is particularly relevant for deep tech technologies which require a unique skillset (a key element here is also addressing gender imbalances in STEM fields). These policies should aim at closing the financing gap and promote business dynamism.

Fostering a strategic approach to the management of intellectual assets within the R&I ecosystem can help generate more breakthrough innovations in Europe. This approach should balance economic interests with the goal of generating societal benefits, such as by adopting open science and socially responsible licensing practices. Facilitating access to and use of intellectual assets such as intellectual property rights (IPRs), know-how and data will support the competitiveness of the EU and help to address societal challenges. Several initiatives have been taken around the globe, for example in Australia[5] and Japan[6], to stimulate use of research results and to offer guidance to R&I actors on efficient intellectual asset management and collaboration between industry and academia.

5 National principles of intellectual property management for publicly funded research, updated in June 2022 and the Higher education research commercialisation intellectual property framework, released in 2022.

6 Intellectual property strategic programme 2022 and University intellectual property governance guidelines.

2. The R&I divide – an opportunity to build bridges and inclusiveness[7]

A serious obstacle to the creation of a thriving EU R&I ecosystem is the persistence of spatial divides in R&I performance highlighted in this report. These gaps are caused by differences in the ability to innovate, levels of cooperation, costs and job opportunities linked to R&I activities. Even though there have been improvements in some regions over the past decade, the persistence of these regional disparities highlights the importance of specific actions to promote cohesion and ensure that the benefits of R&I are widely shared.

At regional level, the map of R&I performance levels largely coincides with national borders, but developments differ across regions. Regions that are innovation leaders and strong innovators are mainly in northern and western Europe. Moderate and emerging innovators are more common in the south and east of the continent. This pattern is not static: some regions are improving their R&I performance while others fall behind. Also, many small and medium-sized enterprises (SMEs) in less advanced regions of Europe have made progress in various R&I indicators. This is in contrast to SMEs in stronger regions, which have declined in several R&I indicators. Degrees of industrial clustering also differ across regions. The industrial structure of European regions and asymmetric developments in productive specialisation across countries and regions have underpinned the emergence of spatial disparities in R&I. The emergence of social innovation clusters adds another layer to these disparities, suggesting that overcoming the R&I divide requires a nuanced approach.

Overall, EU funding for R&I can play a role in narrowing the divide, as regions with low levels of R&I performance rely significantly on it to support their R&I systems. At the same time, EU FP for R&I funding is quite concentrated due to its excellence-driven nature, which gives rise to concerns about exacerbation of disparities. Dedicated actions within programmes such as the EU FP for R&I and the European Structural and Investment Funds, which help with territorial development, build institutional capacity and improve public administration, are important to promote cohesion while counterbalancing a potential 'closed club' effect so as to increase the competitiveness of the EU. The Recovery and Resilience Facility (RRF) funding dedicated to R&I is also expected to play a role in closing the R&I gap, as data shows that it provides significant support for countries with weaker innovation performance. Synergy between sources of funding can help to harness the concentration of innovation in hubs of excellence while connecting these hubs with each other and integrating them in their regional context, to enable redistribution of the benefits of innovation.[8]

The general increase in R&I collaborations across the EU shows how crucial EU-level R&I policies are for encouraging ecosystem linkages. Despite this, the intensity of cross-border cooperation is much lower than that of cooperation across different states in the US. This points to a huge underutilisation of the potential of Europe's innovation ecosystem.

7 Based on Chapters 4.1, 4.2, 9 and 11 of the report.

8 Expert group on the Economic and Societal Impact of R&I, Combining Regional Strengths to Narrow the Innovation Divide, upcoming June 2024.

The EU FP for R&I has played a key role in establishing an extensive EU-wide collaboration network which is helping to overcome national fragmentation and encourage cross-border collaborations. Programmes like Interreg also play a significant role in promoting territorial cooperation and steering R&I collaboration throughout the EU.

The R&I divide manifests itself in different dimensions, which calls for tailored policies at regional and local level that concentrate on increasing inclusiveness and utilising unused potential. It is important that local R&I ecosystems become more dynamic, diverse and attractive to talent from different backgrounds. Actions such as the EIC's gender-balance portfolio and dedicated funding schemes for female entrepreneurs, along with work to improve access to EU financing for newcomers, are good practices for enhancing inclusiveness.

Helping countries and regions to develop capabilities and talent is important for turning existing pockets of excellence into flourishing ecosystems. This can be enhanced by funding policies that are harmonised and aligned so as to foster synergies. Making R&I results from projects more accessible can improve knowledge spillovers. It can also help researchers and innovators to use newly generated knowledge.

3. The technological gap – an opportunity to strengthen strategic focus and build cooperation[9]

The EU still struggles with raising private sector investment for R&I, especially in important sectors like ICT and health, and tends to specialise its R&I in technologies characterised by lower complexity[10] and in mid-tech sectors, a situation that some call a technological trap.[11] An approach that combines R&I with wider industry objectives could help to bring about the necessary change by supporting sectors with high R&D intensity, promoting an environment for private investment in critical technologies like advanced semiconductors, biotech, space tech and advanced materials tech, for which the EU needs to regain technological leadership (European Commission, 2024a).

More generally, at a time when digital strength and green innovation are key factors in competitiveness, the EU's strategic focus on these fields is crucial. This report shows that the EU has already made strong progress with green technologies, but it needs to improve its R&I capabilities in the digital area. As regards digital technologies, especially important technologies such as Internet of Things (IoT), blockchain and cybersecurity, there is a gap between the EU and other global leaders such as the US and China. Moreover, supply chain vulnerabilities for critical raw materials and the manufacturing of semiconductors, batteries and green technologies highlight the need for a strong R&I policy set-up that promotes technological sovereignty and strategic autonomy. At the same time, supported by initiatives such as the Net-Zero Industry Act, the Critical Raw Materials Act and the STEP Regulation, the EU can enhance its role in green technologies thanks to the growing worldwide demand for critical technologies created as a result of decarbonisation efforts. However, this comes with challenges such as the US Inflation Reduction Act, which provides significant incentives, mainly in the form of tax credits, for energy and climate in the US. The STEP regulation is a first element of the EU response.

There is a growing need for actions that reconcile the objectives of adopting a coordinated approach to climate neutrality and securing critical supply chains, while limiting foreign interference. International R&I cooperation has a major role to play in this. Meeting the strategic requirements of encouraging science diplomacy and building collaborations worldwide could enable the EU to harness complementary technologies and mitigate risks associated with technological dependencies. As a strategic framework for international R&I cooperation, this imperative of preserving an open economy while safeguarding EU and national interests is in line with the Global Approach to R&I[12] (as open as possible, as closed as necessary) and

9 Based on Chapters 2.2, 2.3 and 8 of the report.

10 The approach used in SRIP 2024 for complex technologies relies on the economic complexity literature. Less complex technologies are relatively easy to copy and move over space and their development typically requires fewer capabilities. This confers a lower competitive advantage on the countries/regions in which they are located. More complex technologies combine a higher number of capabilities, are more concentrated geographically and have higher potential in terms of growth and overall competitiveness.

11 Fuest et al (2024).

12 COM(2021) 252 final. Communication on the Global Approach to Research and Innovation.

the European economic security strategy[13] (de-risk, not decouple). In this regard, preserving academic freedom by supporting European research-performing organisations also remains crucial to addressing research security risks linked to increasing international conflicts and competition.[14]

The geopolitical landscape, with its emerging threats and conflicts, also highlights the need for a robust EU defence R&I framework and the importance of dual-use technologies to reap the full potential of such a framework. Innovative defence and security technologies are crucial to counter the security challenges posed by climate change, demographic shifts, political polarisation and geopolitical changes and to ensure global stability in a rapidly evolving world. In the EU, there is a notable focus on spending on the later stages of defence technology development rather than on foundational research and technology demonstration. However, at lower technology readiness levels (TRLs), defence R&D spillovers and overlaps between civilian and military interests are expected to be more significant. Within the current EU FP for R&I, activities carried out under the European Defence Fund should have an exclusive focus on defence R&D, while activities carried out under the 'civilian' specific programme and the European Institute of Innovation and Technology should have an exclusive focus on civil applications. Coordination between programmes may strengthen synergies in dual-use technology areas. The EU can fully harness the potential of dual-use technologies by fostering synergies and bridging the divide between civilian and defence R&D, both within the EU as a whole and among its Member States.[15]

13 JOIN(2023) 20 final. Joint Communication to the European Parliament, the European Council and the Council on European Economic Security Strategy.

14 Council recommendation on Enhancing Research Security, C/2024/3510.

15 European Commission (2024c).

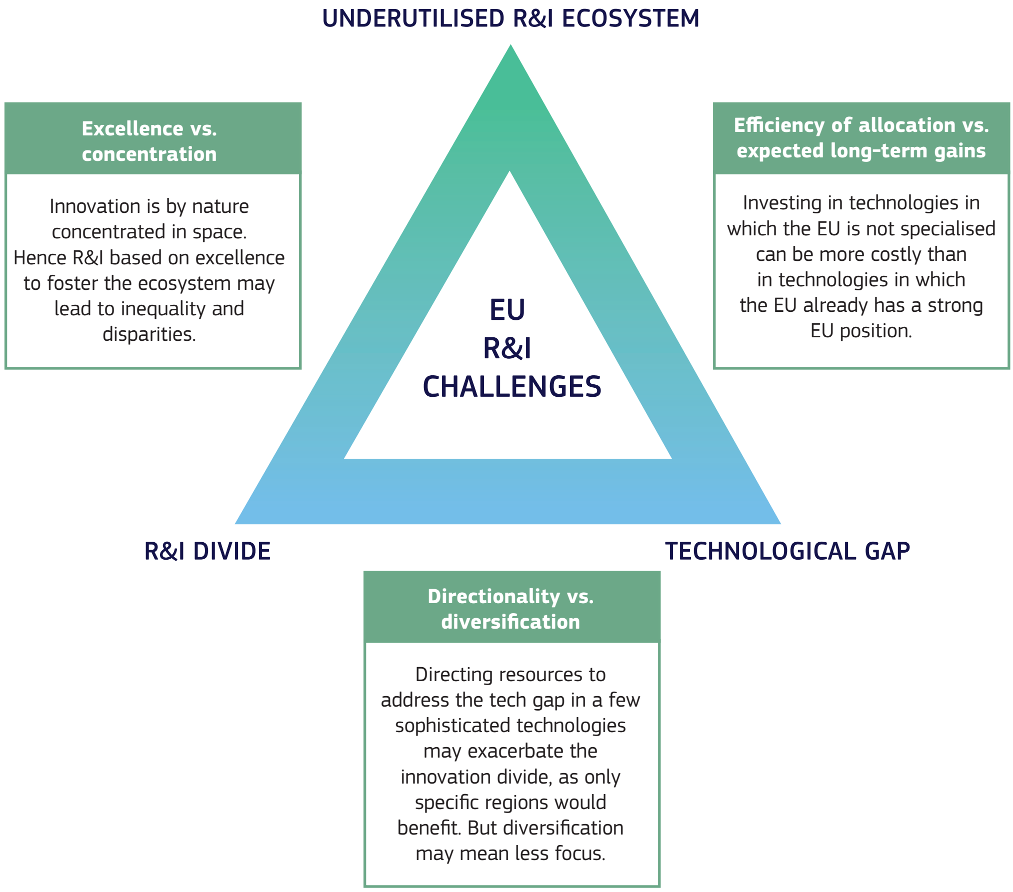
4. Trade-offs

R&I policies need to act along all three dimensions of the innovation triangle. They should make the European R&I ecosystem more performant and connected, especially in terms of producing and diffusing innovations; exploit talent and innovation potential across the EU to achieve inclusive excellence; and ensure that Europe can fully benefit from advances in transversal digital technologies and shape the direction of their development.

Nonetheless, these impacts can generate important trade-offs, which need to be adequately addressed (Figure 0-2). This is particularly true when resources are scarce and policymakers need to make choices regarding their optimal use. One trade-off concerns achieving excellence while avoiding deepening the R&I divide. Promoting the development of the European R&I ecosystem implies promoting excellence. However, R&I activities have an inherent tendency to concentrate in certain places – a tendency that can be reinforced through provision of support to the highest achieving activities and actors. This can exacerbate inequality and regional divides. A second source of tension is that achieving efficiency in resource allocation, such as by focusing on what the EU is already good at, may conflict with the goal of building up capacities in sectors which are strategically important but where Europe lags behind. Investing more in fields where the EU does not have a comparative advantage will be costly and implies risk. This particularly concerns transversal digital technologies, including AI, which are likely to transform our economies in the years to come. Failing to build appropriate technological capacity in these areas could have wide implications for Europe's competitiveness across the board. However, catching up with the EU's global competitors, who are currently well ahead, will require substantial resources and resolute policy action. Finally, a third source of tension arises from the trade-off between directionality and diversification in R&I investments. Concentrating resources mainly on closing specific technology gaps may favour specific regions and actors, thus deepening the R&I divide. Also, focusing investment on cutting-edge technologies might fill certain gaps and bring valuable results but would also runs the risk of the EU missing out on wider gains from diversification. Overall, R&I policies should be aimed at attaining excellence without ignoring equitable progress, maintaining efficiency without jeopardising the achievement of future strategic goals and staying focused while enhancing technology throughout the EU.

Moreover, R&I policies that work in tandem with other policies maximise their impact. It might be a tall order for R&I policies to address all these trade-offs on their own. It is, therefore, important that they are closely aligned with other economic policies, for example, industrial policies.

Figure 0-2 Trade-offs between R&I challenges and their solutions



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

5. A future-proof policy approach to leverage the potential of R&I

In an increasingly complex and uncertain environment, R&I policies must contribute to fostering economic and societal resilience. This has implications for policies themselves, which need to be more adaptable and forward looking. Recent crises, such as the COVID-19 pandemic, have emphasised the need for policies that can be quickly adjusted to new situations – with a focus on preparedness and an agile response system. This requirement goes well beyond crisis management, also covering future planning and readiness, as well as using foresight in policy design with particular emphasis on long-term risk assessment. In this context, the expert group on the economic and societal impact of research and innovation (ESIR) has stressed the need for policies that prevent the EU from falling into the trap of short-termism and instead adopt a 'protect, prepare and transform' approach: protect through a timely and coordinated response to emergencies; prepare for a broad set of future risks, through coordination, foresight, community involvement and re-skilling; transform the economy and society to create a competitive, green and fair Europe. Hence, R&I can be seen as a strategic tool to deal with disruptions and provide future-focused solutions to societal challenges.[16]

The ongoing discussions on the future of the FP provide an opportunity for strategic reflection on European R&I policies. The fundamental changes in the external environment and the increasingly pressing societal challenges and weaknesses in Europe's R&I performance justify a rethink of our R&I policies. More than ever, there is a need for a future-proof policy approach which will leverage the potential of R&I to act as a key instrument for societal progress.

When discussing the specific design of R&I policies, several aspects need to be considered.

- To fully exploit their potential, R&I policies need to be aligned with other policies in a comprehensive and complementary economic policy mix, such as industrial policies.

- R&I policies need to be focused on long-term objectives, while retaining the agility to respond to short-term emergencies. A key factor in enabling R&I to deliver is long-term stability, including as regards funding. This, however, often falls victim to short-term shifts in priorities. As we are entering an era of polycrisis or permacrisis, a balanced approach is warranted to ensure that policies address immediate needs without compromising long-term aspirations.

- Both curiosity-driven and mission-oriented research are part of an effective policy mix. Bottom-up scientific advances are a key driver of disruptive innovation and productivity growth in the longer run. At the same time, transformative changes require directed R&I efforts geared towards results that can help solving wider societal problems.

- Knowledge valorisation is about ensuring that the ideas produced by curiosity-driven research are being put in practice through innovation and widespread adoption. Connecting different spheres of innovation means more than just linking up separate initiatives; it also involves aligning the actors involved: those who perform research, formulate policies and run businesses, and society as a whole.

16 Based on Chapter 2.4 of the report.

- The dual challenge of encouraging excellence and being inclusive requires providing conditions under which R&I activity can flourish, while at the same time fostering the dissemination of the benefits of innovation through all parts of society, leaving no region or group behind. ERA and the single market play a crucial role in this respect by facilitating the free circulation of knowledge in the EU.
- Finally, the meta-challenge of making innovation policy more innovative highlights the need for R&I policies that are as dynamic and forward-looking as the research they support. Continuous learning through experimentation and evaluation helps to adjust policies to changing needs in a fastly evolving world.

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PART

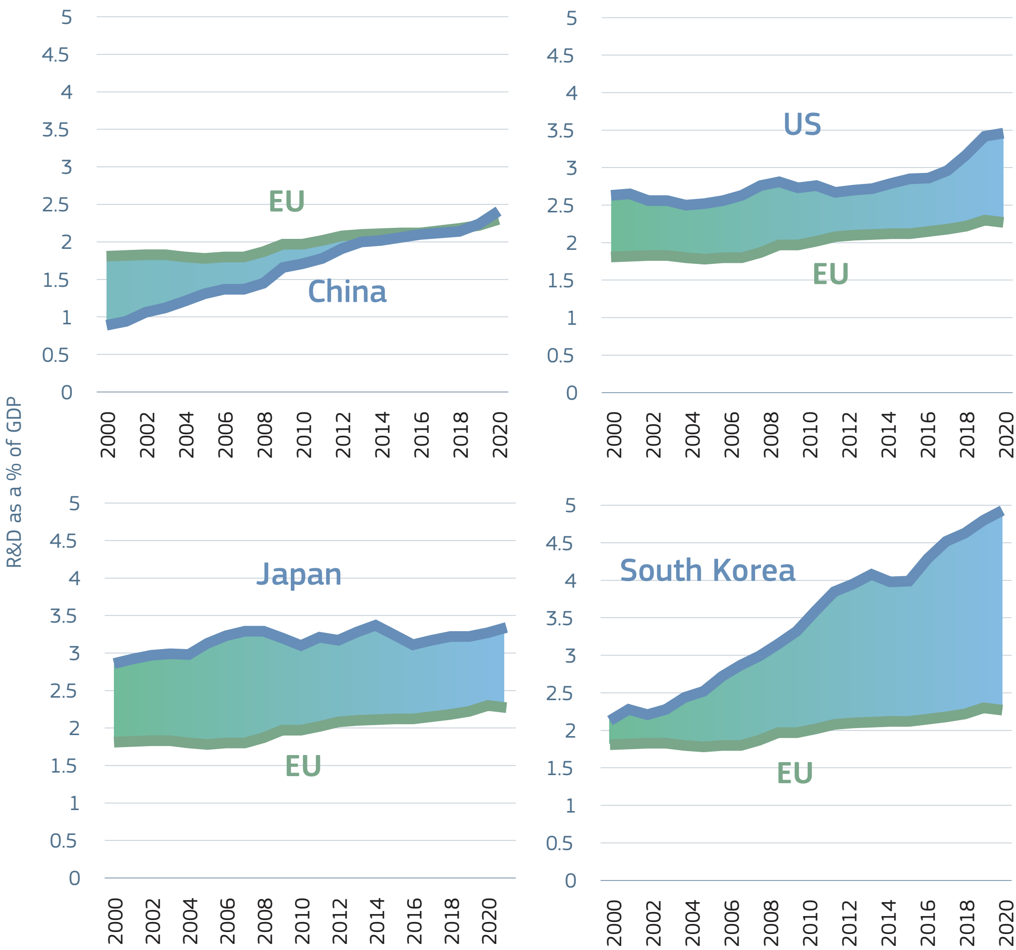
I

CHAPTER 1

KEY TRENDS

1. The EU has increased its R&D investments over the past two decades. Yet a gap remains to some of its main competitors, and the EU's relative weight in the global R&D landscape is decreasing.

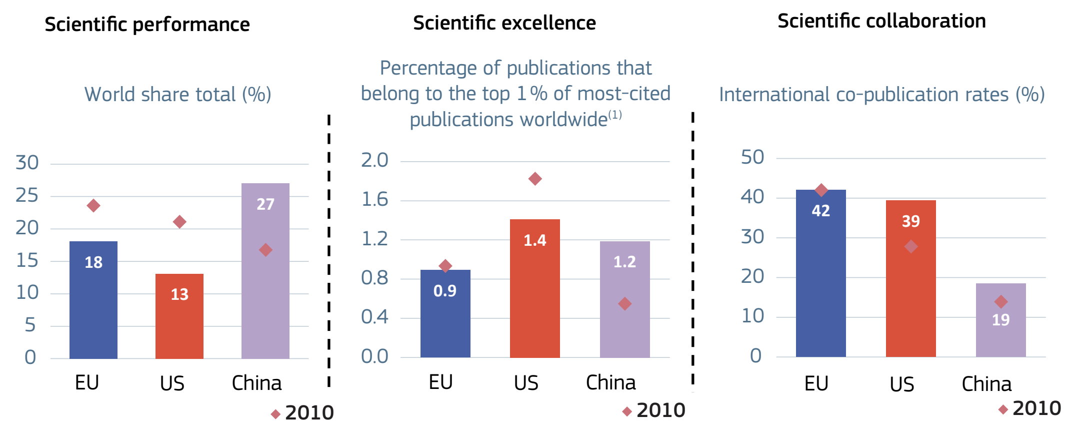
Figure 1-1 The EU's R&D intensity gap with other major economies



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

2. The EU has a strong research base and ranks second globally in terms of scientific output. Despite a lower level of scientific excellence than its main competitors, its performance has remained stable over time, with high rates of international co-publications.

Figure 1-2 **Scientific performance, excellence and collaboration – EU, US and China, 2022**



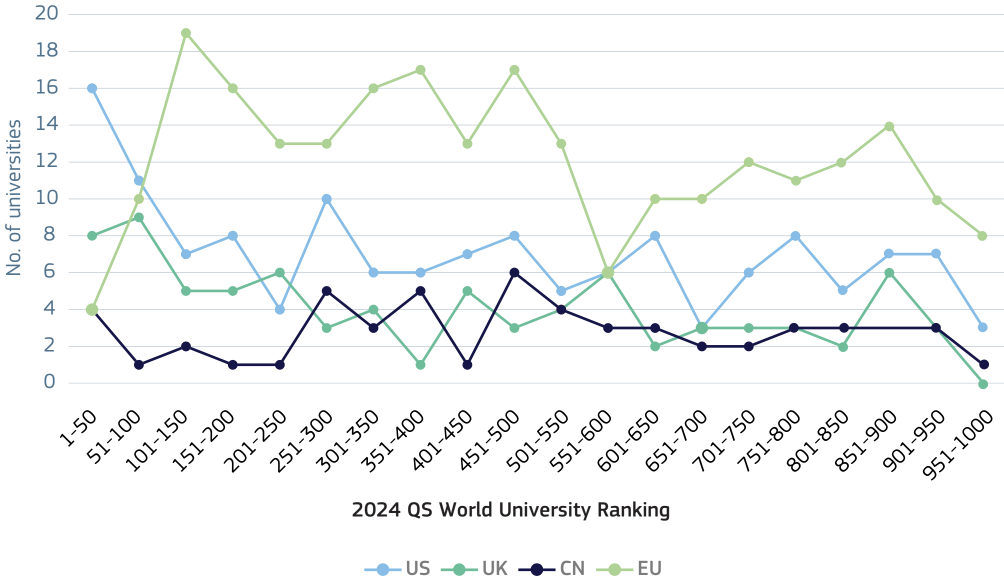
Science, research and innovation performance of the EU 2024

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

Note: (1)2022 citation window: 2020-2022; 2010 citation window: 2008-2010.

3. Anglo-Saxon academic system features a concentration of high-performing institutions, while the EU exhibits a more uniform distribution, prioritising broad-based moderate quality over exceptional peaks.

Figure 1-3 **Distribution of university quality (in absolute terms) worldwide**

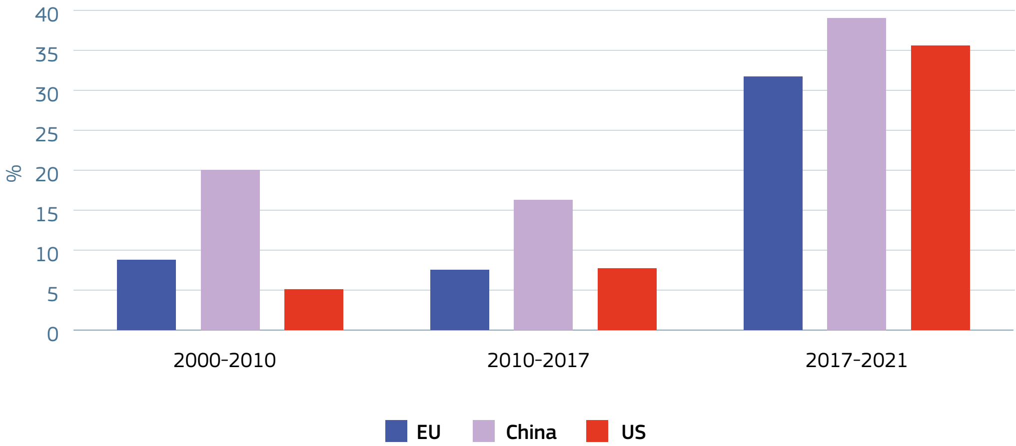


Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on QS World University Rankings 2024.

4. China is the global leader in terms of publications related to AI applications in science, followed by the EU and the US. Based on current growth rates, the gap between China and the EU is expected to widen in the future.

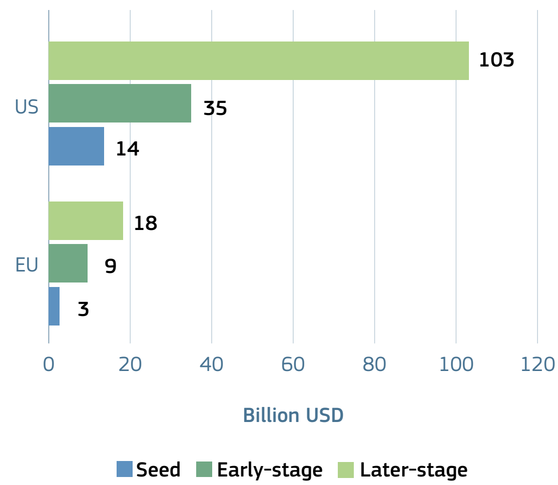
Figure 1-4 **Average yearly growth in numbers of AI-related publications in the EU, the US and China, by period**

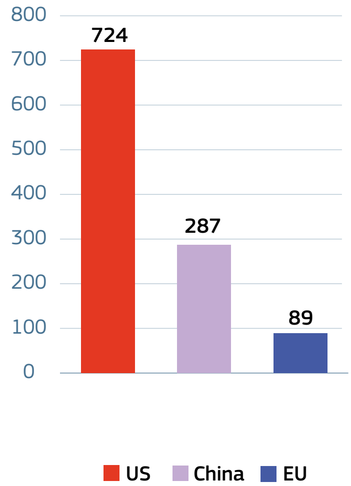


Source: Arranz et al., (2023).

5. The financing gap between the EU and the US is observed at all stages of development but remains more prominent in the scale-up phase. As of November 2023, the numbers of companies with the status of unicorns in the US and China exceeded that in the EU by factors of 8 and 3, respectively.

Figure 1-5 Venture capital investments[1] in the EU and the US, by development stage, 2023 (left)
Number of unicorns[2] by world region, based on location of headquarters, as of November 2023 (right)





Science, research and innovation performance of the EU 2024

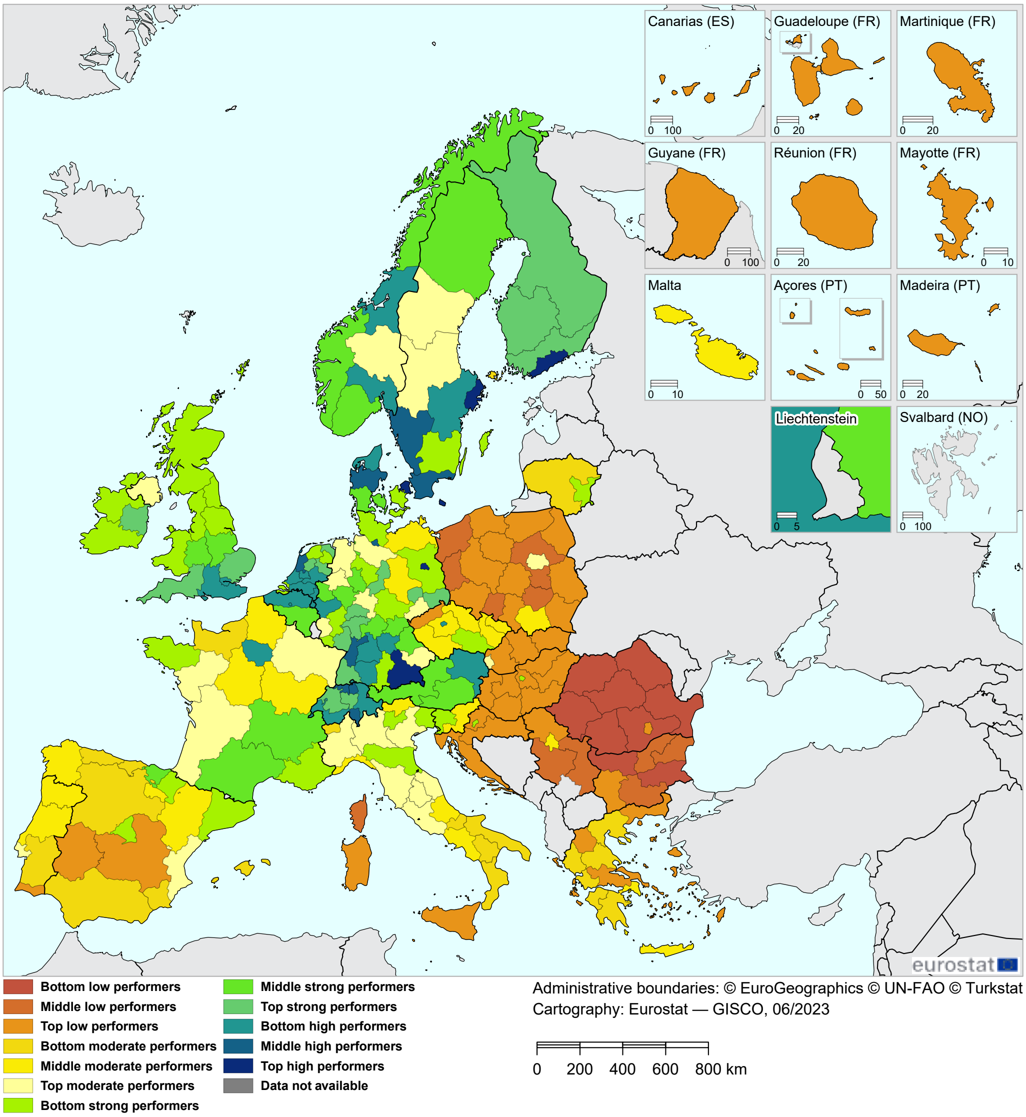
Source: PitchBook data, as of 20 November 2023.

Notes: [1]Investment values are calculated based on the countries in which the companies involved in completed deals have their headquarters.

[2]A unicorn is defined as a venture-backed company that has raised a venture round with a post-money valuation of at least USD 1 billion. An 'active' unicorn is one that has not exited, meaning that it is/was venture-backed as of the year shown.

6. Although innovation performance has increased in most EU Member States, the innovation divide within and between Member States persists. It also persists at regional level. More innovative regions tend to be found in highly innovative countries. However, regional ‘pockets of excellence’ can be seen in less innovative countries.

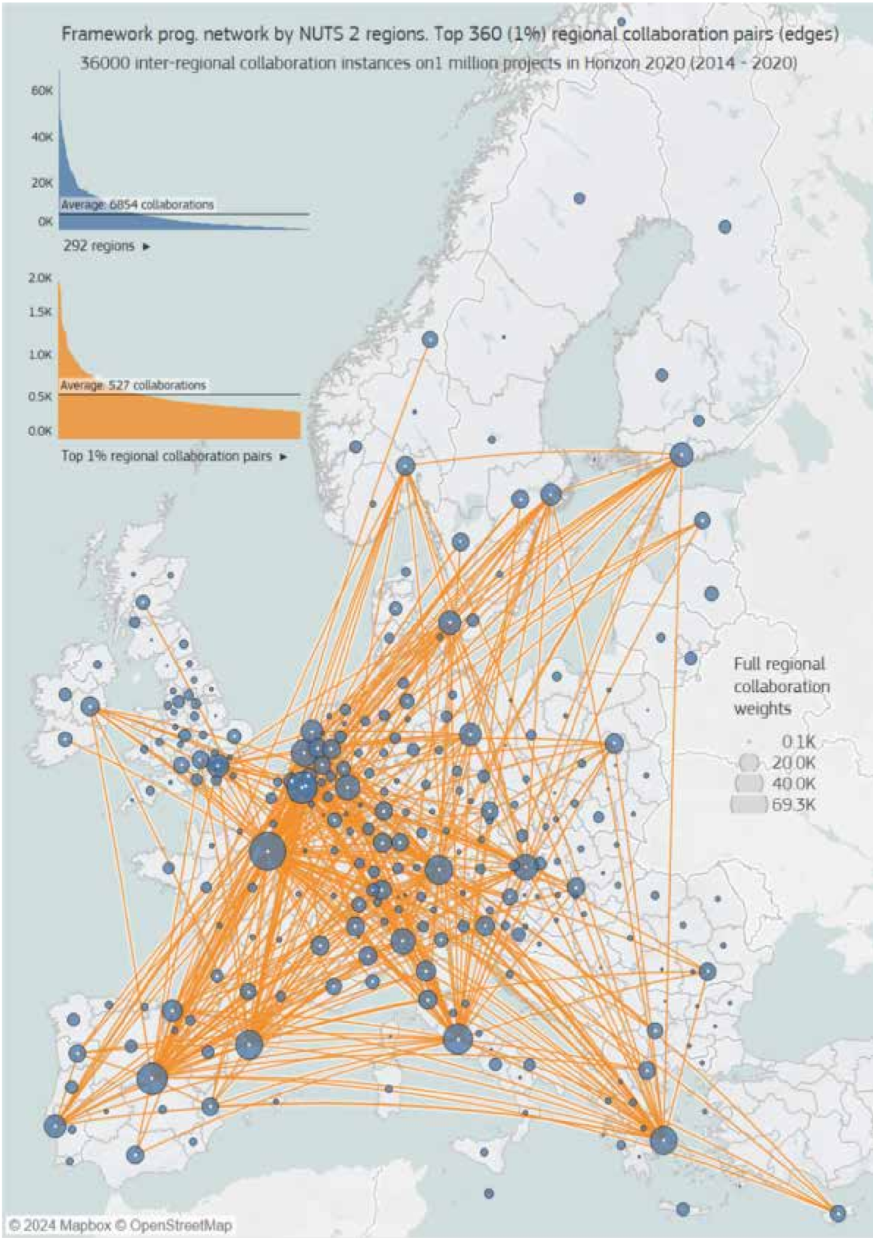
Figure 1-6 **Regional Innovation Scoreboard 2023**



Source: Regional Innovation Scoreboard 2023, Publications Office of the European Union, 2023: https://data.europa.eu/doi/10.2777/70412.

7. The EU framework programme for R&I created an important R&I collaboration network during the 2014-2020 period.

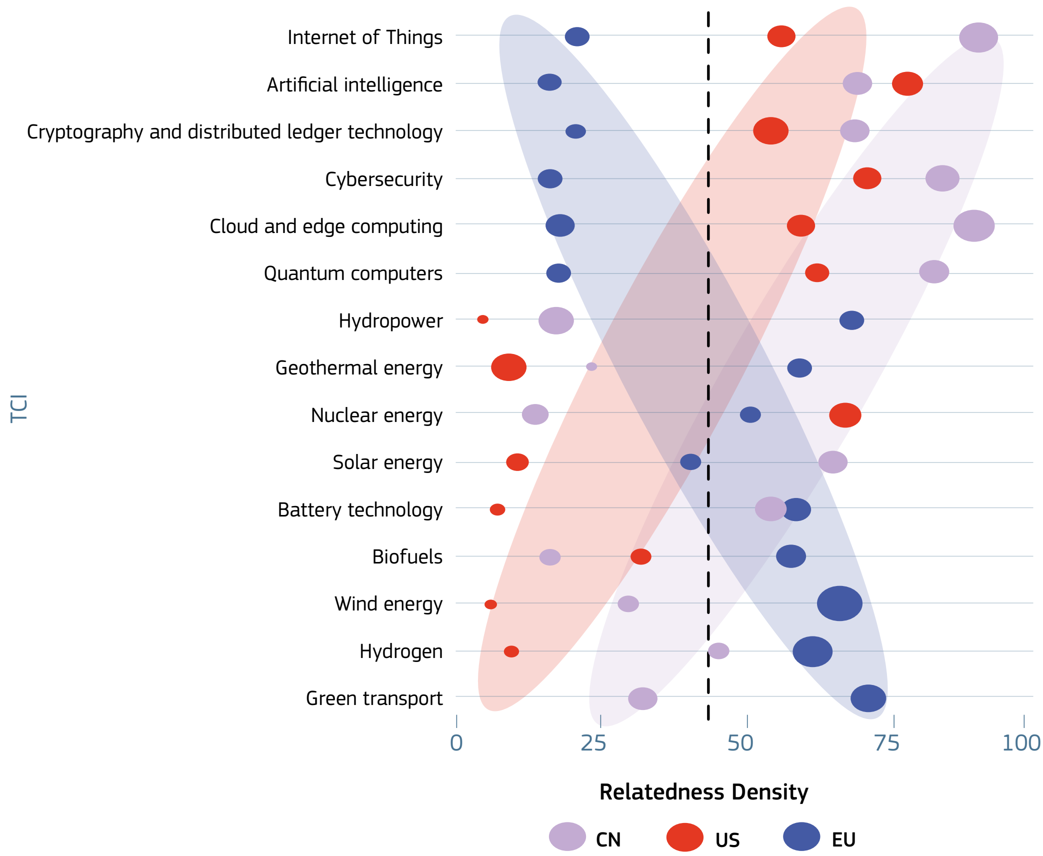
Figure 1-7 Connection maps linking NUTS 2 regions in Europe based on organisations that are involved in collaborations under the EU FP for R&I 2014-2020



Science, research and innovation performance of the EU 2024
Source: Joint Research Centre, Innovation Policies and Economic Impact Unit; and DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on keep.eu and eCorda data.

8. The technological gap between the EU and other key players in strategic productivity-enhancing technologies persists, especially in digital fields such as AI, internet of things, blockchain technologies, quantum computers, etc.

Figure 1-8 **The EU position in complex technologies vs. the US and China, 2019-2022**



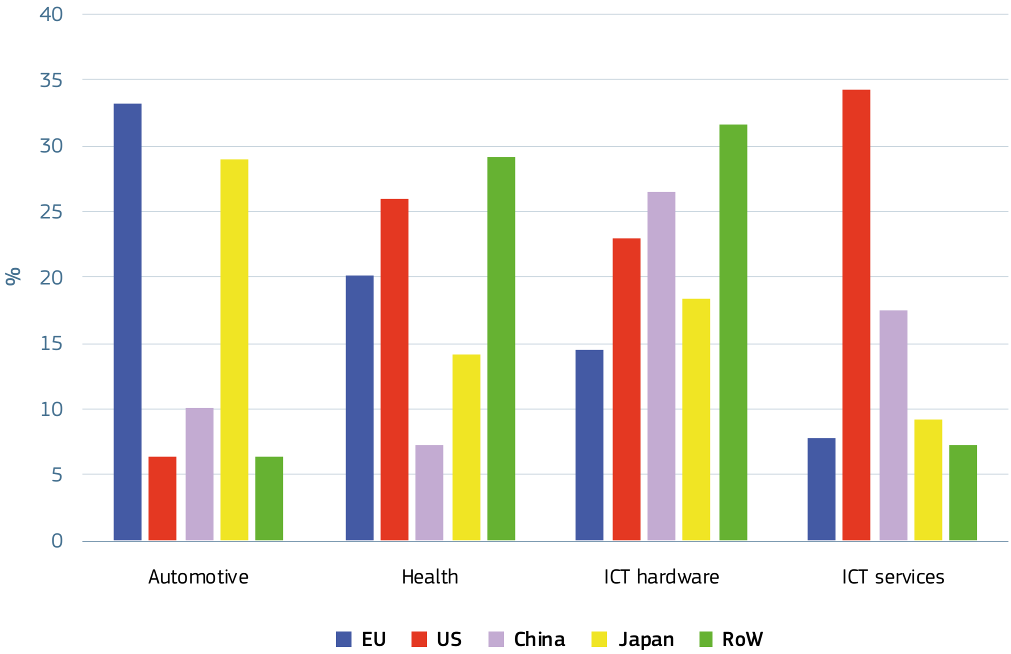
Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on Google Patents data.

Note: The x-axis indicates the relatedness density in each technology field considered. On the y-axis, technologies are ranked by complexity level, normalised between 0 and 100. The size of the bubble captures the degree of specialisation that each country reports in a given technology field, measured by revealed comparative advantage (RCA).

9. Mid-tech industries, particularly the automotive sector, account for a significant proportion of EU business R&D.

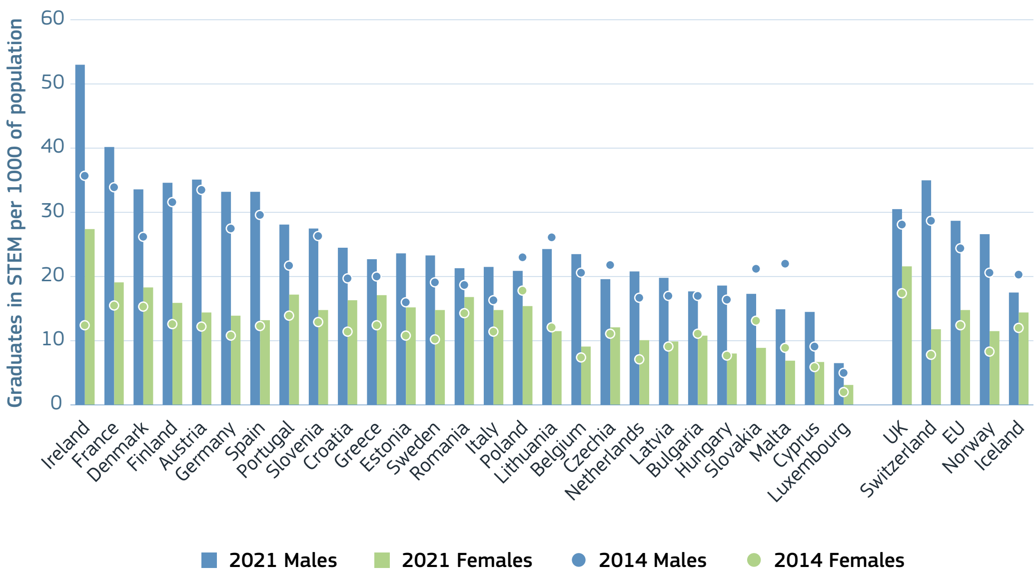
Figure 1-9 Share of private R&D investment by sector and region (% of Total Business R&D), 2022



Science, research and innovation performance of the EU 2024
Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on data from the 2023 EU Industrial R&D Investment Scoreboard.
Note: Due to the scope of the scoreboard, the 'EU' data represents 17 Member States.

10. Across Europe, the number of tertiary graduates in science, mathematics, computing, engineering, manufacturing and construction is increasing for both males and females. Yet the gender gap is still substantial and, in many countries, even widening.

Figure 1-10 **Graduates in science, mathematics, computing, engineering, manufacturing and construction, by sex**

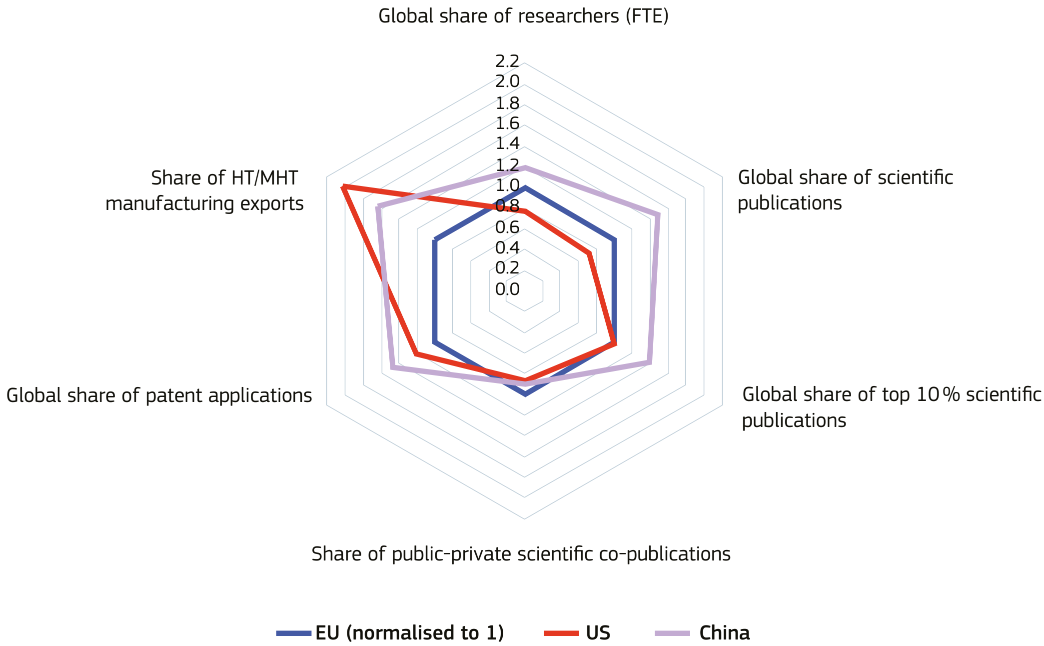


Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on Eurostat (Online data code: educ_uoe_grad04).

11. Although it has a strong research workforce and close ties between academia and business, the EU continues to lag behind the US and China in several areas.

Figure 1-11 Knowledge valorisation approach, latest available year



Science, research and innovation performance of the EU 2024
Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on Science-Metrix, Eurostat, JRC (INNOVA VI), OECD and UNESCO data.
Note: HT/MHT refers to high-tech and medium-high-tech.

CHAPTER 2

R&I, TRANSITION AND GEOECONOMICS

CHAPTER 2.1

R&D INVESTMENTS AND POLICY APPROACHES

Key questions

- What are the latest developments in research and development (R&D) investments (public and private)?
- What policy instruments can be used to support R&I?
- How have R&I policies evolved to become more transformative?

Highlights

- China has overpassed the EU for the first time in 2020 in terms of R&D intensity, and the EU R&D intensity (2.2 %) remains below that of the US (3.5 %), Japan (3.3 %) and South Korea (4.9 %).
- The R&D intensity gap between the EU and its main competitors is mostly due to a gap in private R&D investments.
- Within the EU, private R&D investment is dispersed across high-tech and mid-tech sectors.
- R&D activity in the EU is concentrated within a limited number of countries, although concentration has slightly decreased over the last decade.
- The world's top companies in terms of R&D spending tend to invest much more in R&D than governments (in terms of R&D intensity).
- Global spending on clean energy have increased between 2015 and 2022, and the EU invested more than the US but less than China in 2022.
- The total amount of government support to private R&D in the EU has decreased in 2020 by 3.4 %, due to the decrease in tax support.

Policy insights

- In recent decades, EU governments have increasingly shown a preference for tax incentives over direct subsidies to encourage private investments. This trend, however, saw a slight decrease after the COVID-19 crisis.
- The existence of a positive structural effect between the EU and US may indicate the need to promote the role of the EU in critical high-tech sectors.
- Despite lagging behind the US in total public and private Venture Capital (VC) funding, the EU surpasses Japan and Korea. The EU has the highest relative share of Government Venture Capital compared to total VC.
- Tax support, chosen for its lower administrative burden, poses challenges in monitoring and directing funds, particularly toward societal challenges. There is also a risk associated with tax competition.
- Access to financial and human capital through Government Venture Capital (GVC) has a substantial and lasting impact, but it carries a higher risk of crowding out private investments.
- EU governments increasingly use policy approaches and instruments to support R&D in line with a new frame for R&I policies: the Transformative Research and Innovation Policy (TRIP), which supports transformative change of our economies.
- Evaluating TRIP effectively demands a comprehensive approach involving systems thinking, experimentation, stakeholder involvement, and continuous monitoring. Currently, this evaluation process is still in its early stages.

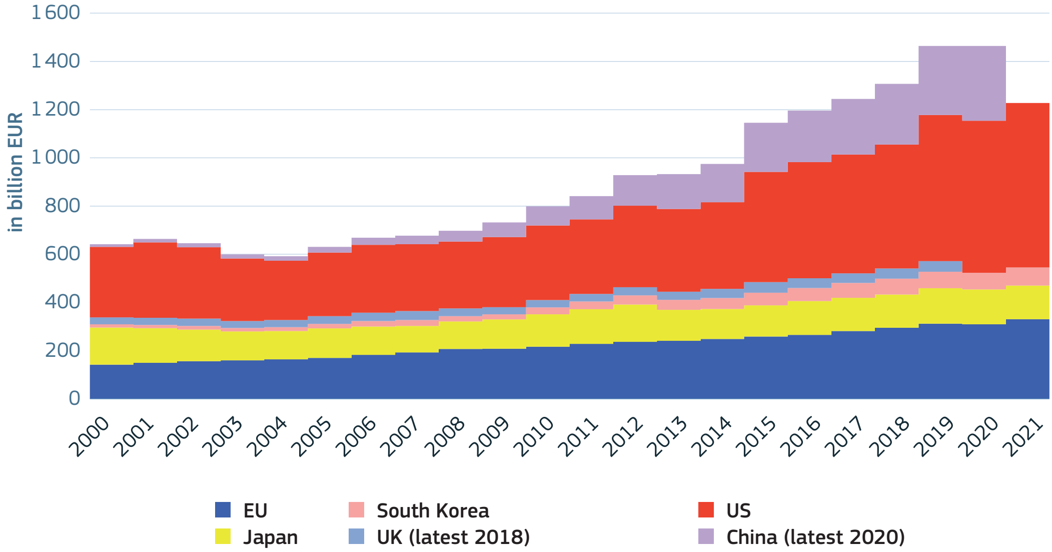
R&D investments drive economic growth by fostering innovation and the development of new technologies, products, and services. Through R&D, new industries can emerge, existing industries can be transformed, productivity can be improved and companies can stay competitive in the global marketplace, spurring job creation. R&D investments have positive spillover effects on the economy; R&D can diffuse across industries and sectors, benefiting other organizations and driving innovation in a broader sense. The first part of this chapter offers an overview of the latest trends in R&D investments in the EU, comparing them with those of its international competitors. It also disentangles these investments, analyzing their distribution across public and private sectors, various industries, and different countries.

By investing in R&D, breakthroughs can be made in areas such as healthcare, energy, environment, transportation, and communication, leading to transformative changes and societal benefits. Overall, it can help address societal challenges. Worldwide and in the EU, governments have implemented various approaches and instruments to support R&D investments and guide private R&D towards societal challenges. This includes R&D tax incentives, subsidies, innovation public procurement, or government venture capital. The second part of this chapter focuses on the evolving approach to Research and Innovation (R&I) policies, highlighting the latest trends and rationale behind the use of different R&I policy instruments in the EU and beyond.

1. Investments in R&D

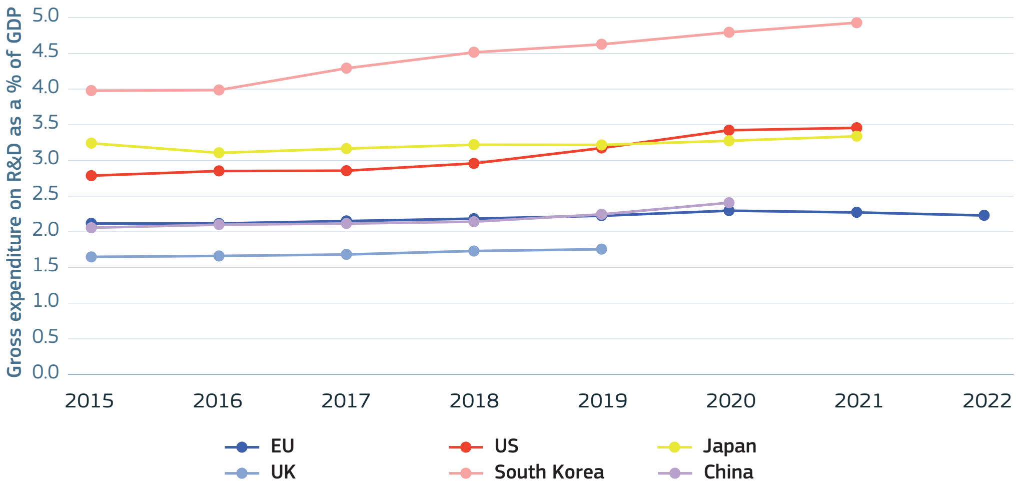
The EU has increased its R&D investments over the past two decades, yet a gap remains compared to some of its main competitors. The EU's relative weight in this global R&D landscape is decreasing (Figure 2.1-1). In 2021, EU R&D intensity (2.3 %, and 2.2 % in 2022) was below that of the US (3.5 %), Japan (3.3 %) and South Korea (4.9 %) (Figure 2.1-2). China experienced steady growth, surpassing the EU level in 2020 for the first time (2.4 %).

Figure 2.1-1 **R&D expenditure in billion EUR, 2000-2021**



Science, research and innovation performance of the EU 2024
Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on Eurostat (online data code: rd_e_gerdtot).
Note: The UK value of 2020 is a prediction based on the annual compound growth rate from 2014-2019.

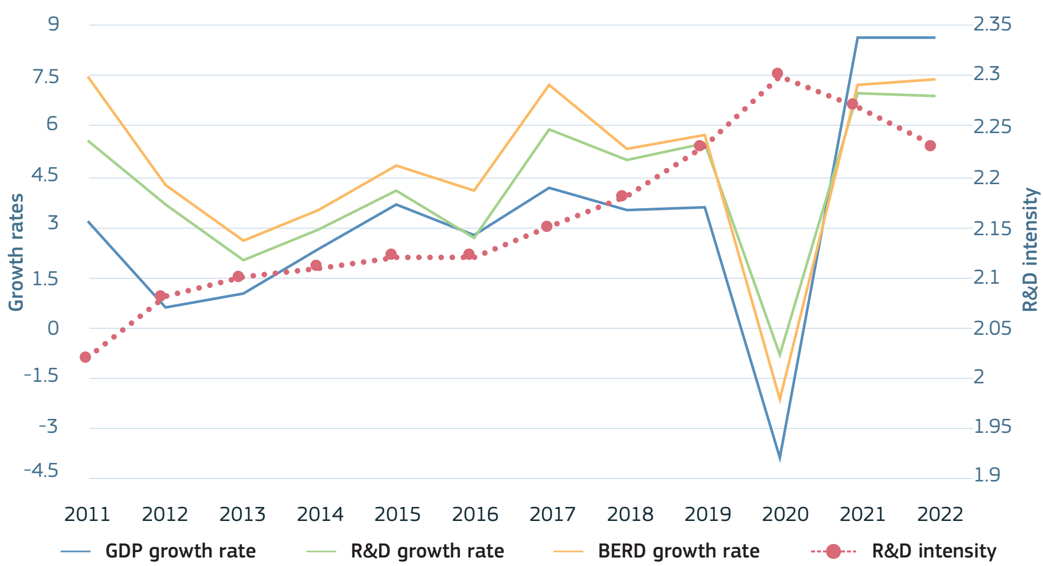
Figure 2.1-2 Gross expenditure on R&D as a percentage of GDP (R&D intensity), 2015-2022



Science, research and innovation performance of the EU 2024
Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on Eurostat (online data code: rd_e_gerdtot).

In 2020, the EU's R&D expenditure decreased less than GDP but still declined, driven by the private sector, while, in 2021, R&D intensity decreased with R&D investments increasing less than GDP (Figure 2.1-3). R&D activities tend to be pro-cyclical (Barlevy, 2007; Fatas, 2000; Rafferty, 2003; Comin & Gertler, 2006), moving in tandem with economic growth: R&D declines during recessions and increases during economic booms (Fabrizio and Tsolmon, 2014; Barlevy, 2007; Sedgley et al., 2019; Aghion et al., 2012).

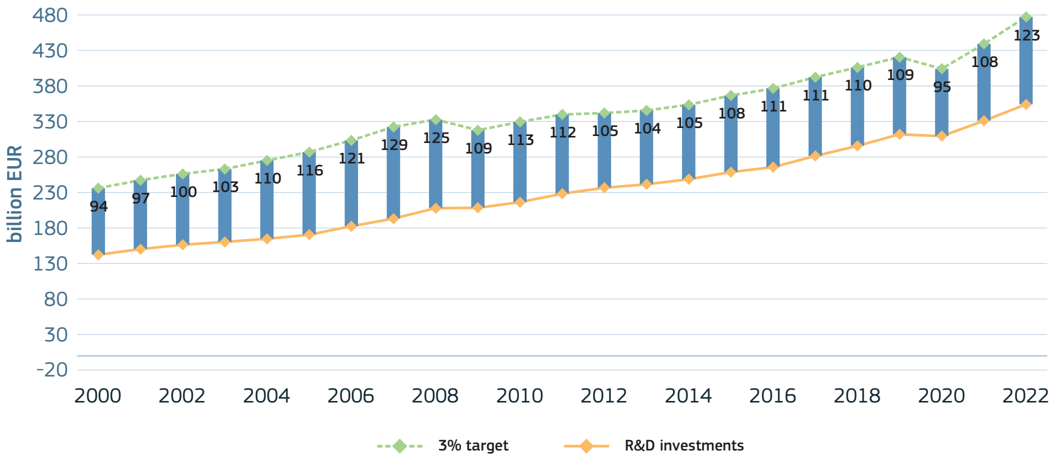
Figure 2.1-3 Annual growth rates and R&D intensity in the EU, 2011-2022



Science, research and innovation performance of the EU 2024
Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on Eurostat (online data code: rd_e_gerdtot).
Note: BERD stands for business enterprise R&D expenditure.

In 2022, the EU would have needed to invest an additional EUR 123 billion to reach the 3% target, more than the budget of an entire 7-year European Commission framework programme for R&I (Figure 2.1-4). It is also worth noting that the decline of the gap from 2019 to 2020 is not due to an increase in R&D investments but to the decrease in GDP that followed the COVID-19 pandemic.

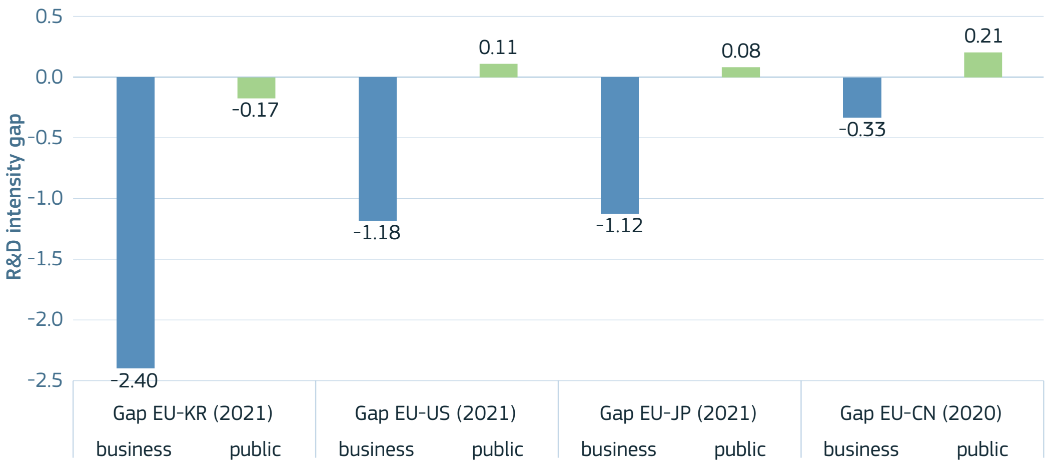
Figure 2.1-4 R&D investment gap in the EU in billion EUR, 2000-2022



Science, research and innovation performance of the EU 2024
Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on Eurostat (online data code: rd_e_gerdfund).

The R&D intensity gap between the EU and its main competitors is due to a gap in private R&D investments. In 2021, the R&D intensity of the EU in the public sector, gathering government and higher education, was higher than that of Japan, the US and China (2020), whereas it was lower in the private sector (Figure 2.1-5). Only South Korea had a higher public R&D intensity than the EU.

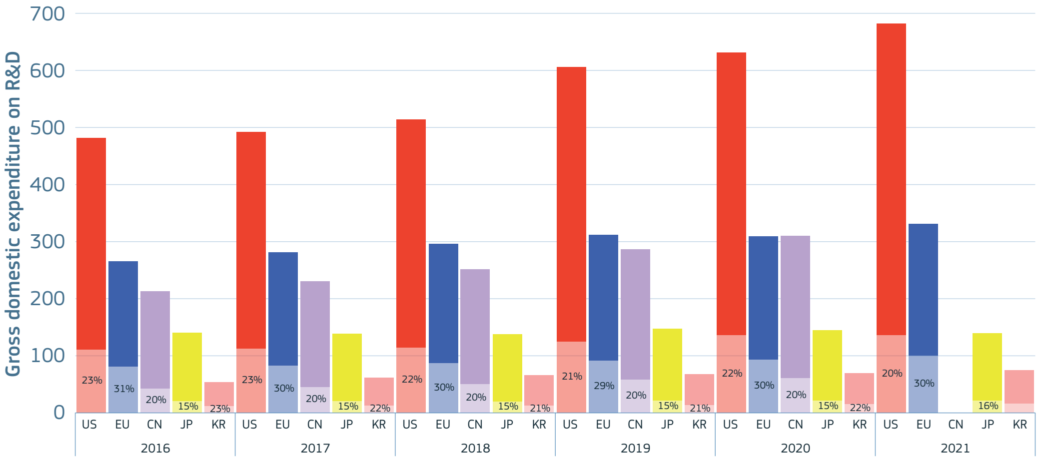
Figure 2.1-5 Public and private R&D intensity gaps between the US, Japan, China, South Korea and the EU, 2021 or latest year available



Science, research and innovation performance of the EU 2024
Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit's own elaboration based on Eurostat dataset.
Note: Public R&D intensity is defined using R&D investments funded by national government and higher education sectors and does not include funding from other public sources, such as the European Commission and international organisations.

Despite not having the highest public spending among all major economies in absolute terms, with the US leading, it is important to note that R&I funding by the public sector is relatively higher in the EU compared to other countries (Figure 2.1-6). Within the EU, the percentage of government-funded R&I is around 30% of the total R&I funding. In contrast, other countries have lower percentages of government-funded R&I, such as China and the US, both at 20%, and Japan even lower at 16% of total R&I funding. These figures are also reflected in the percentages funded by the private sector, with China, Japan and South Korea ranging between 75% and 80%, while the EU is below 60%.

Figure 2.1-6 Gross domestic expenditure on R&D (GERD) – government (light colour) and non-government (other, dark colour) funds, in billion EUR, 2016-2021

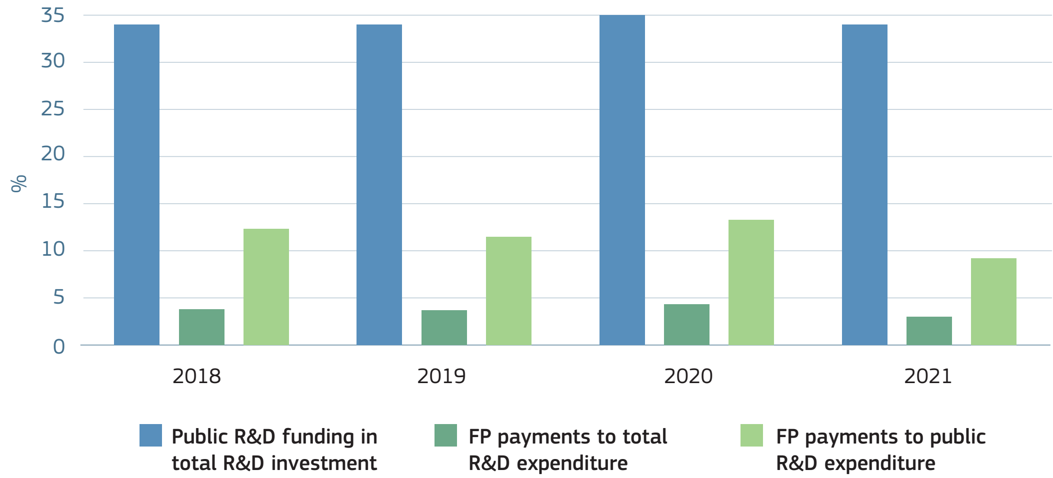


Science, research and innovation performance of the EU 2024
Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on Eurostat (online data code: rd_e_gerdtot).
Note: The labels are the shares of gross expenditure on R&D funded by the national government.

For the EU as a whole, the majority of R&I investments are financed by the Member States themselves. Member States adopt their individual approaches to funding R&I activities, primarily through annual budget allocations to national agencies or dedicated R&I programmes and funds.

Overall, the European FP for R&I funding constituted 9.2 % of public R&I funding and 3.0% of the total R&I funding in Europe in 2021 (Figure 2.1-7). The share of FP payments in the European public and total R&I funding was slightly higher in previous years, representing between 11.5% - 13.3% in the European public R&I funding and around 3.7% - 4.3% in the European total R&I funding. The significance of public R&D funding in the total R&D investment remained more or less stable around an average of 33.5% between 2018 and 2021.

Figure 2.1-7 **The contribution of the Framework Programme for R&I as a percentage of total and public R&D expenditure, 2018-2021**



Science, research and innovation performance of the EU 2024

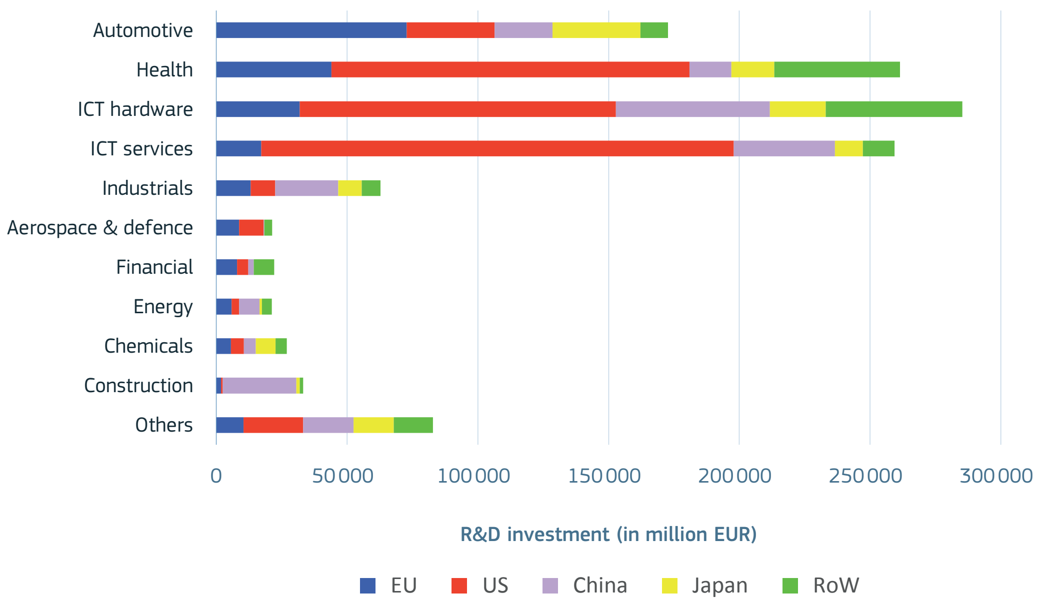
Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit's own elaboration based on Eurostat.

Notes: The contribution of FP is defined as the payments made under Horizon 2020 and Horizon Europe as reported in the consolidated annual accounts of the EU. As the UK is considered as a Member State for all pre-2021 programmes, payments may also comprise payments to the UK. The R&D expenditures of the public sector are defined as the sum of GERD with national governments, the European Commission and international organisations as source of funds.

Comparing the EU R&D to the US, Japan and China, dissimilarities in the sectoral composition of the regions' economy can often explain differences in private R&D investment (Figure 2.1-8). Following a similar approach to Moncada-Paternò-Castello et al. (2016), private R&D investment (BERD) can be decomposed across industrial sectors. Comparing the EU R&D to the US, Japan and China, differences in private R&D investment can be explained by dissimilarities in the sectoral composition of the regions' economy (Figure 2.1-8). Within the US, investment in R&D is largely driven by R&D in high-tech sectors such as health, ICT hardware and ICT services, which account for approximately 85 % of all US private R&D investment (Figure 2.1-9).

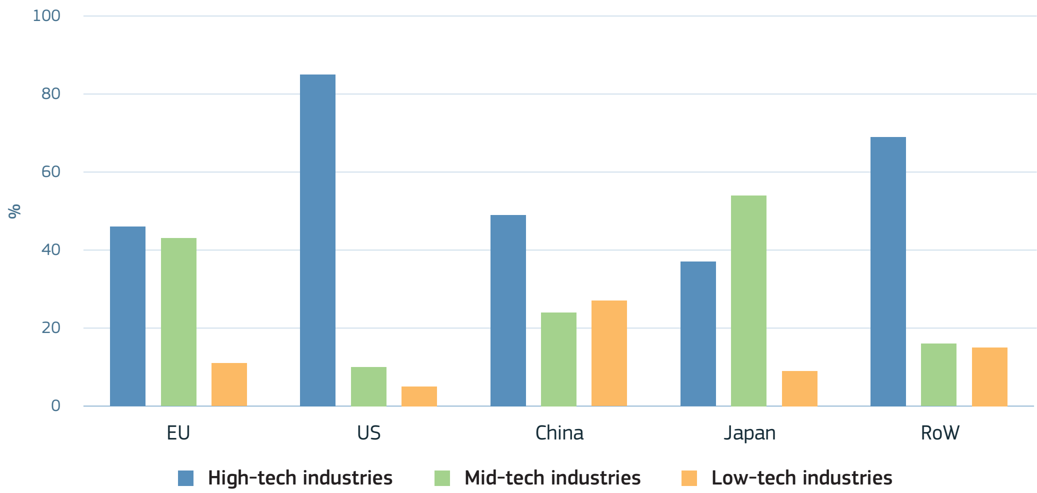
Within the EU, China and Japan, private R&D investment is less concentrated in high-tech sectors, but is more dispersed in comparison to the US. EU private R&D investment seems to be largely driven by R&D in the mid-tech automotive sector, yet substantial investments are also made in the high-tech health and ICT hardware sector. Overall, R&D investment in mid-tech sectors accounts for approximately 43 % of EU private R&D investment, while high-tech sectors account for around 46 %. Japan follows a very similar trend, with mid-tech sectors accounting for approximately 37 % and high-tech sectors for 54 % of total private R&D. Private R&D investment in China is even more dispersed across high-tech, mid-tech and low-tech sectors. While a substantial amount of Chinese private R&D investment is taking place in the high-tech ICT services and hardware sector, substantial investments are also made in the mid-tech industrials sector and the low-tech construction sector. As a result, high-tech sectors make up approximately 49 % of total private R&D investment, in comparison to 24 % and 27 % for mid-tech and low-tech, respectively.

Figure 2.1-8 Sectoral composition of private R&D investment in million EUR, 2022



Science, research and innovation performance of the EU 2024
Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on data from the 2023 EU Industrial R&D Investment Scoreboard.
Note: Due to the scope of the scoreboard, the 'EU' data represents 17 Member States.

Figure 2.1-9 **Private R&D investment by region and sector type (high-tech, mid-tech, low-tech), 2022**



Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on data from the 2023 EU Industrial R&D Investment Scoreboard.

Note: Due to the scope of the scoreboard, the 'EU' data represents 17 Member States.

Sectoral differences in R&D spending can be explained via both 'structural' effects (i.e., related to the size of the sector in relation to other sectors within the economy (Figure 2.1-10)) and 'intrinsic' effects (i.e., effects related to the R&D investment of firms within a particular sector (Figure 2.1-11)). In 2022, the private R&D intensity gap between the EU and the US was positive overall, implying that, within the majority of sectors, the US demonstrated a higher R&D intensity compared to the EU. The opposite situation can be observed for the private R&D intensity gap between the EU and China or Japan. A more in-depth analysis into the different sectors reveals that, in comparison to the US, the EU demonstrates a higher R&D intensity for the mid-tech automotive sector and a lower R&D intensity for the high-tech health, ICT services and ICT hardware sectors. Following this observation, it is possible to conclude that high-tech sectors in the US invest more in R&D, not only due to their extensive size, but also due to higher R&D intensity. This implies the existence of a positive structural effect between the EU and US: sectors that are considered to be more substantial in the EU/US economy than in the US/EU economy, are also considerably more R&D-intensive. This finding is in line with that of Moncada-Paternò-Castello et al. (2016), who identify a positive and more pronounced structural effect between the US and the EU. It is also in line with recent estimations made within Fuest et al., (2024) which concluded that structural factors account for about 60% of the difference, while intrinsic factors account for the remaining 40%.

Japan and China are mainly characterized by positive structural effects with the EU, with the exception of ICT hardware. While R&D investments in this sector are of larger importance to the overall Chinese and Japanese economy, R&D intensity in this sector is higher in the EU. A similar observation can be made for the EU health sector, i.e., despite its overall higher importance to the EU economy, Japan is characterized by higher levels of R&D intensity in the health sector.

Figure 2.1-10 Share of private R&D investment by sector and region, 2022

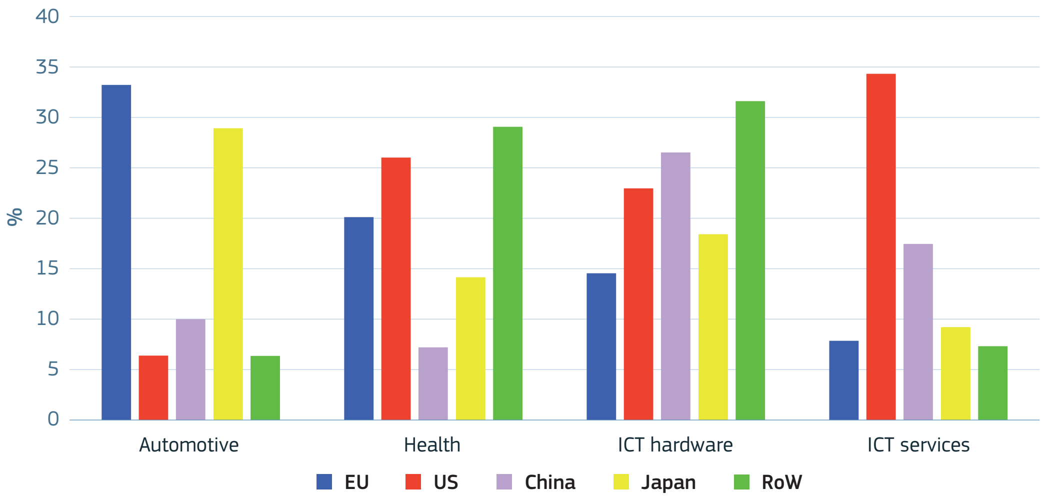
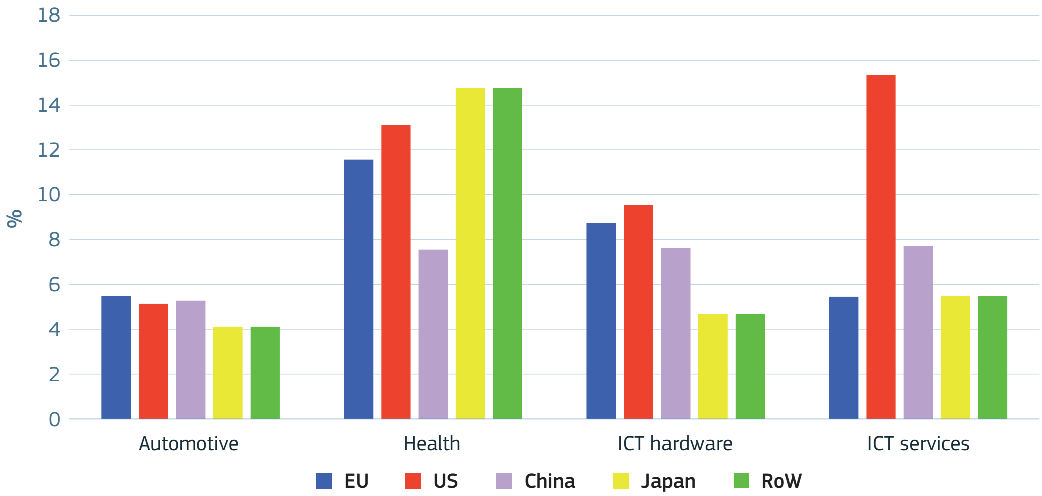


Figure 2.1-11 R&D intensity by sector and region, 2022



Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on data from the 2023 EU Industrial R&D Investment Scoreboard.

Note: Due to the scope of the scoreboard, the 'EU' data represents 17 Member States.

The existence of a mainly positive structural effect between the EU and other regions could indicate the need for policies that promote the role of the EU in critical high-tech sectors. To this extent, policy could focus on improving the innovation ecosystem (e.g., access to finance and improvement of business conditions) as well as providing more directionality in R&D (e.g., via mission-oriented policies). Nevertheless, further in-depth analysis would be required to fully understand all the underlying factors that may drive these relationships.

Box 2.1-1 The development of R&D intensity in the Industrial R&D Investment Scoreboard: the role of reallocation between firms and the importance of the ICT services sector

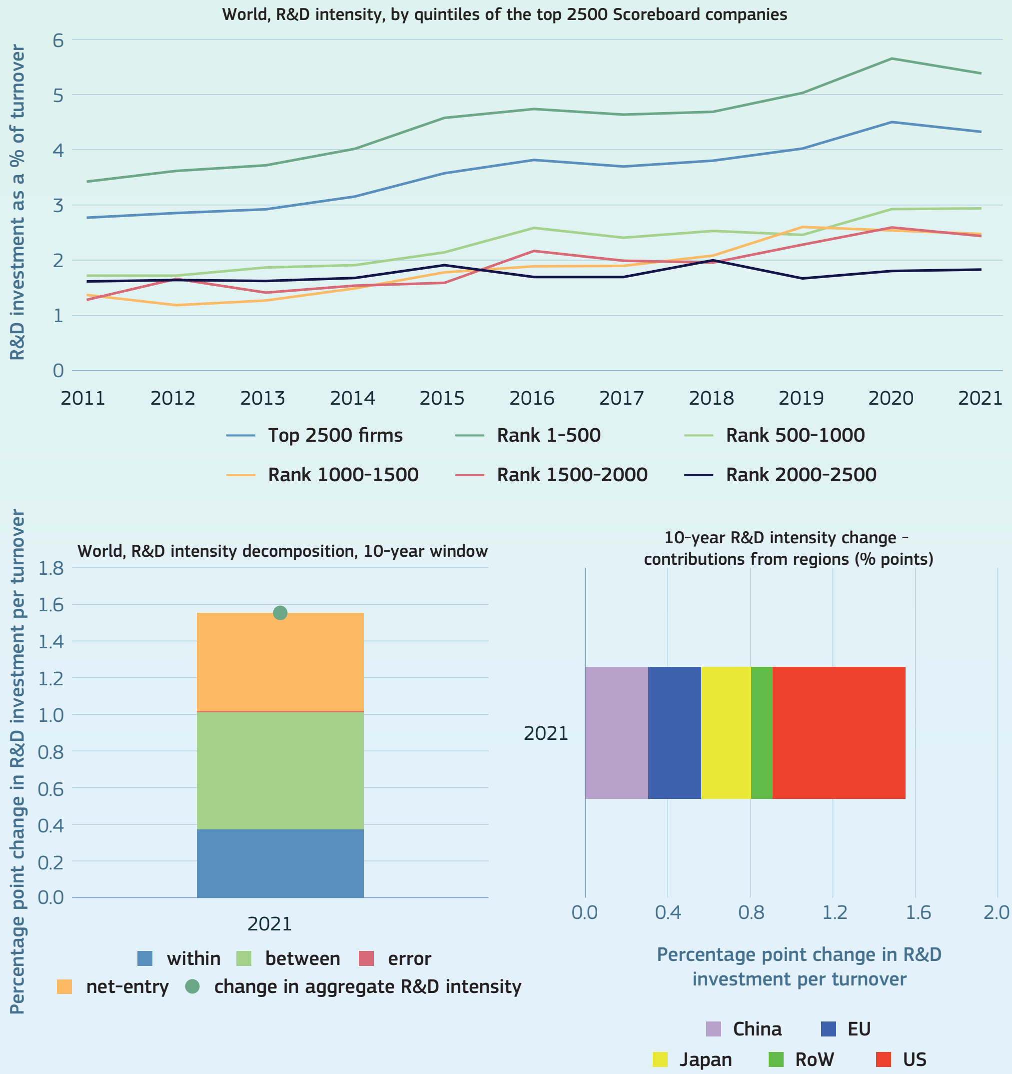
Peter Bauer and Francesco Rentocchini, Joint Research Centre, Industrial Strategy, Skills and Technology Transfer Unit.

R&D intensity is a widely used indicator of R&D efforts. We define R&D intensity as R&D expenditure over turnover of the top 2 500 R&D investors of the world from the Industrial R&D Investment Scoreboard. R&D expenditure and turnover are adjusted by purchasing power parity to take into account the different price levels of different countries.

We analyse the development of R&D intensity over time and the differences of its growth across countries (regions) and sectors. We focus on changes over a 10-year window, from 2011 until 2021. Changes in aggregate R&D intensity are decomposed to within-firm term, between-firm term, entry term and exit term. The within-firm term expresses the change of aggregate intensity coming from the change at firm-level intensities. The between-firm term is the changes to the shares of firms in aggregate turnover, indexed by the deviation of average firm-level intensity from the aggregate average intensity. Thus, this term is larger if more R&D-intensive firms tend to grow, and smaller if more R&D-intensive firms tend to shrink. The entry and exit terms express the effect of entering and exiting firms on aggregate intensity. An entering firm contributes positively (negatively) if its intensity is higher (lower) than the average aggregate intensity, and an exiting firm contributes positively (negatively) if its intensity is lower (higher) than the average aggregate intensity. The sum of the entry and exit term is called the net-entry term. The between-firm term and the net-entry term together comprise the reallocation effect on the change of aggregate R&D intensity.

First, we notice that R&D intensity tends to be greater for higher ranked companies, and there is an increasing gap during the period 2011-2021 between the leading and following firms in terms of R&D intensity. Then, analysis of world-level changes of R&D intensity reveals that the increase during the last 10 years comes mainly from reallocation between firms, especially the gaining of shares in the turnover of high R&D-intensive firms. This is a sign of allocative efficiency, as it shows that firms with high R&D intensity tend to grow faster. Contributions from different regions to world-level intensity show that 40% of the increase was driven by the US, while China, the EU and Japan contributed similarly.

Figure 2.1-12 R&D intensities and its decomposition per within-firm term, between-firm term, entry term and exit term in 2021, and the 10-year intensity change, Scoreboard companies, 2011-2021



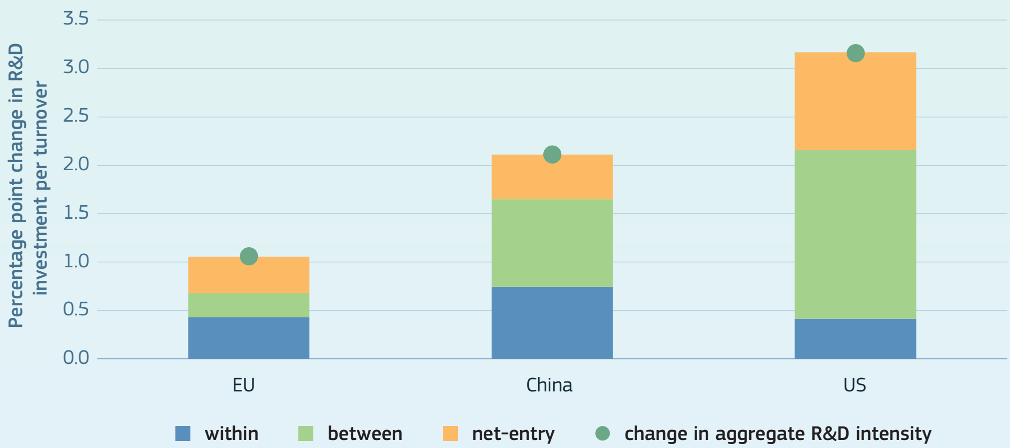
Science, research and innovation performance of the EU 2024

Source: Joint Research Centre, Industrial Strategy, Skills and Technology Transfer Unit, calculations based on the Industrial R&D Investment Scoreboard data.

Note: RoW stands for Rest of the world

Analysing regions separately, we find that R&D intensity (in terms of percentage points) increased the most in the US, followed by China and then the EU in third place. The main difference between the regions stems from the between effects, i.e. the different change in market share of high versus low R&D intensity firms in the different regions. We can assess the role of different sectors within regions. The leading position of the US in terms of R&D intensity growth in the past 10 years has been driven mainly by firms in the health and ICT service sectors that either entered into the market, or gained share at the expense of firms losing market share in less R&D-intensive sectors.

Figure 2.1-13 R&D intensity decomposition, Scoreboard companies, 2011-2021

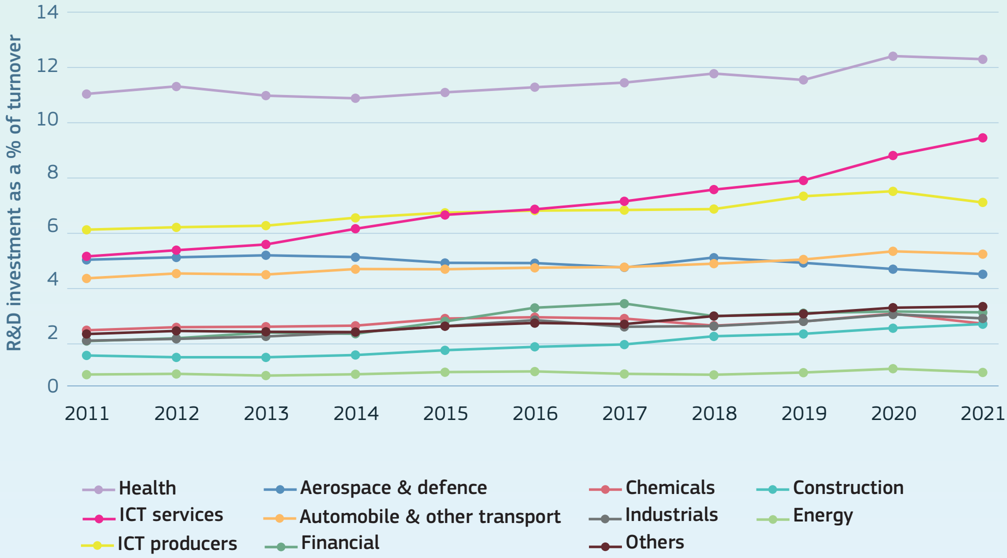


Science, research and innovation performance of the EU 2024

Source: Joint Research Centre, Industrial Strategy, Skills and Technology Transfer Unit, calculations based on the Industrial R&D Investment Scoreboard data.

We can also analyse sectors at the world level – motivated by the global nature of many of the scoreboard companies. First, we can state that health has the highest R&D intensity historically, and it could still grow a bit in the coming 10 years. ICT producers and ICT services also have a high R&D intensity relative to the other sectors; ICT services increased its R&D intensity substantially in the past 10 years, and this increase was by far the highest among the sectors. The energy sector has a permanently low R&D intensity compared to other sectors.

Figure 2.1-14 R&D intensity per sector at world level, Scoreboard companies, 2011-2021

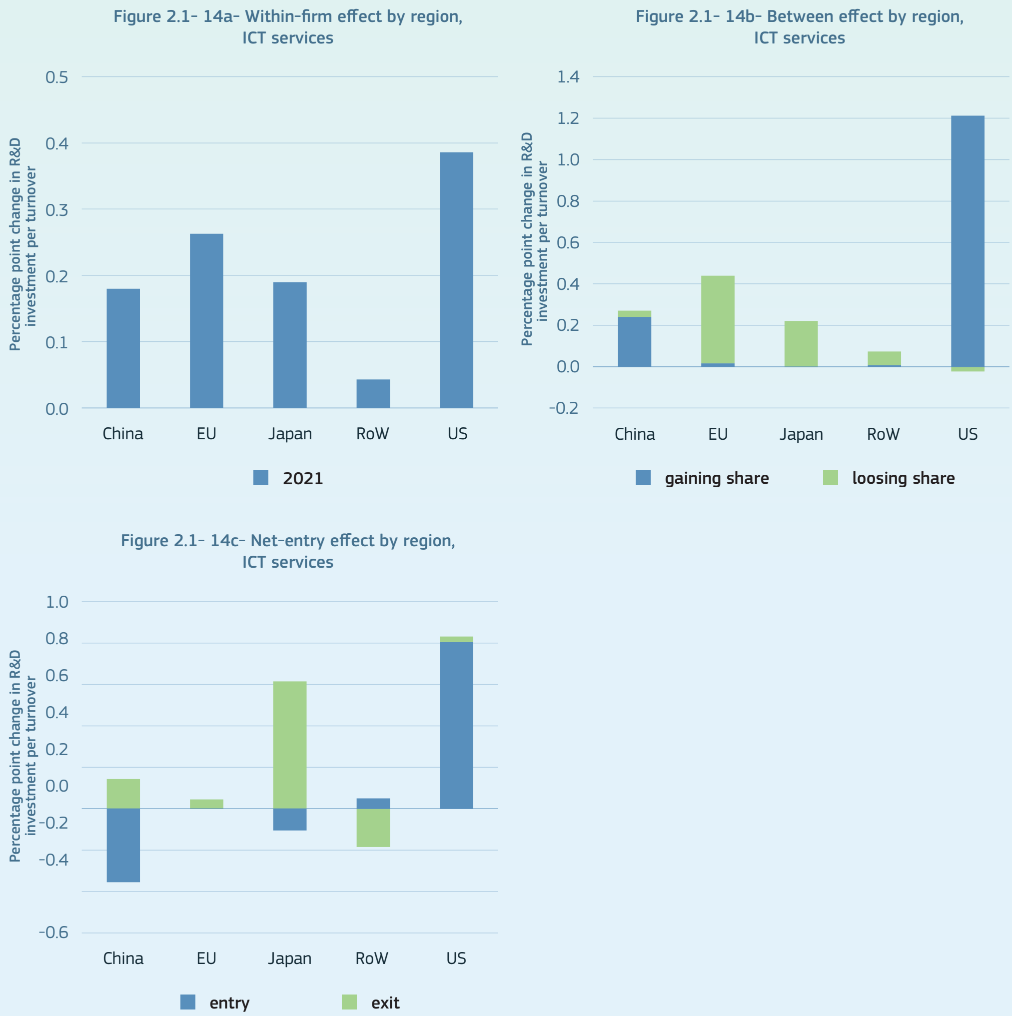


Science, research and innovation performance of the EU 2024

Source: Joint Research Centre, Industrial Strategy, Skills and Technology Transfer Unit, calculations based on the Industrial R&D Investment Scoreboard data.

As the ICT service sector showed the highest growth in terms of R&D intensity, it is warranted to analyse the drivers of this increase in detail. The biggest within-firm effect in ICT services comes from the US, followed by the EU and Japan. In the between effect, the large positive contribution is mainly from US firms, which are highly R&D intensive and gained market share in the world. The net-entry effect also shows the advantage of US firms, as the positive contribution comes from US firms entering the market. All these effects show the US dominance in ICT services.

Figure 2.1-15 Within-firm, between and net-entry effects by region in ICT services, Scoreboard companies, 2011-2021



Science, research and innovation performance of the EU 2024

Source: Joint Research Centre, Industrial Strategy, Skills and Technology Transfer Unit, calculations based on the Industrial R&D Investment Scoreboard data.

R&D activity in the EU is concentrated within a limited number of countries, though concentration has slightly decreased compared to the situation in 2010. In 2021, most R&D was performed in Germany (34%), France (16%) and Italy (7%) (Table 2.1-1). These three countries are responsible for close to 60% of R&D expenditure in the EU in 2022. While several Member States have increased their share in EU-wide R&D spending during the period 2011-2022 (Table 2.1-1), a clear divide persists between these leading countries and the rest of the EU. Total R&D intensity increased between 2011 and 2022 in 20 Member States, but significant heterogeneity remains across European countries.

Table 2.1-1 R&D investment trends across EU Member States, 2011-2022

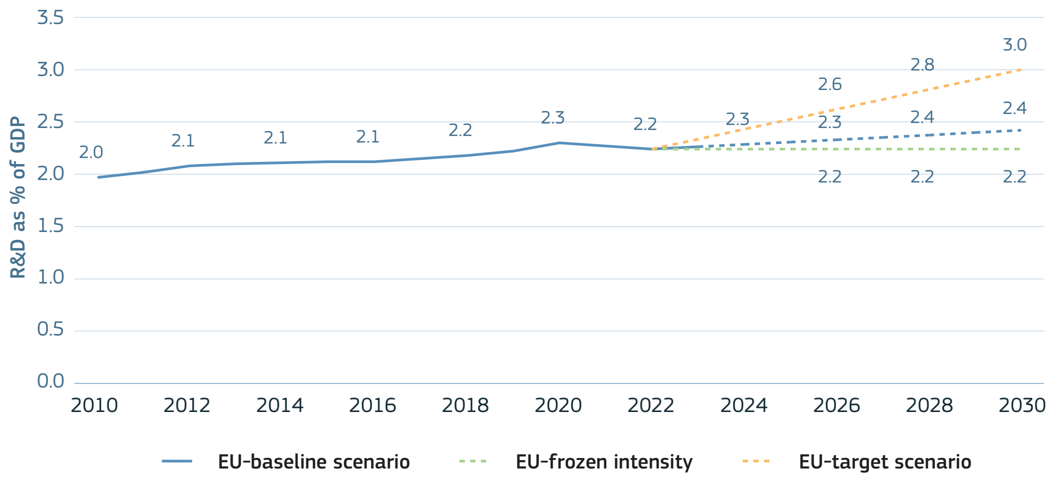
Country	Share of EU R&D investments, 2021	Total R&D intensity, 2021	Trend GERD (2011-2021)	Business sector R&D intensity, 2021	Trend BERD (2011-2021)	Public sector R&D intensity, 2021	Trend public (2011-2021)
BE	5.23%	3.43	↑↑	2.53	↑↑	0.90	↑↑
BG	0.18%	0.77	↑↑	0.52	↑↑	0.24	↑
CZ	1.53%	1.96	↑↑	1.26	↑↑	0.69	↑
DK	3.10%	2.89	→	1.78	↓	1.11	↑
DE	34.24%	3.13	↑	2.11	↑	0.95	→
EE	0.18%	1.78	↓	1.00	↓	0.77	→
IR	1.37%	0.96	↓↓	0.77	↓↓	0.20	↓↓
EL	0.87%	1.48	↑↑	0.73	↑↑	0.75	↑↑
ES	5.45%	1.44	↑	0.81	↑	0.62	→
FR	16.19%	2.18	→	1.43	→	0.70	↓
HR	0.27%	1.43	↑↑	0.78	↑↑	0.65	↑↑
IT	7.31%	1.33	↑	0.78	↑	0.53	↑
CY	0.06%	0.77	↑↑	0.31	↗↗	0.36	↑
LV	0.08%	0.75	↑	0.27	↑↑	0.48	→
LT	0.19%	1.02	↑	0.50	↑↑	0.52	↓
LU	0.21%	0.98	↓↓	0.50	↓↓	0.48	→
HU	0.66%	1.39	↑	1.00	↑↑	0.38	↓
MT	0.03%	0.69	↑	0.46	↑	0.23	↑
NL	6.21%	2.30	↑	1.56	↑↑	0.74	↓
AT	4.04%	3.20	↑	2.20	↑	0.98	↑
PL	2.69%	1.46	↑↑	0.96	↑↑	0.50	↑
PT	1.16%	1.70	↑	1.06	↑↑	0.60	→
RO	0.37%	0.46	→	0.28	↑↑	0.17	↓↓
SI	0.34%	2.11	↓	1.48	↓	0.60	→
SK	0.30%	0.98	↑↑	0.56	↑↑	0.42	↑↑
FI	2.24%	2.95	↓	2.01	↓↓	0.93	↓
SE	5.40%	3.40	↑	2.51	↑	0.89	↓

→	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 2024
Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on Eurostat (online data code: rd_e_gerdtot).
Note: Public sector is defined as government and higher education sectors.

If EU R&D intensity continues the trend observed in the past decade (1.1 % annual growth rate during the period 2011-2022), it will reach 2.4 % by 2030 (Figure 2.1-16). In order to attain the 3 % target by 2030, the average annual growth of the intensity must be 3.8 %, which is approximately 3 times higher than the average rate observed during the period 2010-2021.

Figure 2.1-16 Scenarios of EU R&D intensity until 2030



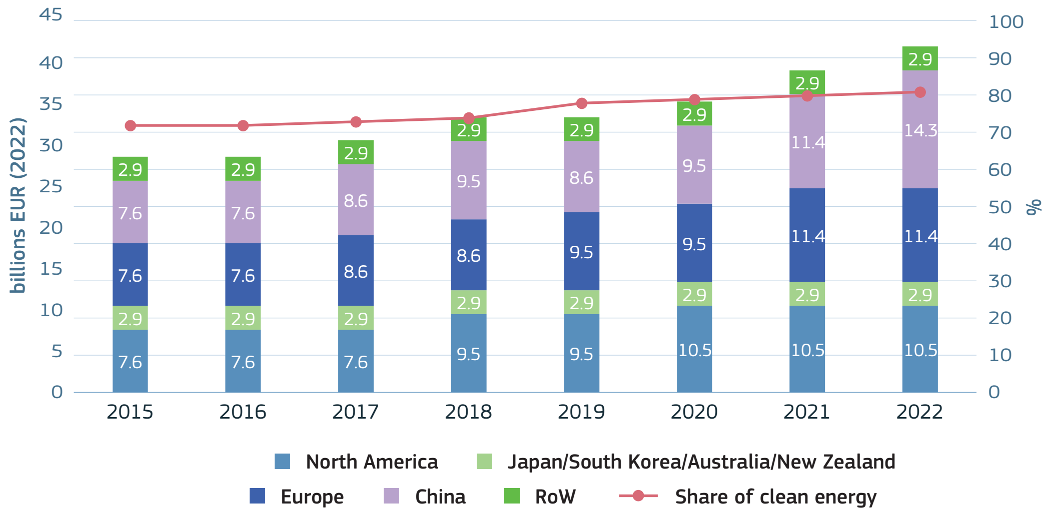
Science, research and innovation performance of the EU 2024

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

R&D investments and the twin transitions

Global R&D spending on clean energy increased between 2015 and 2022, with Europe investing more than the US but less than China in 2022 (Figure 2.1-17) (IEA, 2023; European Commission, 2023a). However, to achieve the European Green Deal's objectives and the Fit for 55 package's targets, it is crucial to keep accelerating the transfer of EU clean energy innovations into the market. According to the European Commission (2023a), in 2020, the private sector in the EU continued to invest comparable amounts – in absolute terms – with the US and Japan, accounting for around 80% of all R&I funding. In terms of private R&I investment per GDP, this still positions the EU ahead of the US but behind the major Asian economies.

Figure 2.1-17 Spending on energy R&D by governments, 2015-2022



Science, research and innovation performance of the EU 2024

Source: International Energy Agency, Spending on energy R&D by governments, 2015-2022, IEA, Paris.

Note: R&D is defined as spending reported by governments and state-owned enterprise spending. Estimations for 2022 are preliminary based on data available by mid-May 2023. US data is estimated from public sources. 'Rest of world' comprises Brazil, Chile, India, Indonesia, Russia, Saudi Arabia and South Africa.

Governments R&D intensities worldwide are much smaller than those of several top R&D spending companies. In the top R&D spending countries, government budgets for R&D (performed either by public or private sector) worldwide ranged from 0.48 % of GDP (China) to 1.07 % (South Korea) in 2020, while in the private sector, top spenders dedicated between 6 % and 28 % of their net sales to R&D in 2020. In the ICT sector, the tech giants dedicated budgets that amount to the same as some governments in absolute terms (Table 2.1-2).

Table 2.1-2 R&D investments and intensities for top spending countries and companies, 2020

	Industry sector (for companies)	R&D expenditure by government (in billion EUR)	R&D intensity (R&D investments as % of GDP for countries, % of net sales for companies), 2020
US Government		135.9	0.74
EU Governments		93.4	0.69
Chinese Government		61.3	0.48
Japanese Government		22.0	0.5
South Korean Government		15.5	1.07
Amazon	**Retail**	37.4052	11
Alphabet	**ICT services**	24.1776	15
Huawei	**ICT hardware**	19.272	16
Microsoft	**ICT software and services**	16.9068	13
Apple	**ICT hardware**	16.4688	7
Samsung	**ICT hardware**	16.4688	9
Meta	**ICT software and services**	16.206	21
Volkswagen	**Automotive**	13.86	7.6
Intel	**Semiconductors**	11.9136	5.6
Roche	**Pharmaceuticals, biotechnologies**	11.388	23.8
Johnson & Johnson	**Pharmaceuticals, biotechnologies**	10.6872	28.3

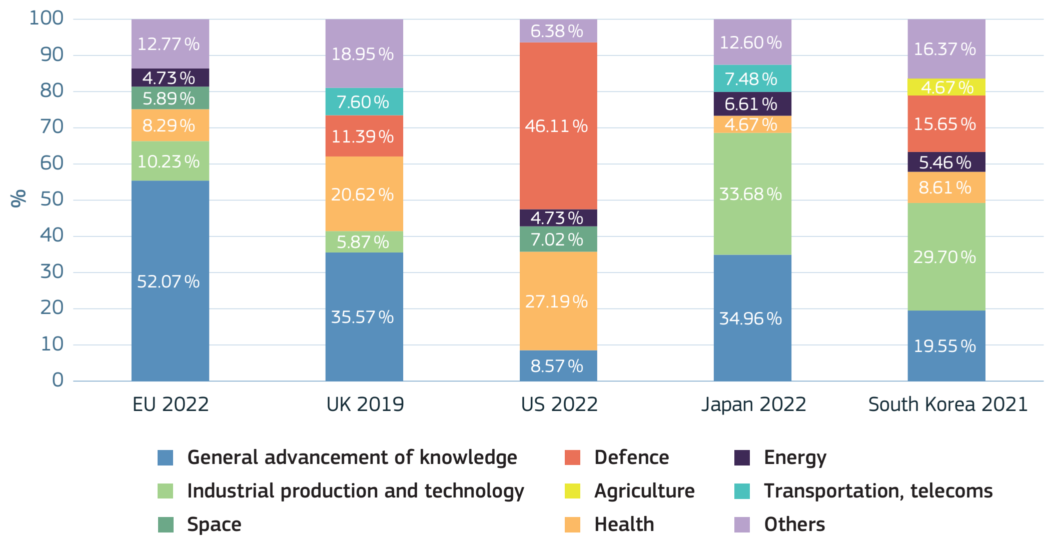
Science, research and innovation performance of the EU 2024

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

Note: R&D expenditures from private companies also include support through government tax incentive schemes.

International competitors of the EU, such as the US, Japan and South Korea have adopted a strategic approach to R&I funding. Government budget allocations for R&D per socioeconomic objectives in these countries are concentrated in a few strategic sectors (Figure 2.1-18). For example, the US Government dedicates 46 % of its R&D allocation to defence, 27 % to health and only 9 % to general advancement of knowledge, whereas the Japanese and South Korean Governments dedicate 34 % and 30 % respectively to industrial production and technology, and 35 % and 20 % to the general advancement of knowledge. No data is available for China at this level, but recent studies tend to demonstrate that the Chinese Government has concentrated resources allocated to R&D in a few strategic sectors. The Made in China (MIC) 2025 strategy has set out 10 priority sectors and its successor, the 14th Five-Year plan, has created national laboratories in key S&T areas. Concerning the EU, data reporting categories are not allowed to have detailed information on the budget allocated to the higher education sector per precise socioeconomic objectives. Therefore, it appears that the EU allocates more than 50 % of its budget to the general advancement of knowledge. Hence, it is difficult to conclude that the EU is less strategic in its approach, but it seems that EU governments give more freedom to higher education institutions to direct R&D funding than their international counterparts. To conduct a meaningful comparative analysis, data collection on the actual public spending per socioeconomic objectives would be needed.

Figure 2.1-18 Government budget allocations for R&D (GBARD) by socioeconomic objective, 2022 or latest year available



Science, research and innovation performance of the EU 2024

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

Note: For each region/country, all sectors with a percentage below 4.5 % have been included in the category 'others'.

As far as the EU is concerned, socioeconomic objectives are not reported by the statistical offices for the budget allocated to the higher education sector.

2. Policies, instruments and approaches to boost and direct private R&I investments

To boost R&I investments towards achieving societal goals, governments worldwide employ different policy approaches. One of them is the mission-oriented policy. It is likely that this approach originates from the US, where the Manhattan project and the Apollo mission were launched in the 1940s. Since then, this approach for R&I policies has attracted attention by policymakers. Recently, the US and China have implemented mission-oriented policies such as the Cancer Moonshot 2.0 (US) and the MIC 2025 strategy and Major projects (China) with targeted objectives that require multi-agency and cross-sector cooperation. Missions are often designed to attract both public and private stakeholders and orient business R&I investments towards the purpose of the missions.

The EU Missions, launched under Horizon Europe (2021-2027), are a new way to focus investments and bring solutions. They address societal and global challenges, which the EU has addressed in past years, investing through various methods of intervention – from the scientific fellowships, general advancement of knowledge and lab research to the innovations of highly technological market potential. Therefore, the Missions naturally benefit from the indirect support of the EU framework programme, as well as other instruments such as LIFE, the instrument for environmental and climate action, the Innovation Fund, and Interreg, for European territorial cooperation, creating synergies across EU sectoral policies.

Over the past decade, around 5 000 R&I projects representing a total funding of EUR 13 billion are relevant to the Missions' objectives (Table 2.1-3). The EU continued its investments in 2023, notably through Mission-targeted investments (Mission work programmes), but also other actions, which to date account for EUR 3.2 billion, including around EUR 1.4 billion in Mission-specific calls[1].

Table 2.1-3 EU Missions in Horizon 2020, Horizon Europe (2014-2022)

	R&I projects (actions x 1 000)	Estimated EU funding (billion EUR)
Climate adaptation	0.5	2.2
Cities	1.2	3.2
Cancer	1.9	3.3
Ocean	0.5	3.4
Soil	0.4	1.3
R&I project values	4.7*	13

Science, research and innovation performance of the EU 2024
Source: European Commission, EU mission portfolio as of November 2022.
Note:*Total figure represents the value of unique investments. EU mission portfolios can consist of overlapping actions, such as, for example, Cities and Climate action.

1 31 mission-specific calls as of October 2023.

Examples of solutions funded under Horizon 2020 and Horizon Europe, contributing to the missions' objectives:

The Climate adaptation mission:

- Vineyards' Integrated Smart Climate Application (VISCA);
- Supporting viticulturists in climate change adaptation with VISCA DSS;

Mission ocean:

- Cleaning litter by developing and applying innovative methods in European seas (CLAIM);
- Floating rooms – marine litter collection and recovery system (Clean trash).

For more examples on Mission ocean, please see the *Ocean mission dashboard*, which presents the results of the analysis of a portfolio of 841 EU projects relevant to the Mission's objectives. These projects have been funded by 16 EU programmes over a period of 9 years between January 2014 and December 2022. It offers a structured overview of the projects' results and contribution to the objectives of the Mission, the Green Deal targets and geographical areas.

Mission soil:

- Cost-effective robots for smart precision spraying (SCORPION);
- Exploiting the multifunctional potential of belowground biodiversity in horticultural farming (EXCALIBUR)

Mission cities:

- Building green and climate-neutral city hubs (CLIMABOROUGH);
- Smart public transport initiatives for climate neutral cities in Europe (SPINE);

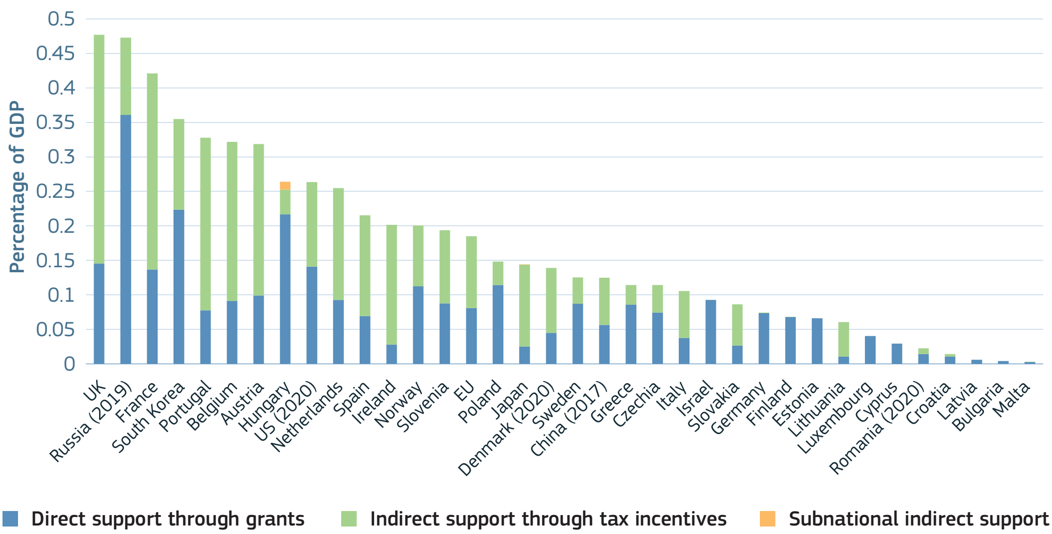
Mission cancer:

- Streamlined identification of tumour neoantigens for personalised anti-cancer immunotherapy (PeptiCHIP);
- PeptiCHIP platform for fast and accurate neoantigen identification.

Globally, public-private partnerships (PPPs), launched notably through innovative public procurement, represent one of the main instruments for national programmes and strategies to support R&I, partly since public finances are scarcer and programmes to support R&I activities are designed to leverage private investment.[2] The US has one of the longest and best track records of using public-private partnerships (PPPs) for R&I purposes (since the 1940s) with a wide diversity in the types of PPPs. China started later but has put increasing efforts into PPPs. As for the EU, some Member States launched their first initiatives into PPPs for R&I in the 1960s. The European Union introduced them in 2007 and has since increased their dedicated budgets incrementally (European Commission, 2023b).

Over the past decades, EU governments have increasingly favoured tax incentives to support private R&D investments over direct funding, even if this preference decreased slightly after the COVID-19 crisis (Figure 2.1-19). To support private R&D investments, governments worldwide also use different funding instruments, including direct support tools, such as R&D grants or government procurement of R&D services, and indirect support through R&D tax incentives, i.e., a preferential tax treatment of business R&D expenditures in the form of a tax credit, enhanced tax deduction or exemption. In 2020, R&D tax incentives accounted for close to 55 % of total support for business R&D in the EU compared to 58 % in 2019, while direct support to business R&D accounted for 45 % compared to 42 % in 2019. Besides, in a context of economic contraction due to the COVID-19 crisis, the total amount of government support to private R&D in the EU decreased in 2020 by 3.4 %, due to the decrease in tax support. While direct funding of business R&D increased in 2020, this increase was, in absolute terms, not large enough to offset the decline in R&D tax support (OECD, 2023a).

Figure 2.1-19 Direct government funding and tax support for business R&D, 2021 or latest year available

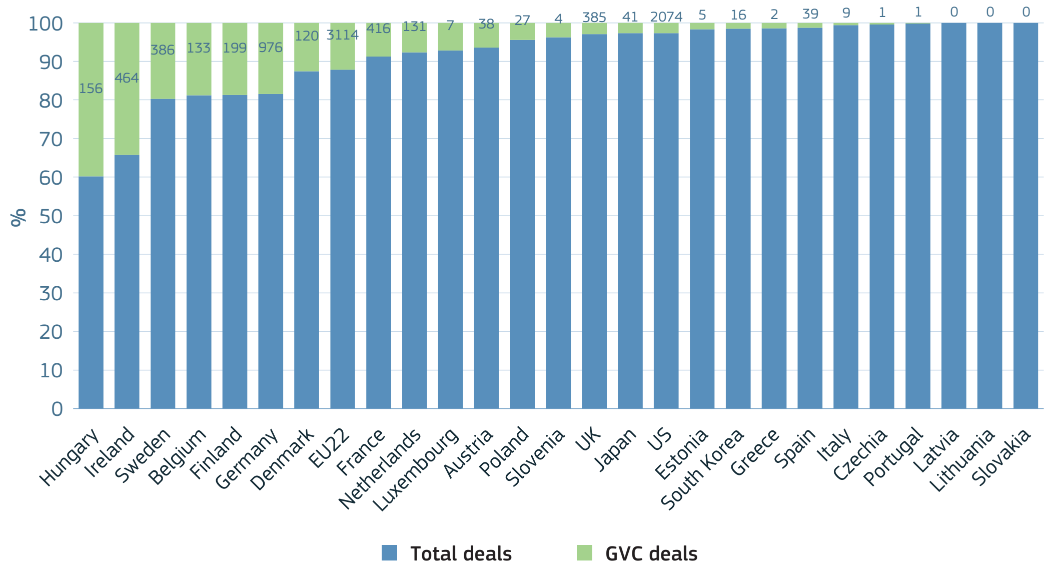


Science, research and innovation performance of the EU 2024
Source: OECD R&D tax incentives database (https://oe.cd/rdtax), April 2024.
Note: Data on subnational tax support for business R&D are only available for a group of countries. For additional information on the availability, design and implementation of R&D tax incentives in the EU region and OECD area, see OECD INNOTAX Portal, https://stip-oecd.org/innotax/

2 As argued by OECD (2005), public/private partnerships (P/PPs) offer a framework for the public and the private sectors to join forces in areas in which they have complementary interests but cannot act as efficiently alone.

Governments around the world have also taken a strong interest in government venture capital (GVC). This interest stems in part from the fact that some of the world's most influential enterprises, such as Google, Intel and Apple, were financed by venture capitalists (Brander et al., 2015). The creation of GVC funds is primarily meant to correct supply-side failures in domestic venture capital (VC) markets (Colombo et al., 2016) and to promote innovation. The EU[3], while being far behind the US in terms of total public and private VC funding, but well ahead of Japan and South Korea, is the region with the highest relative share of GVC in total VC funding (Figure 2.1-20).[4] GVC investments are observed in around 8 % of all VC investments, a number similar to the one found by Alperovych et al. (2015). In the US, GVC represents between 2 % and 3 % of investments, whereas in other regions it is about 1 % of investments. However, despite the high number of GVC funds in Europe (e.g. Biotech Fonds Vlaanderen in Belgium, SITRA in Finland, Caisse des Dépôts et des Consignations Innovation in France, the Technologie-Beteiligungs-gesellschaft in Germany, Piemontech in Italy, Axis Participaciones Empresariales in Spain), the existing literature and evidence on the impact of GVC on portfolio companies' performance in Europe is rather limited (Ariffin et al., 2023).

Figure 2.1-20 Number of total and government venture capital deals per country, 2000-2019



Science, research and innovation performance of the EU 2024

Source: OECD calculations according to Dechezleprêtre & Fadic (2020). Can Government Venture Capital help bring research to the market? OECD publishing office.

Note: The sample used in the analysis only includes firms that have investor information.

3 Only 22 EU Member States could be included in the analysis due to lack of data.

4 Related evidence from a pilot mapping exercise of business innovation support (OECD, 2023b) in five volunteer countries (Australia, Canada, France, Netherlands, Norway) highlights the important role of equity investments within the national business innovation policy mix. Equity investments, which inter alia include GVC, feature as the third most used instrument on average among the five countries considered.

Tax incentives and direct funding demonstrate a similar degree of effectiveness with a gross incrementality ratio (IR) of around 1.4 for both policy instruments, i.e., one extra unit of R&D tax or direct support translates into 1.4 extra units of R&D (OECD, 2023c). However, while R&D tax incentives can be easier to implement than direct subsidies, they can complicate the tax code and increase compliance costs on a recurrent basis (Table 2.1-4). This can also increase the burden for taxpayers and tax authorities. In addition, they are also harder to monitor and to direct, including towards societal challenges. Several studies also point to potential risks of tax competition (Alstadsæter et al., 2018; OECD, 2016; OECD, 2020). As for GVC, administrative costs are high, but budget control is stringent. Nevertheless, while access to financial and human capital through GVC tends to have bigger and longer effects on access to finance than subsidy (Söderblom et al., 2015), it seems to be associated with a higher risk of crowding out private investments, including R&D investments (Cumming et al., 2017; Kirihata, 2017).

Table 2.1-4 **Main use, characteristics and impacts of R&I policy instruments used worldwide**

	Direct funding of business R&D (R&D grants)	R&D tax incentives	Government venture capital funds
Definition and use	Main instrument to support public R&I performed by public institutions and basic research in all sectors, according to direction set by governments.	Firms in the information & communication and computer & electronics industries often account for a large share of R&D tax benefits.	GVC is an entity established, owned, funded and operated by the government to provide venture financing.
Main characteristics	▸ High budget control; ▸ Higher administrative burden and compliance costs; ▸ Risk of government failure in 'picking losers' (Dechezleprêtre et al., 2023); ▸ Often directional as governments select R&D projects with the highest social returns; ▸ Best suited to encourage high-risk projects and to meet policy goals; ▸ Adequate to target R&D activities with the highest discrepancy between social and private returns; ▸ Encourage cooperation and technology transfer.	▸ More limited ability to forecast and manage impact on public finances; ▸ Comparatively lower administration and compliance costs, but can complicate the tax code and increase compliance costs on a recurrent basis; ▸ Non-discretionary nature (ex-ante non-directional in terms of allocation of support to specific R&D projects, e.g. fields of research, technology or industrial sectors), and thus more easily compliant with competition and international trade rules (OECD, 2014); ▸ Greater risk of dead weight loss (subsidising R&D investments which would have been undertaken in the absence of support); ▸ Risk of entities relabelling other activities as R&D; ▸ Risk of tax competition and relocation of R&D activities (Alstadsæter et al., 2018; OECD, 2016; OECD, 2020).	▸ High budget control; ▸ Best suited to encourage high-risk projects and to meet policy goals, even if they are not immediately profitable; ▸ High administrative burden; ▸ Bureaucratic red tape and delays, making it more difficult for start-ups to access funding quickly; ▸ Less efficient allocation of resources and potentially 'picking winners' based on political considerations; ▸ Risk of crowding out private capital; ▸ Risk of not exiting investments in a timely and profitable manner in order to prioritise social or political goals over financial returns.
Impacts	OECD (2023) analysis shows a similar degree of input additionality for direct funding as a gross IR of around 1.4 for both instruments (one extra unit of R&D support translates into 1.4 extra units of R&D). It hints at the complementarity of direct and indirect support measures. It should be noted that most countries prevent directly funded R&D amounts to be claimed for tax purposes.		When GVC co-invests with international VC, it yields a positive effect on sales growth (Islam et al., 2018). Access to financial and human capital tends to have effects that are substantially bigger and longer than subsidy (Söderblom et al., 2015).

Science, research and innovation performance of the EU 2024
Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on multiple sources (see references section).

Innovation procurement or innovative public procurement is also an important tool to stimulate innovation, as it enables the public sector to steer the development of new solutions by private actors directly towards its needs. As defined by the European 2021 guidance[5], innovation procurement refers to any procurement that has one or both of the following aspects: buying the process of innovation – research and development services – with (partial) outcomes and/or buying the outcomes of innovation. The public buyer first describes its need, prompting businesses and researchers to develop innovative products, services or processes, which do not yet exist on the market, to meet the need. Aiming at triggering the demand to develop and/or purchase innovative solutions, the EU supports innovation procurement mainly through two different procurement approaches and funding schemes, notably pre-commercial procurement (PCP) and public procurement of innovative solutions (PPI).

In the EU, over the past two decades, policy approaches and instruments to support R&D have been designed increasingly in line with a new framework for R&I policies: the transformative innovation policy (TIP), or, extending to R&I, the transformative research and innovation policy (TRIP), which supports the transformative change of our economies (Steward, 2012; Schot and Steinmueller, 2018; Diercks et al., 2019; Haddad et al., 2022; European Commission, 2023b). Transformative change is focused on using science and technology to address grand societal challenges such as climate change, inequality and poverty. It is based on the idea that innovation can be used to create a more sustainable and equitable society (Schot and Steinmueller, 2018). TRIP differs from more traditional approaches to R&I policies on several aspects, including the policy rationale and the monitoring of these policies (Table 2.1-5). TRIP is still a relatively new concept, and there is no one-size-fits-all approach to implementing it. However, there are a number of principles that can be followed (Haddad et al., 2022; Schot and Steinmueller, 2018), such as:

- directionality and sustainability, which focuses on long-term, systemic impacts;
- involving a wide range of stakeholders;
- policy coordination, which involves using a mix of policy instruments and coordinating across levels of government;
- learning and experimentation, which includes evaluating the impact of policies over time.

5 DocsRoom – European Commission (europa.eu).

Table 2.1-5 Key differences between traditional R&I policy and TRIP

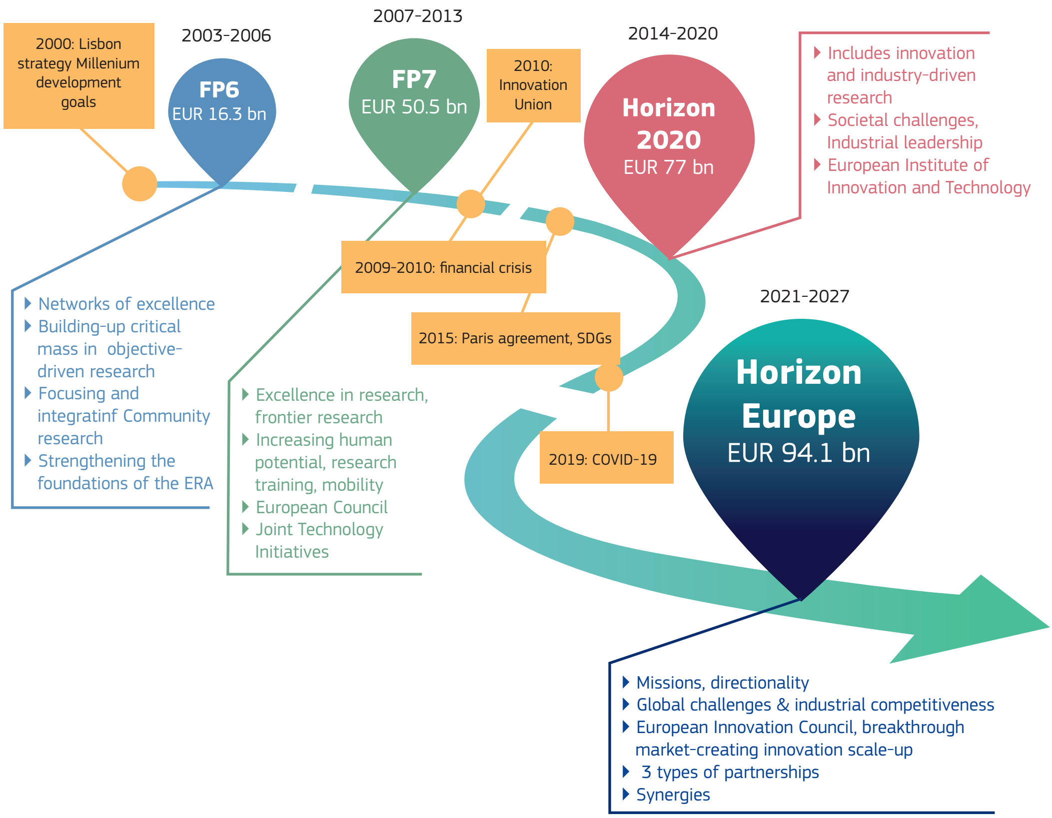
Characteristic	Traditional R&I policy	Transformative innovation policy
Focus	▸ Addressing market failures to boost economic growth and competitiveness.	▸ Achieving long-term, systemic impacts.
Policy rationale	▸ Stimulate and support innovation by directly funding R&D activities, providing incentives for firms to engage in R&D, and facilitating the transfer and diffusion of knowledge; ▸ The 'more the better' approach (Anderson et al., 2014), i.e. belief that increasing funding for R&D will inevitably lead to more and better innovations.	▸ Provide a direction of change, focusing on specific societal challenges and desired outcomes. Achieve systemic change through innovation.
Approach to innovation	▸ Linear innovation model, which assumes a sequential progression from basic research to applied research, development and ultimately commercialisation, and which can be stimulated by investing more money.	▸ System-level and mission-oriented approach that emphasises co-creation, experimentation and learning.
Instruments	▸ State financing of R&D; subsidies or tax incentives for business R&D, regulatory changes to improve access to finance and framework conditions for R&I.	▸ Policy mixes involving multiple sectors and stakeholders, such as regulatory change, market incentives, public-private partnerships through subsidies, tax incentives and innovation public procurement.
Evaluation	▸ Experts' ex-post assessment based on economic, research and innovation input and output indicators.	▸ More participatory/deliberative methods to agree on targets and indicators, long-term evaluation and monitoring, and formative and developmental analysis, as well as reflexivity; ▸ Identify strengths and weaknesses, in moving away from output indicators to focus more on impacts and the implementation process.

Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on multiple sources, including European Commission (2023); Santos and Coad (2023); European Commission (2023a).

Over the past 20 years, the European framework programme for R&I (EU FP for R&I) has not only grown in terms of budget but also in its scope, objectives, programme parts, pillars, instruments, and planning processes (European Commission, 2021; Figure 2.1-21). As part of its evolution, an increasing emphasis has been placed on activities to generate innovations with the potential to address societal challenges. While 'excellence' remains a key driving principle of FPs, new instruments based on 'directionality' of funding, i.e., defining the specific objectives which the supported R&I activities should achieve or targeting specific areas of R&I, have gradually been introduced. Moreover, the policy approach under the framework programme has taken on an increasingly more systemic approach and benefited from more inclusive and participatory design (European Commission, 2023a). This evolution throughout the years has therefore resulted in the FP embedding key elements of transformative research and innovation policies.

Figure 2.1-21 Evolution of the European framework programme for R&I in terms of budget, scope and objectives, 2002-2023



Science, research and innovation performance of the EU 2024
Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit.
Note: Budgets refer to planned budgets as the maximum overall amount included in the EU regulations.

The effectiveness of TRIPs requires using methods and approaches that are different from those of traditional R&I policy (Table 2.1-6). Designing, implementing and evaluating TRIPs effectively requires a comprehensive approach that encompasses systems thinking, experimentation, data collection, stakeholder involvement, continuous monitoring and evaluation (European Commission, 2023a; Santos and Coad, 2023). Evaluating TRIPs effectively requires innovative methods, which should:

- be holistic in scope, capable of addressing a diverse array of contexts without privileging any particular setting (e.g., high- or middle-income countries, 'free market' or more regulated economies);

- be able to address a diversity of options, without unduly favouring particular kinds of intervention (e.g., public or private, supply- or demand-side, or technology- or organisationally based innovations);

- rather than being hardwired to identify a notionally single 'best' prescription, be capable of addressing interactions, complementarities and tensions across portfolios of possible options (i.e., leaving open the possibility for finding mixes, not single interventions);

- engage with conditionalities in respect of particular features of options, contexts or the unfolding of time (e.g. interrogation at the granularity of particular instruments rather than general policies);

- give balanced attention to a plurality of relevant specialist understandings and perspectives (e.g., engaging diverse stakeholder interests);

- be capable of addressing uncertainties ex-ante (e.g., exploring the full range of possibilities for how innovations or their contexts may unfold over time, without artificial probabilistic aggregations) (Coburn et al., 2021).

Table 2.1-6 Key differences in evaluation methods for traditional and transformative R&I policy

Feature	Traditional R&I policy	Transformative innovation policy
Focus	▸ Measure the impact of R&I investments on economic growth and competitiveness; ▸ Focus on analysing the effectiveness and additionality of one single policy instrument, leaving context and conditions aside: what is the best policy option?	▸ Assess the ability of R&I to address societal challenges, sustainable development goals (SDGs) and achieve systemic change; ▸ Focus on a policy mix considering interactions with other policy instruments: which policy instruments are expected to perform more or less favourably, under which conditions and why?
Evaluation time frame	▸ Summative assessment approach: ▸ End-of-term or end-of-project focus: ▸ Summative assessments are usually administered at the conclusion of a programme; ▸ High-stakes nature: ▸ Results of summative assessments often carry significant impacts, such as certifications, or decisions regarding programme effectiveness; ▸ Objective measurement: ▸ Designed to provide quantifiable and objective data on specific outcomes or criteria.	▸ Formative assessment approach: ▸ Continuous programme progress evaluation to enable improvements;. ▸ Sense making process: ▸ Actors involved express expectations and a sense of urgency to take action, understanding the system and using system mapping (a powerful tool to attain the goal); ▸ Change trajectories of the assessment framework: ▸ Learning plans, theories of change for the system; ▸ Focus on the development, validation and rollout of the assessment / user journey, and not on output indicators.
Methods	▸ Quantitative methods, such as cost-benefit analysis and econometric modelling.	▸ Employs a mixed-method approach that combines quantitative and qualitative data to capture the complexity of transformative change, e.g., case studies, bibliometric analysis, simulation, deliberative decision analysis interactive metrics, uncertainty appraisal, multi-criteria mapping (Coburn et al; 2021; Santos and Coad, 2023; Haddad and Bergek, 2023; TIPC, 2019).
Stakeholders involved	▸ Primarily focuses on the perspectives of researchers, policymakers and industry leaders.	▸ Actively engages with a broader range of stakeholders, including civil society organisations, community groups and end users.
Challenges	▸ Attributing impacts to specific R&I investments, accounting for long-term effects, measuring intangible benefits;	▸ Hard to conceptualise systems – all policy cases have a different understanding of the systems; ▸ Hard to integrate different analytical levels, cover long time spans of missions (and impacts), and capture diversity and heterogeneity (Wittmann et al., 2022); ▸ Defining and measuring system-level changes, dealing with uncertainty and complexity, lack of data to measure impacts on societal challenges and SDGs; ▸ Significant time investment from both evaluators and participants.
Examples	▸ Evaluations of R&D tax credits, evaluations of research programmes, evaluations of technology transfer programmes.	▸ Evaluations of mission-oriented R&I programmes, evaluations of sustainability transitions, evaluations of transformative innovation policy.

Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on multiple sources.

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CHAPTER 2.2

TECHNOLOGICAL LEADERSHIP AND GEOECONOMICS

Key questions

- What are the latest trends in the EU technological performance vis-à-vis other major global players?
- What are the EU's main industrial strategic dependencies?
- What can policy do and is it currently doing to strengthen the EU's technological sovereignty and strategic autonomy?

Highlights

- The EU retains its strength in green technologies, but needs to step up within the digital domain.
- Digital technologies are instrumental in enhancing competitiveness and fostering growth. Nevertheless, the EU's position to lead technological change in areas related to strategic productivity-enhancing technologies (e.g. Internet of Things, blockchain, artificial intelligence and cybersecurity technologies) remains weaker than that of the US and China.
- The EU remains vulnerable to supply chain disruptions in several key sectors, including critical raw materials and the manufacturing of green technologies, batteries and semiconductors.

Policy insights

- R&I policy remains key to building the EU's technological sovereignty and guaranteeing its strategic autonomy, calling for increasing efforts for the EU to remain a main actor in the development and governance of strategic technological fields.

- Increasing R&I investments remains key, calling for a structural approach towards strategic funding and technological development, targeted at bridging the specialisation gap between the EU and its main counterparts in those technologies more likely to deliver important productivity gains in the long term.

- At the same time, the EU can continue to leverage its comparative advantage in green technologies, whose demand is expected to increase given the type of industrial policies put forward by the EU's main counterparts.

- Furthermore, the risk for the EU to remain technologically dependent on other global players in strategic fields raises the stakes for science diplomacy and collaborations with international partners, from which the EU can gain in terms of technological complementarities.

- Addressing strategic dependencies along key supply chains also remains important, especially for clean energy technologies, to guarantee the ability of the EU to pursue its energy security and decarbonisation ambitions.

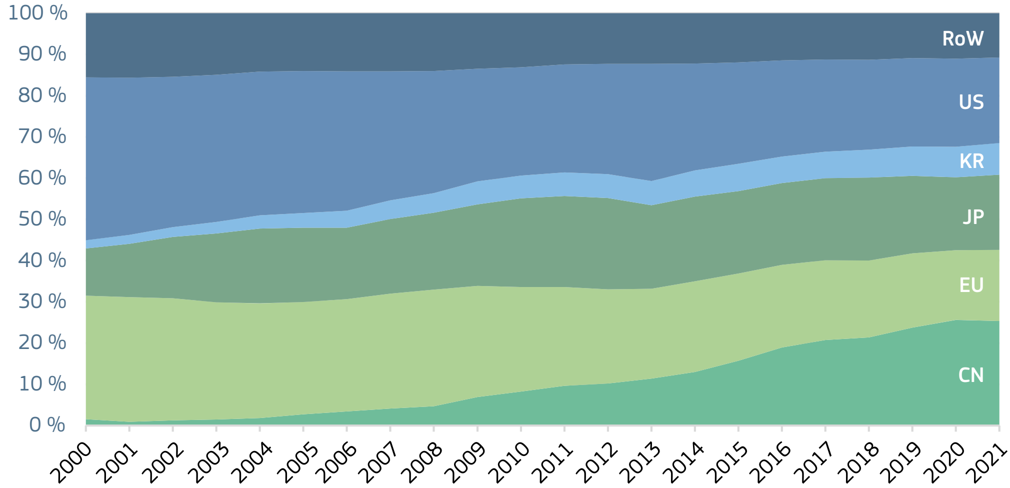
Since 2020, **a series of shocks have put into question the existing globalisation-driven growth model in the EU and worldwide**. The cumulative impacts of the COVID-19 pandemic, the Russian invasion of Ukraine, and the energy crisis have not only intensified geopolitical tensions, but also created a more inflation-prone and competitive global environment, marked by value chain fragmentation. On top of this, the trade war between the US and China, currently revamped by new Chinese export restrictions on important critical raw materials (such as gallium and germanium), threatens to drive up the cost of the clean-energy transition, and to intensify the technology race between global powers. Given current economic and political trends, the globalisation process may undergo significant changes, moving towards a restructuring of production networks in which regional blocks may start emerging more prominently.

From a policy standpoint, these factors have prompted a change in the European policymakers' agenda, now marked by three competing priorities: **achieving strategic autonomy, enhancing economic efficiency and advancing global decarbonisation**, (Aghion et al., 2023). The discussions on how to strike a balance between pursuing economic efficiency and ensuring economic and geopolitical resilience, while maintaining efforts to promote cohesion and social protection, have become central in policy and political debates. These discussions hold significant implications for future economic policies, including those related to research and innovation (R&I) and industrial policy.

1. Strengths and weaknesses of the EU's technological performance

The EU's share in total patent applications has been declining in recent decades. In 2000, the EU accounted for around 30% of the world's patent applications, while its share had declined to 17.3% in 2021 (Figure 2.2-1). On the contrary, China has experienced a significant increase over time, overtaking both Japan and the EU in 2017. In 2019, China was able to also outperform the US, with 23.8% of total patent applications against 21.5%, respectively. Since then, the position of the US has kept weakening, while Chinese performance has continued to improve, recording a global share of 25.4% in 2021, against the 20.7% observed in the US.

Figure 2.2-1 World share (%) of patent applications filed under PCT[1], 2000-2021



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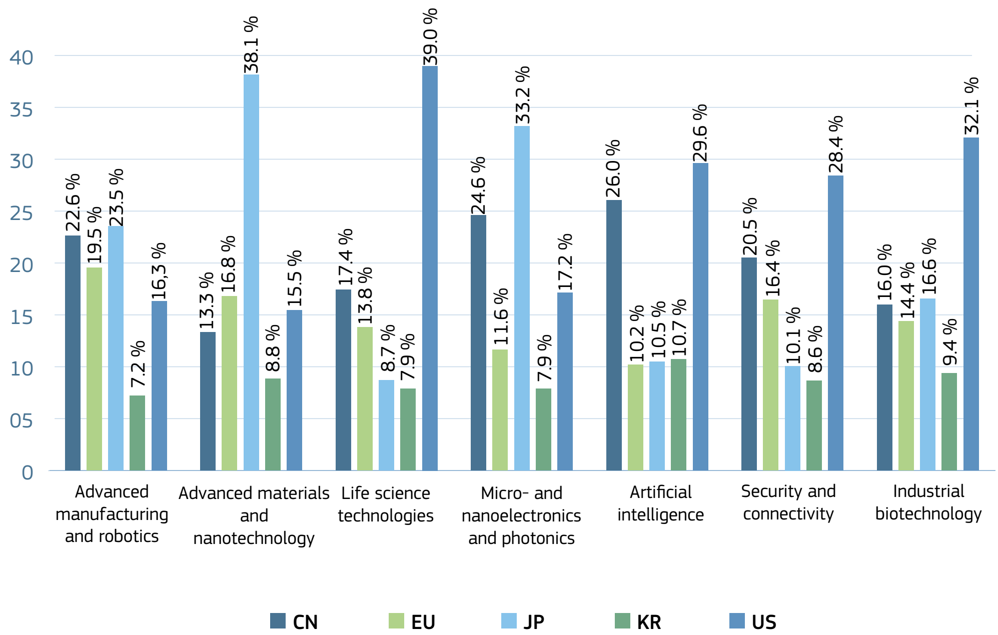
Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on Fraunhofer ISI, using PATSTAT.

Notes: [1] Patent Cooperation Treaty (PCT) patents. Fractional counting method, inventor's country of residence and priority date used.

The EU underperforms in several key enabling technologies (KETs) compared to other big global innovators, in terms of world share of patent applications. In 2021, the EU's share in the world patent applications was lower than that of the US and China in several KET fields, including life science technologies, and security and connectivity. The fields in which the EU's performance is lowest are micro- and nano-electronics and photonics, as well as artificial intelligence (AI), in which the EU reported a share of 11.3 % and 10.2 % respectively in 2021, against the 24.6 % and 26 % recorded in China, and the 17.2 % and 29.6 % observed in the US (Figure 2.2-2). The EU's performance is also weak in the field of industrial biotechnology, where it ranks fourth after the US, Japan and China, with the gap with the US remaining substantial (14.4 % against 32.1 %). On the contrary, the EU maintains a stronger position in advanced materials and nanotechnologies, in which it outperforms both China and the US although it remains significantly behind Japan. Furthermore, the EU also retains strength in the areas of advanced manufacturing and robotics, positioning itself above the US (with 19.5 % versus 16.3 %, respectively), but remaining well below China and Japan (Figure 2.2-2).

Figure 2.2-2 **World share (%) of patent applications filed under PCT[(1)], by key enabling technologies, 2021**



Science, research and innovation performance of the EU 2024

Source: DG Research and innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on Fraunhofer ISI, using PATSTAT.

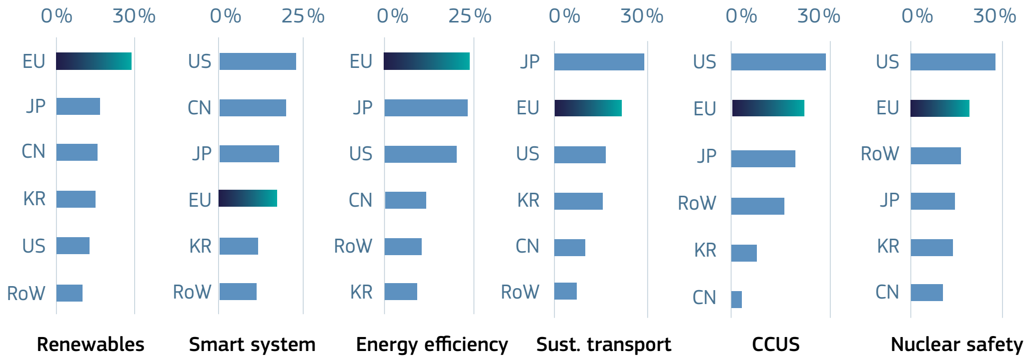
Notes: [(1)] Patent Cooperation Treaty (PCT) patents. Fractional counting method, inventor's country of residence and priority date used.

However, the EU remains strong in green sectors, although it faces increasing competition, especially from China. In 2019, China ranked first in terms of patent activities in green technologies. Nevertheless, when focusing on high-value green inventions, the EU remains in the lead, despite reporting a significant decrease as compared to the previous year.[1]

Furthermore, between 2014 and 2020, the EU kept leading in global high-value patent filings related to renewables (29 %) and energy efficiency (24 %), but lost ground in smart systems (17 %) ranking fourth after the USA, China and Japan (Figure 2.2-3).

1 Joint Research Centre, European Commission.

Figure 2.2-3 Share in global high-value patent filings relevant to the Energy Union R&I priorities, 2014-2020



Science, research and innovation performance of the EU 2024

Source: Georgakaki et al., (2023).
Note: CCUS stands for Carbon Capture, Utilisation, and Storage.

In terms of climate change mitigation technologies (CCMTs), the EU continues showing a positive degree of specialisation in most of the fields. In 2019, the EU showed the highest specialisation in the categories of buildings, production, transportation and waste, while reporting a negative specialisation index for adaptation technologies and ICT (Table 2.2-1). China was the most specialised in ICT (despite reporting a declining trend as compared to 2010), South Korea in energy, and the US in adaptation and carbon capture and storage (CCS).

Table 2.2-1 Specialisation index by CCMT group for major economies (2019) and change over 2010-2019: all applicants

CCMTs	EU		CN		JP		KR		US		RoW	
	Index	Change	Index	Change	Index	Change	Index	Change	Index	Change	Index	Change
Adaptation	-0.1	↓ -0.2	0.0	↑ 0.4	-0.5	↑ 0.1	0.0	↑ 0.4	0.2	↓ -0.4	0.7	↑ 0.2
Buildings	0.2	↑ 0.1	0.0	↑ 0.1	-0.1	↓ 0.0	-0.1	↓ -0.5	-0.2	↑ 0.1	0.2	↓ 0.0
CCS	0.2	↑ 0.0	-0.8	↓ 0.0	-0.1	↑ 0.4	-0.1	↑ 0.4	0.4	↓ -0.2	0.7	↑ 0.3
ICT	-0.5	↑ 0.1	0.6	↓ -0.7	-0.6	↓ -0.5	0.5	↓ -0.3	0.5	↑ 0.3	-0.4	↓ -0.4
Energy	0.1	↑ 0.0	-0.1	↑ 0.2	0.1	↓ 0.0	0.9	↑ 0.5	-0.4	↓ -0.3	-0.3	↓ -0.1
Production	0.3	↑ 0.3	-0.2	↑ 0.1	0.1	↑ 0.1	0.0	↓ -0.2	0.0	↓ -0.1	-0.1	↓ -0.1
Transport	0.6	↑ 0.3	-0.7	↑ 0.2	0.1	↓ -0.1	0.0	↑ 0.3	0.0	↓ 0.0	-0.2	↑ 0.4
Waste	0.5	↑ 0.2	-0.1	↑ 0.1	-0.4	↓ 0.0	-0.4	↓ -0.2	-0.2	↓ -0.3	0.6	↑ 0.3
Systems	0.2	↑ 0.3	-0.4	↑ 0.1	-0.2	↓ 0.0	0.1	↓ -0.4	0.2	↓ -0.1	0.4	↑ 0.3

Science, research and innovation performance of the EU 2024

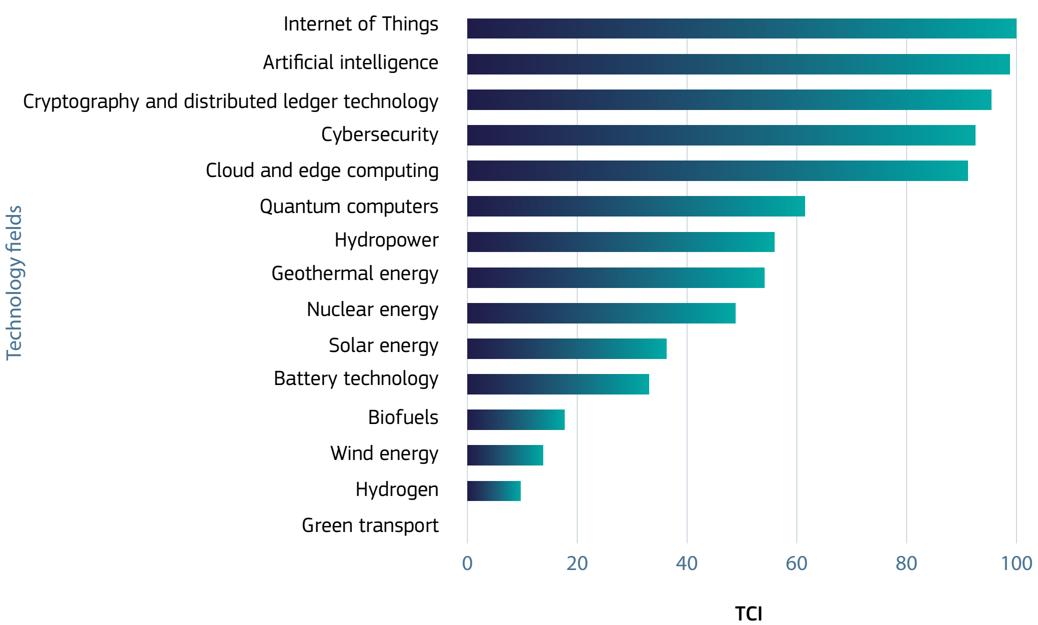
Source: Georgakaki et al., (2023).
Note: Based on high-value inventions.

Overall, the EU's knowledge base is characterised by a relatively higher degree of diversification than other global key innovators. Big global innovators such as China, the US, Japan and South Korea tend to report higher levels of technological specialisation in a lower number of technologies, which also appear to be less common than those characterising the technological portfolio of the EU and other countries (Di Girolamo et al., 2023).

The EU tends to specialise in technologies with lower growth and competitiveness potential (Box 2.2-1). Specialising in technologies that are less easy to replicate (such as digital technologies, semiconductors, medical technologies, etc.) confer a higher advantage in terms of growth potential and overall competitiveness (Balland and Rigby, 2017; Pintar and Scherngell, 2021). However, the EU is not currently well equipped to gain comparative advantage in these technology fields (e.g. computer technologies, digital communication, audio-visual technologies, optics, telecommunications and semiconductors), as compared to the US and China (Di Girolamo et al., 2023).

Digital technologies are instrumental in enhancing competitiveness and fostering growth. Among these, the Internet of Things (IoT), blockchain, AI and cybersecurity technologies, followed by cloud and edge computing and quantum computers stand out as technologies primed to significantly boost long-term productivity (Figure 2.2-4). Strategically important green technologies include hydropower, nuclear energy and advanced battery technologies, which remain key to the Union's ongoing commitment to the decarbonisation process.

Figure 2.2-4 The complexity of key strategic technologies



Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on Google Patents data.

Note: On the y-axis, technologies are ranked by Technology Complexity Index (TCI), which measures complexity at the technology level, normalised between 0 and 100.

Box 2.2-1: Complexity and the concept of relatedness

The concept of **knowledge complexity** is receiving increasing attention in both academic and policy literature. It studies the geography and dynamics of innovation activities, adopting an outcome-based approach, i.e. data on the geography innovation activities (such as patent data) is used to infer the presence of bundles of capabilities.

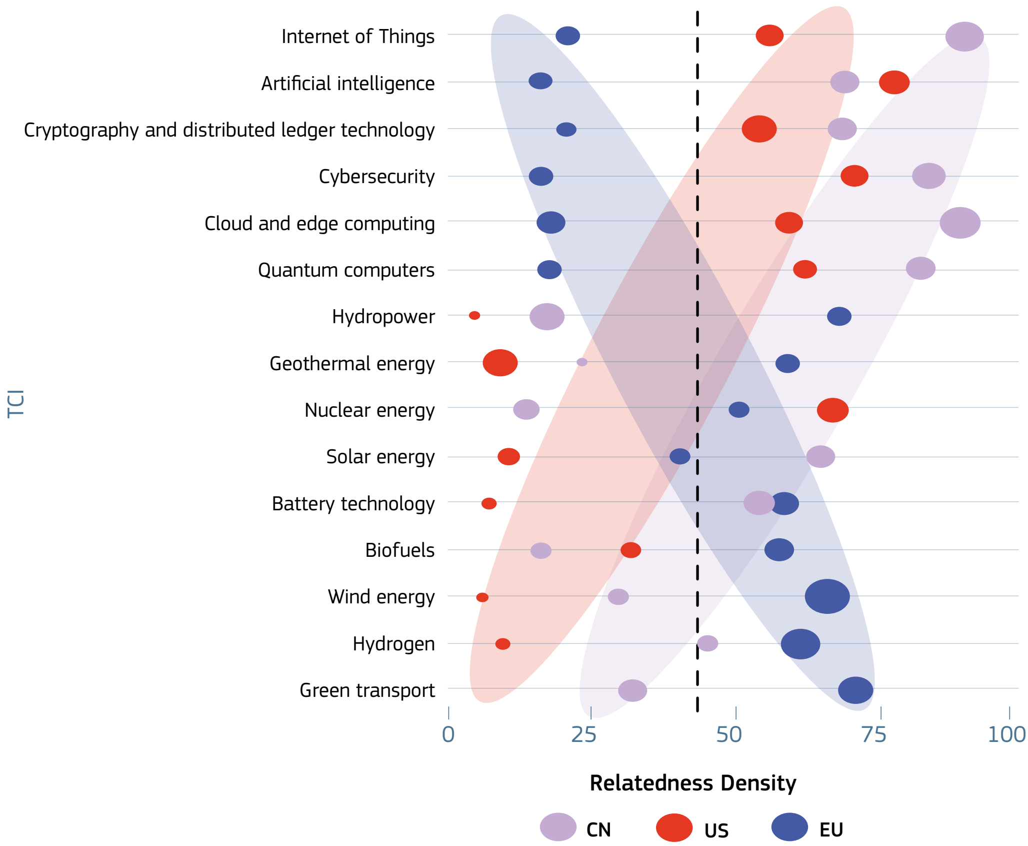
Specifically, the **Knowledge Complexity Index (KCI)** is an indicator measuring regions/countries' innovation capacity from data connecting such regions/countries to different types of technologies present in their portfolio. Similarly, the **Technology Complexity Index (TCI)** measures the complexity required to patent in a given technological field.

The intuition behind these indicators is that **technologies vastly differ in terms of value and growth potential**. Technologies relatively easy to copy and move over space typically require a lower number of capabilities to be undertaken, thereby conferring a lower competitive advantage to the countries/regions in which they are located. On the contrary, more complex technologies combine a higher number of capabilities, are more concentrated in space and are characterised by a higher potential in terms of growth and overall competitiveness (Balland and Rigby, 2017). Therefore, these indicators are calculated by studying the number of countries/regions able to patent in a given technological field, and infer the quality of a country/region's knowledge base by looking both at the technology fields in which it is able to specialise and at the other places where those technologies are also present (Balland and Rigby, 2017; Hidalgo, 2021).

Close to knowledge complexity is the concept of **technological relatedness**. Two technologies are considered related when they rely on the same knowledge and competencies to be produced (Hidalgo et al., 2018; Balland et al., 2019). Generally, relatedness provides information on the technological potential of a country/region in a given technology, as it refers to the costs that a country/region has to sustain when moving into a new technology (Boschma, 2017; Hidalgo et al., 2018). Intuitively, the more related current and new technologies are, the lower the cost to specialise in the new field. It follows that it is relatively easier to diversify in technologies requiring capabilities that largely overlap with those already present in a country/region. On the contrary, when the overlap between existing and new capabilities is small, jumping into a new technology field becomes more risky and costly (Bachtrogler-Unger et al., 2023).

The technological gap between the EU and other key players in strategic technologies persists. The EU's position to lead technological change in areas related to strategic productivity-enhancing technologies remains weaker than that of the US and China (Figure 2.2-5). In particular, the EU presents limited existing knowledge to develop specialisations in important digital fields (e.g. AI, IoT, blockchain technologies, quantum computers, etc.). Additionally, the position of the EU remains relatively weak also in other strategic areas, such as biotechnology, which have a major enabling and transformative nature in areas such as agriculture, environment, healthcare, life science, food chains or biomanufacturing (European Commission, 2023e). The EU has been making progress in this field, improving its scientific performance, but its specialisation potential remains significantly lower than the US (Di Girolamo et al., 2023). This implies that it will be challenging for the EU to build up capacity in such technologies in the future, calling for increasing efforts to reduce the gap with key competitors.

Figure 2.2-5 The EU positioning in complex technologies vs the US and China, 2019-2022



Science, research and innovation performance of the EU 2024

Source: DG Research and innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on Google Patents data.

Note: The x-axis indicates the relatedness density in any of the technology fields considered. On the y-axis, technologies are ranked by complexity levels, normalised between 0 and 100. The size of the bubble captures the degree of specialisation that each country reports in a given technology field, as measured by the revealed comparative advantage (RCA).

Furthermore, the current pace of innovation appears to be insufficient to meet carbon neutrality goals. The global production of new climate-related inventions has been slowing down in the last decade, with a similar pattern being observed across all the main innovating countries. Between 2011 and 2020, global innovation efforts in climate-related technologies have been declining as a share of global patenting, decreasing from 12.6% to 9% (Cervantes et al., 2023).

On the contrary, **the share of trademarks covering climate-related goods and services has quadrupled in Europe in the last two decades**, suggesting that while firms appear to have reduced their R&D efforts in climate-related endeavours, the commercialisation and diffusion of existing technologies have kept increasing (Cervantes et al., 2023).

Climate targets set for 2050 cannot be met by only relying on existing technologies. Accelerating renewable energy use and enhancing energy efficiency, combined with increased electrification using current technologies, can achieve more than 80% of the required emission reductions by 2030 (IEA, 2023a). The rapid expansion of clean tech is expected to drive the reduction in fossil fuel demand by more than 25% in the decade. On the contrary, around 35% of the CO_2 reductions targeted by 2050 will have to hinge on technologies currently at the demonstration or prototype phase (IEA, 2023a). Carbon neutrality, thus, calls for a rapid and large-scale deployment of available technologies (such as wind and solar), as well as the development and broad uptake of technologies that are still not available on the market, such as green hydrogen (Cervantes et al., 2023).

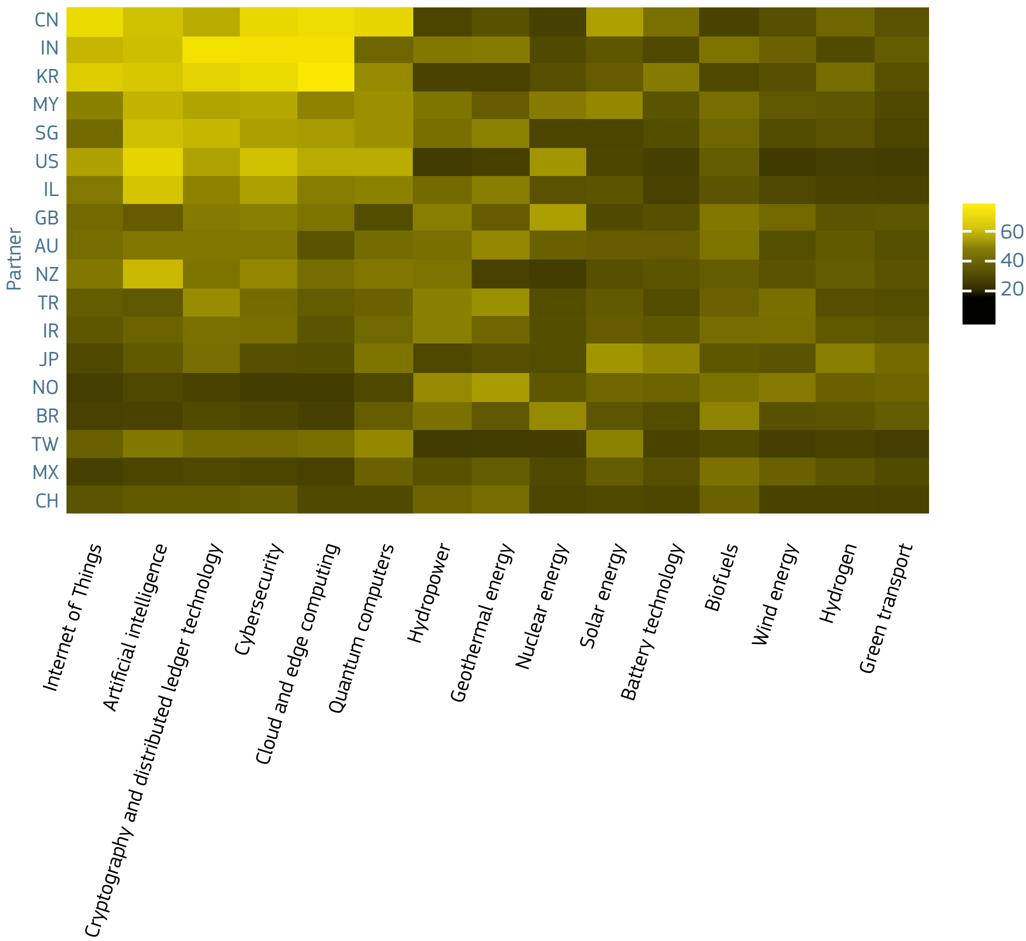
In this regard, the EU has important strengths on which to leverage. The EU remains leader in green infrastructures, outperforming both China and the US in areas related to climate adaptation and energy technologies, as well as in environmental technologies (Di Girolamo et al., 2023). Over the period 2019-2022, the EU reported a specialisation index higher than the US and China in technologies related to wind energy, hydrogen and green transportation, while little difference is observed for biofuels (Figure 2.2-5). Furthermore, although currently showing a lower level of specialisation in nuclear energy, solar energy, hydropower, geothermal energy and battery technologies, the EU has a high specialisation potential in these fields, indicating that the cost to further specialise in these types of technology would be relatively lower, as the EU could leverage on capabilities that largely overlap with those already present in the EU Member States (for more details, please refer to Box 2.2-1).

The risk for the EU to remain technologically dependent on other global players raises the stakes for science diplomacy and collaborations with international partners, from which the EU can gain in terms of technological complementarities. This is particularly relevant for more sophisticated technologies, which are strategic to the attainment of the EU's policy objectives. Figure 2.2-6 maps the EU's technological complementarities (i.e. to what extent non-EU countries can complement the EU's technological deficiencies in different technology fields) for 15 strategic technological areas. The highest degree of technological complementarity[2] is observed in fields related to IoT, AI, blockchain, cybersecurity, quantum computers, and cloud and edge computing. The countries showing the highest degree of complementarity (above 40%) in these areas are China,

2 Technological complementarities are measured exploiting the notion of relatedness density added, which allows to capture technological capabilities that are missing in a given country, but that can be accessed by strengthening external relations (Balland and Boschma, 2021).

India, South Korea, the US and Singapore for AI and blockchain technologies. A lower degree of complementarity (between 30% and 40%) is observed with Malaysia, Singapore, Russia and, to some extent, Israel. Biotechnology, medical technologies and pharmaceutics are other areas characterised by significant complementarities between the EU and other countries, notably the US, Taiwan, Canada and Israel (Di Girolamo et al., 2023).

Figure 2.2-6 The EU's technological complementarities, 2019-2022



Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on Google Patents data.

Note: On the x-axis, technologies are ordered according to the degree of technology complexity (TCI index). On the y-axis, countries are ranked according to the average relatedness density added.

2. The need to reduce dependencies in strategic supply chains

The increasing pressure of achieving climate neutrality, combined with global economic instability and geopolitical shifts, poses new challenges for the EU's industry. Europe and the world are assisting to a new revival of industrial policies, which will have to face a different level of complexity and be equipped to address multiple objectives, including the decarbonisation process and the quest towards strategic autonomy (Aghion et al., 2023).

From an economic standpoint, **industrial policies are typically designed to address market failures**, such as coordination failures between economic actors and externalities. The latter refers to situations in which the costs or benefits of an economic activity are not uniquely borne or recouped by the economic agent that carries out such activity. Externalities may also take the form of national security externalities, which call for reducing dependence on a foreign source of supply (Juhasz et al., 2023).

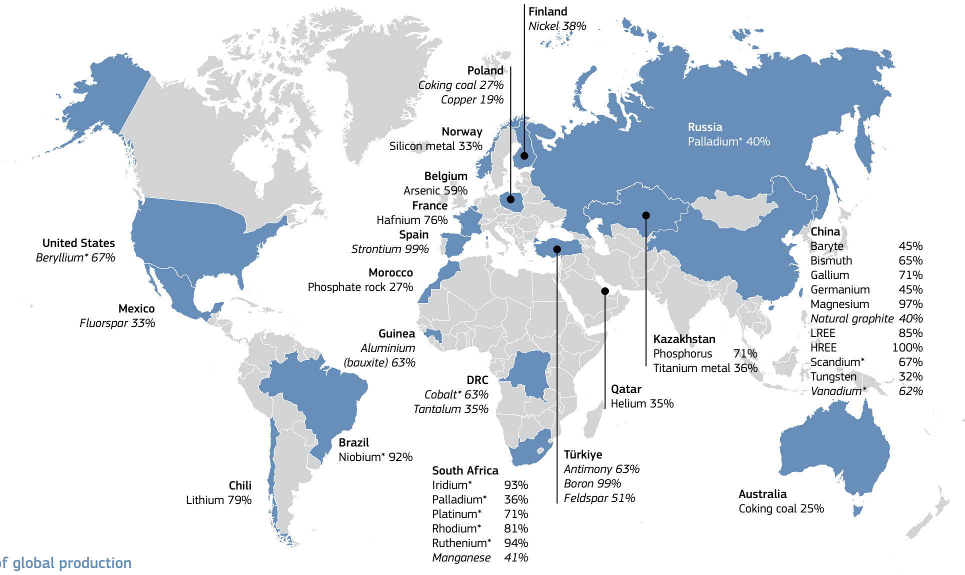
Supply chains have become increasingly and globally interconnected over recent decades, providing not only substantial economic benefits but also posing significant challenges. Global value chains (GVCs) have improved companies' market positions by reducing costs, but they have also made them more vulnerable to external demand and supply shocks (European Commission, 2021). Many companies have opted to specialise in specific tasks and source inputs internationally, rather than producing a complete product. This has led to a significant increase in the trade of intermediate goods, which accounted for approximately half of global trade in 2020 (EBRD, 2022). At the same time, the increased integration of GVCs also made economies more vulnerable to unforeseen disturbances (Dixson-Declève et al., 2021).

The EU vulnerabilities in strategic supply chains have reignited the debate on the trade-off between the costs and benefits of international specialisation in GVCs, which are susceptible to the rapid and widespread global transmission of demand and supply shocks. As a result, a reshaping of supply chain structures is taking place (Dadush, 2022), with the increasing tensions in international relationships pushing global enterprises to redefine their behaviour in an attempt to guarantee the resilience of their business activities (EBRD, 2022).

Increasing geopolitical risks and supply chain fragmentation are likely to push up the costs of the green transition, exacerbating the development of strategic dependencies and likely producing a negative impact on innovation. Among these strategic dependencies, raw materials require specific attention, as the green and digital transition will lead to significant increase in their demand (Bobba et al., 2020).

The supply of many critical raw materials to the EU is highly concentrated, which makes it particularly vulnerable to supply chain disruptions (Blengini et al., 2020). In particular, China is the largest supplier of several critical raw materials (e.g. baryte, bismuth, palladium), Russia and South Africa are the primary source for palladium and platinum group metals (such as iridium, rhodium and ruthenium), Brazil is the primary source of niobium, Australia supplies lithium, and the US is important for beryllium and helium (Figure 2.2-7).

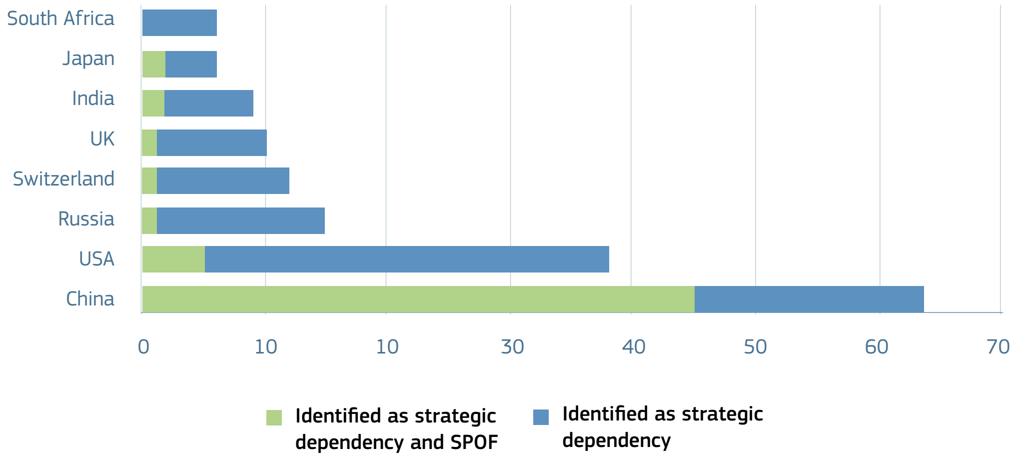
Figure 2.2-7 Major EU suppliers of critical raw materials



Source: European Commission, Directorate-General for Internal Market, Industry, Entrepreneurship and SMEs, Grohol and Veeh (2023).

In particular, most of the EU's strategic dependencies on China carry exceptionally high risks and can be defined as global single points of failure (SPOFs). These SPOFs are characterised by two main features: firstly, the dominance of a single exporter in the trade network affecting numerous countries; and, secondly, a high concentration of world exports in that area (Vandermeeren, 2024). Unlike the EU's dependencies on other third countries, a significant portion of its dependencies on China also qualifies as SPOFs (Figure 2.2-8), introducing an extra level of risk and vulnerability.

Figure 2.2-8 Identified strategic dependencies and single points of failure (SPOFs)



Source: Vandermeeren (2024) based on Arjona et al., (2023).

The green transition will require an enormous quantity of 'green metals'. Seventy-two countries, accounting for around 80% of global emissions, have committed themselves to net-zero targets (Energy Transition Commission, 2023). To achieve these goals, the world is expected to require 35 million tonnes of green metals annually by 2050. Specifically, there may be a 50-70% increase in copper and nickel demand by 2030, a 150% increase in cobalt and neodymium demand, and a six- to seven-fold increase in demand for graphite and lithium. Furthermore, the world will need a 15-fold increase in today's wind power, a 25-fold increase in solar power capacity, a three-fold expansion of the grid's size, and 60 times more electric vehicles (EVs) (Energy Transition Commission, 2023).

Despite its technological strengths, Europe remains a net importer of clean energy tech, due to cost-efficiency disadvantages in terms of manufacturing capacity. About one-quarter of electric cars and batteries, and nearly all solar photovoltaic (PV) modules and fuel cells in Europe are imported. In particular, the EU strongly depends on China's manufacturing capacities (which exceeds 90% in certain upstream segments of the value chain, such as ingots and wafers) for solar PV cells and modules; also, the cost of producing solar modules in Europe is currently estimated to be between 25-30% more expansive than in China (European Commission, 2023a). Similarly, China holds at least 60% of the world's manufacturing capacity for several other mass-manufactured technologies (e.g. wind systems and batteries). As an example, China holds more than 75 % of the manufacturing capacity for batteries for electric vehicles (EVs) (Vandermeeren, 2024).

On the contrary, **European manufacturers have a stronger international business in wind turbine components, although the industry is currently under duress**. In 2022, wind energy accounted for 16 % of electricity consumed in the EU on average. Furthermore, the technologies to harness wind energy that are developed and scaled up in Europe have become significantly cheaper over the last 10 years, making this form of energy the cheapest source of electricity in many European countries (European Commission, 2023c). Around 65 % of Europe's supply of wind turbine components is installed in other regions, where they have built local manufacturing facilities (IEA, 2023b). Moreover, European companies hold a significant share of the expanding global wind equipment market, although in decline with respect to the 2020 levels (European Commission, 2023c). Such a decline is largely due to the rapid deployment of wind energy in China. The increasing Chinese presence[3] combined with the difficulties experience by the European wind industry in 2022 are putting the EU's wind industry under distress, calling for pragmatic initiatives to address some of the key issues the EU wind manufacturing sector is facing (European Commission, 2023c).

Furthermore, **the EU has been developing its battery ecosystem, but still lacks the necessary technological production capabilities to keep pace with the swiftly rising demand for gigafactory-level production**. China, on the other hand, boasts an average cost of approximately EUR 68 million for constructing new battery gigafactories, resulting in 1 GWh of additional battery production capacity. In contrast, the EU's expenses for establishing new battery gigafactories average about EUR 100 million per GWh (European Commission, 2023a).

The EU also reports significant weaknesses in the semiconductor industry. Europe accounts for less than 10 % of the global semiconductor production, mainly focusing on the production of larger chips of 22 nanometres or more (European Parliament, 2022). The capacity to manufacture cutting-edge chips, ranging from 2 to 7 nanometres, is currently concentrated in two Asian companies, TSMC in Taiwan and Samsung in South Korea. However, the essential equipment required for producing these advanced chips is exclusively provided by ASML in the Netherlands. In addition, **European manufacturers also exhibit significant dependencies on the US**, mainly linked to the use of US-owned chip design tools (European Parliament, 2022).

3 China has also increased its capacity for the production of blades used in offshore wind turbines to almost 85 % (Vandermeeren, 2024).

3. The key role of technological progress for strategic autonomy

Recent geopolitical tensions and crises have contributed to the revival of industrial policy, which is providing the basis for a broader shift in the global economic paradigm. Open trade policies are being replaced by initiatives aiming at reducing the reliance on imports from other countries, while boosting national innovation, investment, production and employment (Aghion et al., 2023). This is particularly true for the US and China, while the EU opted for a balanced approach to achieve strategic autonomy, relying on both trade diversification (through the establishment of several new international partnerships) and strengthening in-house capacities in critical areas, as set out in the updated industrial strategy (European Commission, 2021) and the Green Deal Industrial Plan (European Commission, 2023d).

As a result of these systemic changes, European policymakers are faced with competing challenges. On the one hand, the objective of carbon-neutrality requires a complete restructuring of production and consumption processes, which calls for a global coordinated approach, and for green technologies to be produced rapidly and on a large scale. On the other hand, the risk of further exacerbation of geopolitical rivalries and other supply chain disruptions is likely to spur the friend-shoring and on-shoring of critical technologies and strategic manufacturing production to account for national security and defence concerns (Aghion et al., 2023).

In this context, R&I policy has an important role to play. R&I remains key to build the EU's technological sovereignty and guarantee its strategic autonomy. In its Communication on *European Economic Security Strategy*, the European Commission identified 10 technology areas (e.g. advanced semiconductor technologies, AI, quantum technologies, biotechnologies, energy technologies, etc.), set to play a pivotal role in enhancing the EU's economic security (European Commission, 2023b). The accelerated development of new strategic technologies, such as AI or high-performance computing, requires increasing efforts for the EU to remain a main actor in the development and governance of these fields.

This calls for higher R&I investments and a more structural approach towards strategic funding and technological development, as outlined by the new Strategic Technologies for Europe Platform (STEP), targeting R&I investments at bridging the specialisation gap between the EU and its main counterparts, while focusing on those technologies more likely to deliver important productivity gains in the long term.

At the same time, the EU can continue to leverage its strengths in green technologies where demand is expected to increase. Policies put forward by the EU's main counterparts are expected to significantly accelerate the global decarbonisation process (Kleimann et al., 2023). The global energy transition will increase the use of raw materials in the manufacture of wind turbines, PV panels, batteries, hydrogen production and storage, and other systems. The transition to e-Mobility will require batteries, fuel cells and lightweight traction motors, and not just for cars, but also for e-Bikes, scooters and heavy-duty transport. The EU could benefit from this market trend by capitalising on its strong leadership in green technologies and also by making the best of its strength in advanced materials.

Furthermore, investing in green innovations also remains crucial to reducing the short-term costs of the decarbonisation process. While there exists little doubt on the positive long-term effects of climate policies, the short-term effects of the green transition are quite different. On the one hand, the development of low-carbon technologies is likely to disrupt existing production processes, entailing significant costs for those sectors currently heavily relying on carbon-intensive inputs (Hasna et al., 2023). On the other hand, green innovation has the potential to create important knowledge spillovers on carbon-intensive industries, leading to a higher level of innovation in the economy as a whole (Porter and van der Linde, 1995). Notwithstanding the possible short-term negative economic effects of green transition, increasing green innovation remains key to producing alternative and less expensive low-carbon technologies, thereby helping to reduce the costs of the decarbonisation process (Hasna et al., 2023).

The European Commission has committed to **boosting breakthrough innovation in renewable and low-carbon technologies through the REPowerEU Plan.** Furthermore, the **industrial technology roadmaps for R&I**, under the *New ERA for Research and Innovation*, map the investments needs and conditions for some key products and processes to achieve the sustainable transition in the EU, while proposing technological options for low-carbon technologies in energy-intensive industries (including the use of green electricity and hydrogen), and pointing to available support instruments, synergies and action to accelerate the transition while ensuring the EU's competitiveness.

The strengthening of the EU's technological leadership needs to be accompanied by a reduction of supply chain dependencies. This is particularly relevant for clean energy technologies, for which the EU's significant dependency on imports of raw materials and components necessary for the low-carbon transition (coupled with potential global supply disruptions, political instability, concentrated sources of supply and international price volatility) may result in significant shortages that could pose a considerable risk for the Union's energy security and its decarbonisation ambitions.

The role of innovation in this sense remains key. Technological innovation can influence material demand through substitution, efficiency enhancement and design refinement, as well as the development of novel materials (IRENA, 2023). As an example, the chemical composition of materials used in EV battery production has evolved significantly over the past decade, with important implications for the demand for critical materials related to this type of technology (IRENA, 2023). Today, lithium-ion batteries with graphite-based anode chemistry, which accounts for about 70% of the market, are prevalent due to their superior performance. Nevertheless, the advent of new battery technologies, such as sodium-ion batteries, presents an opportunity to shift away from lithium and cobalt to more economical and abundant alternatives like sodium, potentially transforming the EV battery industry landscape.

The EU is launching several initiatives in this regard. The **European Chips Act** proposes a comprehensive strategy to advance semiconductor technology in Europe. It includes investments in next-gen tech, access to design tools, energy-efficient chip certification, investor-friendly policies, support for start-ups, talent development, supply security measures and international partnerships with likeminded nations. **The European Raw Materials Act** aims to ensure a secure and sustainable EU supply of critical raw materials (such as lithium, cobalt and nickel to produce batteries; gallium for solar panels; raw boron for wind technologies; titanium and tungsten for the space and defence sectors) by reinforcing domestic supply chains and reducing the EU's import dependencies. The **Net-Zero Industry Act** aims to scale up the manufacturing of clean technologies in the EU, simplifying the regulatory framework, as well as cutting red tape and unnecessary administrative burdens for the development of net-zero manufacturing projects.

Reducing strategic dependencies also calls for keeping the EU Single Market strong, the most important tool in the EU's arsenal, to accelerate the roll-out of strategic technologies by avoiding regulatory costs associated with fragmentation, uncertainty and bureaucracy. Similarly, developing appropriate sets of skills within the EU remains also key to avoid labour shortages (for more details, please refer to Chapter 5.2).

Reconciling the need for a global coordinated approach against climate change and that of securing strategic supply chains by strengthening in-house capacities or relying on close allies remains key. Geopolitical tensions fostered by ideological divide and mistrust between competing economic powers can increase the fragmentation of international supply chains, with a likely negative impact on innovation. R&I activities have become increasingly internationalised, and the EU needs to balance the benefits of research collaborations with the risks related to foreign interference.

In response to the current global trends, **the EU can use its international relationships to promote its values, defining areas of mutual interest as well as a division of knowledge with key partners**. Without reinforcing the role of the EU as a leading actor to foster international R&I cooperation, current technological dependencies will more likely put the EU's technology sovereignty and strategic autonomy in jeopardy.

This calls for higher international openness and reinforced cooperation (Dixson-Declève et al., 2023). Reacting to current geopolitical shifts and protectionist tendencies with similar types of policies may benefit the EU in the short run, but risk being counterproductive longer term. Achieving technological sovereignty does not have to come at the expense of multilateralism. Reducing cooperation would undermine the EU's credibility as a global actor committed to multilateral cooperation, and likely harm the EU's trade interests (Kleimann et al., 2023).

Building on the lessons learned from the COVID-19 pandemic and in response to the current global geopolitical trends, **the EU strategy on international R&I cooperation promotes rules-based multilateralism, pursues openness and modulates bilateral cooperation to make it compatible with EU interests**. With its 2021 Communication on the Global Approach to R&I, the Commission has reaffirmed the EU's commitment to preserve openness in bilateral and multilateral cooperation in science and technology in a spirit of reciprocity and safeguarding fundamental values and principles. The Communication aims to build partnerships that strengthen the EU's open strategic autonomy and leverage the EU's capacity to develop and take up strategic technologies, thereby increasing EU competitiveness and avoiding future dependencies. As an example, the EU's initiative on **Raw Materials Diplomacy** is designed to set up dialogues with strategic partners involved in raw materials, through various frameworks of cooperation (i.e. bilateral, regional or multilateral cooperation).[4]

4 https://single-market-economy.ec.europa.eu/sectors/raw-materials/areas-specific-interest/raw-materials-diplomacy_en

Partnerships and openness are also part of one of the three pillars of the new European economic security strategy. The strategy acknowledges the key role that openness plays in fostering innovation ecosystems, while calling for actions to mitigate security risks linked to foreign interferences. In this regard, the Commission adopted an Economic Security Package in January 2024, including two initiatives related to R&I: a White Paper on *Enhancing R&D support involving technologies with dual-use potential* (for more details, see Chapter 2.3); and a Proposal for a Council Recommendation on Research security (adopted in May 2024). The latter recognises the primary role of higher education institutions and research organisations in international cooperation, as well as the need to preserve academic freedom by supporting European research-performing organisations in addressing research security risks linked to increasing international conflicts and competition (European Commission, 2024).

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CHAPTER 2.3

SECURITY & DEFENCE R&I

Key questions

- What are the global trends in defence R&I investment?
- What is the impact of dual-use technologies on security and innovation?
- What is the role of strategic defence R&I in response to global challenges?

Highlights

- Russia's unprovoked invasion of Ukraine emphasises the crucial need for EU defence research and development (R&D) and technological superiority in deterring aggression and protecting peace, freedom and democracy.
- Russia (4.3%) and the US (3.3%) have, relative to their gross domestic product (GDP), the highest defence expenditures, almost three and two times as much as China (1.6%) and the EU (1.5%).
- In nominal terms, the EU defence spending surpasses that of Russia and closely approaches China's levels. The US, by contrast, leads significantly in this regard, outspending the EU by roughly threefold in defence.
- EU defence investments are focused on the acquisition of defence equipment rather than funnelling resources into defence R&D. Within the R&D spectrum, there is a notable allocation towards non-research and technology (R&T) activities, underscoring a EU focus on the later stages of defence technology development, rather than on foundational research and technology demonstration.
- The EU (25%) is globally the second exporter of defence equipment, behind the US (40%) and in front of Russia (16%) and China (5%), exemplifying EU's technological defence capabilities. However, while the EU is relatively well positioned, the biggest arms-producing companies are non-EU, as the top 10 defence equipment producing companies are all non-EU based (US, China, UK and Russia).
- In Horizon 2020, projects with dual-use technology potential have been funded, with ICT and cybersecurity as the main areas.
- The further development and implementation of dual-use technologies can play a significant role in shaping the future landscape of both technological innovation and EU's and member states' security.

Policy insights

- The convergence of climate change, demographic shifts, political polarisation and geopolitical changes presents challenges to global security. EU's innovation efforts in security and defence can be regarded as essential in addressing these multifaceted difficulties.
- Under the current EU Framework Programme for R&I, activities carried out under the European Defence Fund should have an exclusive focus on defence research and development, while activities carried out under the 'civilian' specific programme and the EIT should have an exclusive focus on civil applications. Coordination between programmes may strengthen synergies in areas of dual-use technology.
- At a lower level of technology readiness levels (TRLs), defence R&D spillovers and overlaps between civilian and military interests are greater.
- For the EU to fully harness the potential of dual-use technologies, and maximise the utility of technological investments, it is imperative to foster synergies and bridge the divide between civilian and defence R&D, both within the Union and among its Member States, which can be enhanced by collaboration and co-investing.

The unprovoked invasion of Ukraine by Russia has placed the EU's (territorial) security and defence back at the centre of the EU's policy debate. In an era marked by rapid technological advancements and geopolitical shifts, the role of R&I in defence cannot be overstated. This chapter aims to explore the multifaceted impact of R&I in the realm of security and defence, underscoring the pivotal role it plays in maintaining and enhancing the EU's defence and security capabilities.

The significance of R&I in defence is further magnified when considering the concept of dual-use technologies. These technologies, developed initially for military purposes, find extensive applications in the civilian sector, leading to significant technological spillovers and advancements in various fields. Conversely, innovations in the civilian sector often contribute to the advancement of military technology, creating a symbiotic relationship between the two domains.

1. Defence and security R&I around the world

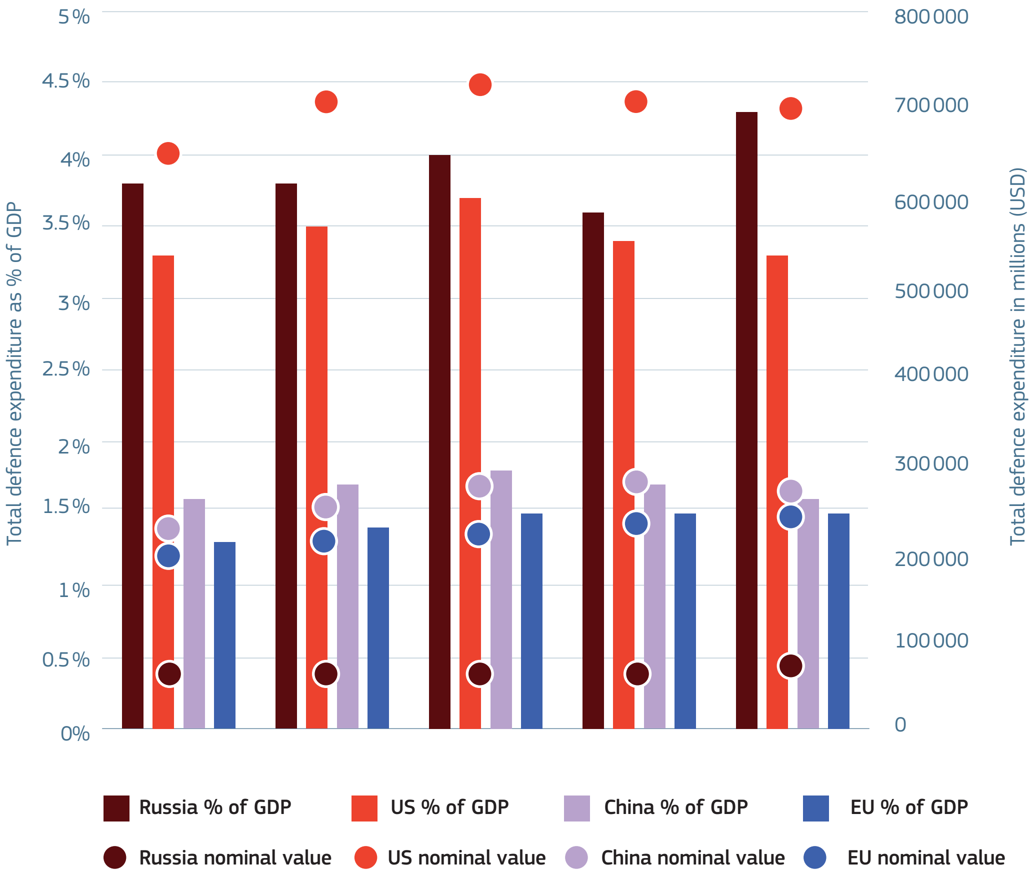
The defence sector is distinct and complex, characterised by its unique market structure and regulatory environment. Unlike the civilian sector, where there is a broad and diverse customer base, the defence industry primarily caters to a very specific set of clients, mainly national defence ministries and, occasionally, authorised private entities. This market limitation is further compounded by stringent export regulations and national security considerations that govern the sale and distribution of defence-related products and technologies. These regulations are often in place to prevent the proliferation of arms, and to ensure that sensitive technologies do not fall into the hands of potential adversaries or are used for purposes that could destabilise regions or global peace (Ball and Leitenberg, 2021).

Due to the highly sensitive nature of defence products and the limited market, companies in this sector face unique challenges regarding R&D investments. Private defence companies do invest significantly in R&D, although the source of funding is often the state. The nature and scope of this investment are substantially different from those in the civilian sector. Defence R&D is heavily supported and funded by government contracts, as the products being developed are often specific to the needs of the national military and security services. This close relationship with government entities means that defence R&D is often aligned with national security priorities and long-term defence strategies (Uttley, 2018).

Much of the information pertaining to defence R&D budgets, project details and technological advancements is classified. This secrecy is maintained to protect national security interests and to prevent sensitive technological information from being accessed by potential adversaries. This level of confidentiality often extends to the financial aspects of defence R&D, making it difficult for analysts and the public to gain a clear understanding of the actual investment levels and the distribution of funds across various projects. Hence, available data is often the result of rough, yet informative, approximations. Moreover, the defence sector is known for its long development cycles, especially for advanced weapon systems and platforms. The development of new technology in this sector is not only capital-intensive but also time-consuming, often spanning several years or even decades.

In 2022, the European Union allocated approximately 1.5% of its GDP to defence spending. This figure is slightly lower than China's 1.6%, significantly less than the US's 3.3%, and substantially lower than Russia's 4.3%. However, when examining defence expenditures in nominal terms, the European Union's (USD 232 billion) spending surpasses that of Russia (USD 63 billion) and closely approaches China's (USD 261 billion) levels. The US (USD 691 billion), by contrast, leads significantly in this regard, outspending the European Union by roughly threefold in defence (Figure 2.3-1).

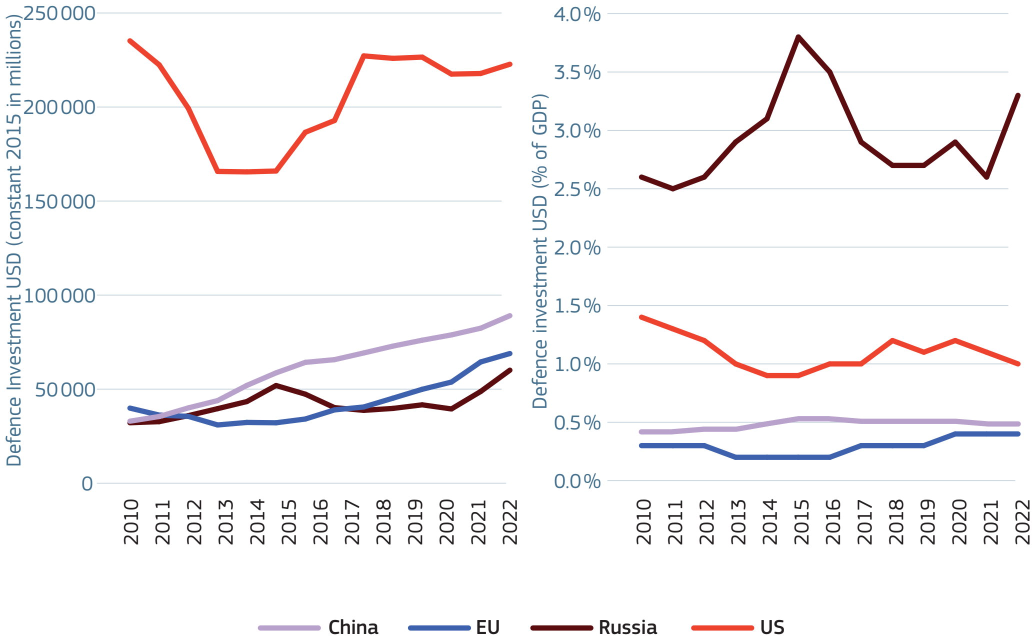
Figure 2.3-1 **Defence spending across the world**



Science, research and innovation performance of the EU 2024
Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit's own elaboration based on EDA Defence Data 2022, the IISS Military Balance+, and World Bank data.
Note: Total defence expenditure as % of GDP is collected from EDA Defence Data 2022 (which uses the IISS Military Balance+ for the USA, Russia and China). Total defence expenditure in nominal values is derived from the EDA % of GDP figures by multiplying for the World Bank GDP (constant 2015 USD).

In 2022, the EU allocated approximately 0.4% of its GDP to defence investments (defence equipment procurement[1] + defence R&D[2]). This figure is slightly lower than China (0.5%), significantly less than the US (1%), and substantially lower than Russia (3.3%). However, when examining defence investments in real terms, The EU's (USD 64 billion) spending surpasses that of Russia (USD 49 billion) and closely approaches China's (USD 82 billion) levels. The US (USD 218 billion), in contrast, leads significantly in this regard, outspending the EU roughly threefold in defence investment. (Figure 2.3-2).

Figure 2.3-2 **Defence investment spending across the world**



Science, research and innovation performance of the EU 2024

Source: DG Research and innovation, Common R&I Stategy and Foresight Service, Chief Economist Unit's own elaboration based on DG DEFIS extractions from the IISS Military Balance+, and World Bank data.

Note: Defence investments in measured as Def Investment USD (constant 2015) and GDP is measured as GDP (constant 2015 US$). Defence Investment = defence equipment procurement + R&D (including R&T) expenditure.

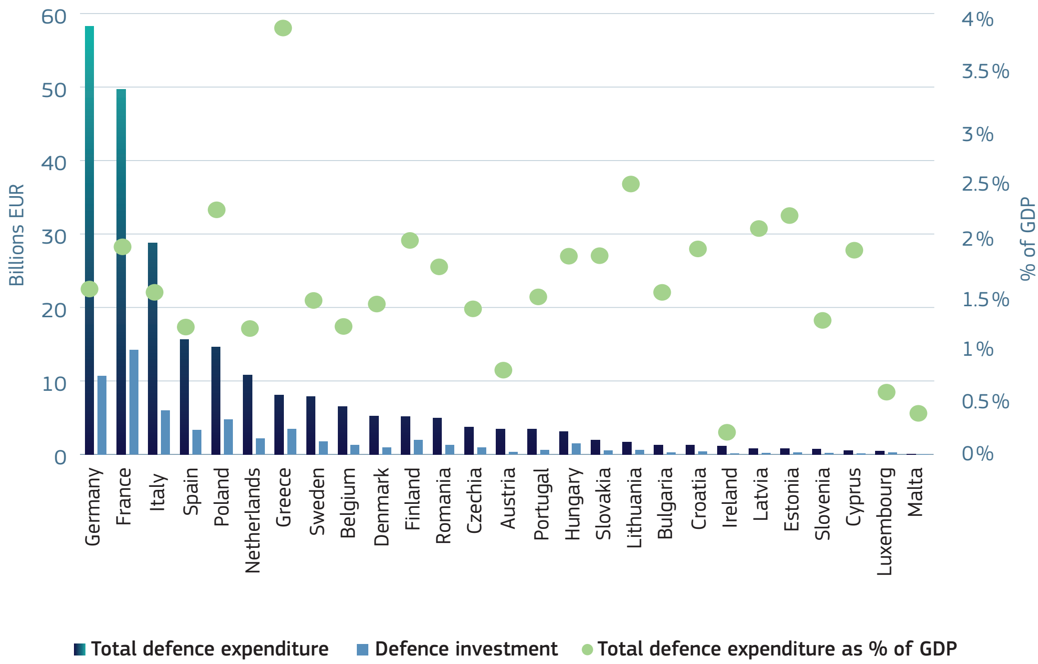
1 Expenditure for all major equipment categories, that are not included in operations and maintenance spending.

2 Defence R&D indicates any defence R&D programmes up to the point where expenditure for production of equipment starts to be incurred. R&D includes R&T. R&T indicates expenditure for basic research, applied research and technology demonstration for defence purposes. R&T is a subset of R&D expenditure.

In 2022, Germany, France and Italy were the primary contributors to the European Union's defence spending. Germany, allocating 1.5 % of its GDP to defence, equivalent to EUR 58 billion, accounted for 24 % of the EU's total defence expenditure. France, with a defence budget comprising 1.8 % of its GDP or EUR 49.7 billion, contributed 21 % to the EU's overall defence spending. Italy, also dedicating 1.5 % of its GDP to defence, amounting to EUR 28.7 billion, was responsible for 12 % of the total defence expenditure within the EU (Figure 2.3-3).

Looking at defence investments, France emerges as the leading contributor in the EU. In 2022, France topped the list with defence investments amounting to EUR 14.2 billion, followed by Germany with EUR 10.6 billion and Italy with EUR 5.9 billion. This distribution suggests that Germany allocates a larger portion of its defence budget to military personnel, while France prioritizes investments in military equipment and R&D to a greater extent (Figure 2.3-3).

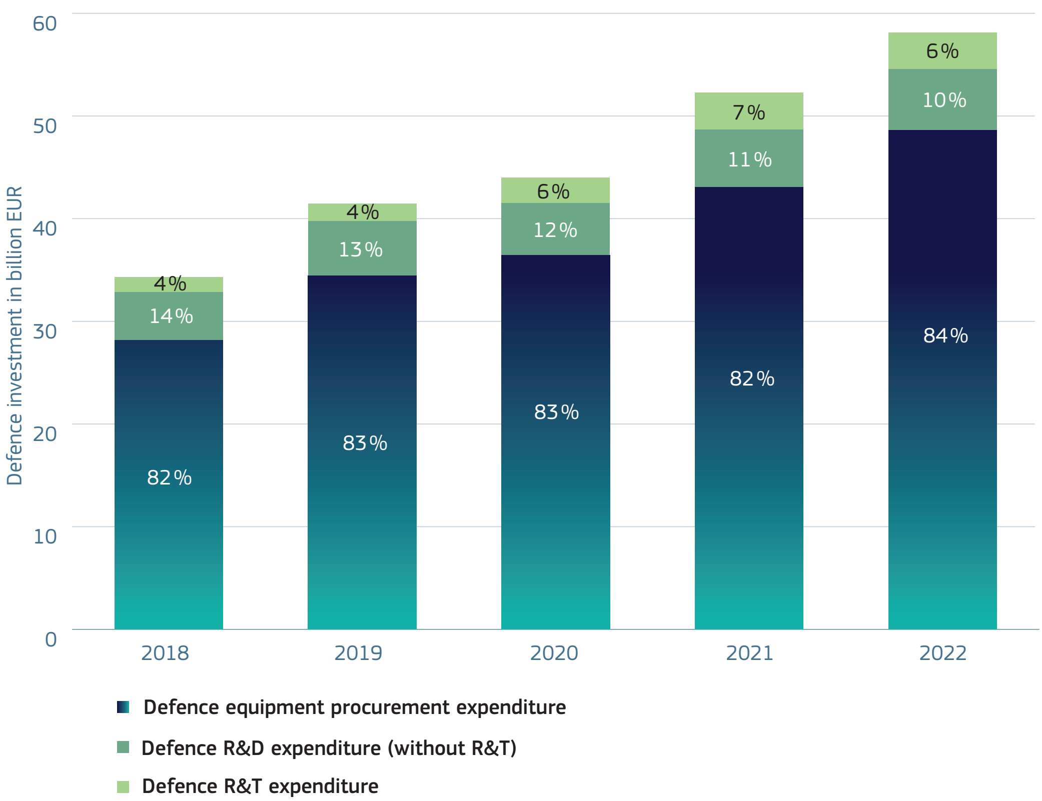
Figure 2.3-3 Distribution of defence expenditure within the EU (2022)



Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit's own elaboration based on EDA Defence Data 2022.
Note: Defence Investment refers to defence equipment procurement and R&D (including R&T) expenditure. Nominal values are expressed in constant 2022 prices.

EU defence investments predominantly prioritise the acquisition of defence equipment over R&D. Moreover, within the R&D sector, a significant proportion of the funding is allocated to non-R&T activities. This emphasises the EU focus on the latter stages of defence technology development and production, as opposed to expenditures on basic research, applied research and technology demonstration for defence purposes. Furthermore, from 2018 until 2022, has seen a slight increase in the proportion of funds directed towards defence equipment procurement, while the share allocated to R&D has decreased. However, within the R&D domain, there has been a gradual shift from non-R&T components to R&T components. Overall, in constant 2022 prices, EU investment spending has experienced an upward trend over the past five years (Figure 2.3-4).

Figure 2.3-4 **EU Defence investment decomposition by investment type (2022 prices)**



Science, research and innovation performance of the EU 2024

Sources: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit's own elaboration based on EDA Defence Data 2022.

Note: Defence investment refers to defence equipment procurement and R&D (including R&T) expenditure. Nominal values are expressed in constant 2022 prices.

Box 2.3-1: US approach to defence R&D and critical technologies

The United States Government has a long-standing tradition of investing heavily in R&I within the realms of defence and security, as well as in related sectors like aeronautics and space. This investment is reflected in the substantial funds allocated to various federal agencies, with the Department of Defence (DoD) receiving the largest share of the federal R&D budget. In 2020, the DoD was granted around USD 67 billion (approximately EUR 59 billion) for R&D, representing nearly 39 % of the total federal R&D budget. Another key player in this area is the National Aeronautics and Space Administration (NASA), which received about USD 11 billion (approximately EUR 9 billion) in R&D funding for the same year. Combined, the DoD and NASA account for roughly 45 % of the US' public R&D funding, highlighting the Federal Government's focused approach in supporting R&D initiatives.

The type of R&D of these funds, however, varies significantly between agencies. The DoD primarily invests in experimental development, with 86.6 % of its R&D budget dedicated to this area, while applied research and basic research receive 9.6 % and 3.7 %, respectively. In contrast, NASA's expenditure is more evenly distributed across different types of R&I: 36.4 % for basic research, 24.2 % for applied research and 39.3 % for experimental development.

A notable aspect of the US' R&I system is the presence of several agencies that focus on the development of critical technologies and disruptive innovations. The most prominent among these is the Defence Advanced Research Projects Agency (DARPA), a part of the DoD emphasizing the development of technologies used by the military. DARPA has set a precedent for other similar agencies, such as the Intelligence Advanced Research Projects Activity (I-ARPA), which emphasises artificial intelligence (AI), quantum computing, machine learning, high-performance computing and synthetic biology. There's also the Advanced Research Projects Agency-Energy (ARPA-E) under the Department of Energy, focusing on advancements in solar energy, batteries, transportation, radiation, grid and energy conversion technologies. Furthermore, the Home Security Advanced Research Projects Agency (HSARPA) works on technology development in areas like border and maritime security, cybersecurity, and chemical and biochemical defence. In 2022, a new addition was the Advanced Research Projects Agency for Health (ARPA-H), under the National Institutes of Health, concentrating on biomedical breakthroughs.

Source: Steeman, J.T., Peiffer-Smadja, O. and Ravet, J. (2024, forthcoming), European Commission, Directorate for Research and Innovation.

The available data on defence R&D spending is informative, but high expenditure in defence doesn't automatically equate to an efficient use of funds or a technological edge for the countries investing the most. Therefore, it is also important to consider arms sales and trade dynamics. These provide valuable insights, as buyers are unlikely to repeatedly purchase weapons that have proven to be flawed, inefficient or excessively priced relative to their technological capabilities. Arms sales can be seen as a complementary indicator of the true competitiveness of the technology developed through defence R&D.

On a global scale, private arms-producing companies of EU Member States are relatively well positioned but largely ranked after the main US and Chinese companies, with Leonardo (Italian) and Airbus (Trans-European) ranked globally in 13th and 14th place in 2022 in term of arms-selling revenues (Table 2.3-1). The main EU defence technological and industrial base is concentrated in 3 EU countries: France, Germany, Italy (ASD, 2022).

The US (40%) is by far the main exporter of arms in the world, followed by Russia (16%) and France (11%), together accounting for 67% of world volume, with the EU as a region as the second largest exporter globally (25%) for the period 2018-2022. EU Member States are, in general, well positioned as global exporters of arms, with France (3rd, 11%), Germany (5th, 4.2%), Italy (6th, 3.8%), Spain (8th, 2.6%), The Netherlands (11th, 1.4%) and Sweden (13th, 0.8%) among the global suppliers (Table 2.3-2).

Countries from Asia and the Middle East are the main importers of arms globally, marked by India (1st), Saudi Arabia (2nd) and Qatar (3rd) as the top three importing countries, with 11%, 10% and 6% of total global arm imports, respectively, for the period 2018-2022. EU Member States are not major importers. Overall, the global distribution of arms imports is more fragmented and evenly dispersed across various nations, unlike arms exports, which are concentrated in a handful of countries that possess the requisite technological infrastructure and production capabilities (Table 2.3-2).

Table 2.3-1 Arms sales, 2022, by company

Rank (2022)	Company	Country	Arms revenue in million USD (2022)	Arms revenue as a % of total revenue (2022)	Arm revenue growth (2022-2015)
1	Lockheed Martin Corp.	United States	59 390	90	+32 %
2	Raytheon Technologies	United States	39 570	59	+47 %
3	Northrop Grumman Corp.	United States	32 300	88	+30 %
4	Boeing	United States	29 300	44	-15 %
5	General Dynamics Corp.	United States	28 320	72	+19 %
6	BAE Systems	United Kingdom	26 900	97	-1 %
7	NORINCO	China	22 060	27	+23 %
8	AVIC	China	20 620	25	+28 %
9	CASC	China	19 560	44	+49 %
10	Rostec	Russia	16 810	55	-2 %
11	CETC	China	15 080	27	+18 %
12	L3Harris Technologies	United States	12 630	74	-25 %
13	Leonardo	Italy	12 470	83	+24 %
14	Airbus	Trans-European	12 090	20	-14 %
15	CASIC	China	11 770	32	+11 %
16	CSSC	China	10 440	20	+61 %
17	Thales	France	9 420	51	+9 %
18	HII	United States	8 750	82	NA
19	Leidos	United States	8 240	58	+103 %
20	Amentum	United States	6 560	75	NA
21	CSGC	China	6 460	15	-33 %
22	Booz Allen Hamilton	United States	5 900	64	+22 %
23	Dassault Aviation Group	France	5 070	70	+157 %
24	Elbit Systems	Israel	4 960	90	+43 %
25	Rolls-Royce	United Kingdom	4 930	32	+5 %
26	CACI International	United States	4 820	72	+60 %
27	Honeywell International	United States	4 630	13	+11 %
28	Rheinmetall	Germany	4 550	67	+41 %
29	Naval Group	France	4 530	99	+6 %
30	Peraton	United States	4 410	63	NA

Source: SIPRI Arms Industry Database.
Note: 2022-2015 growth is computed using 2015 arms revenue defined in 2022 constant dollars.

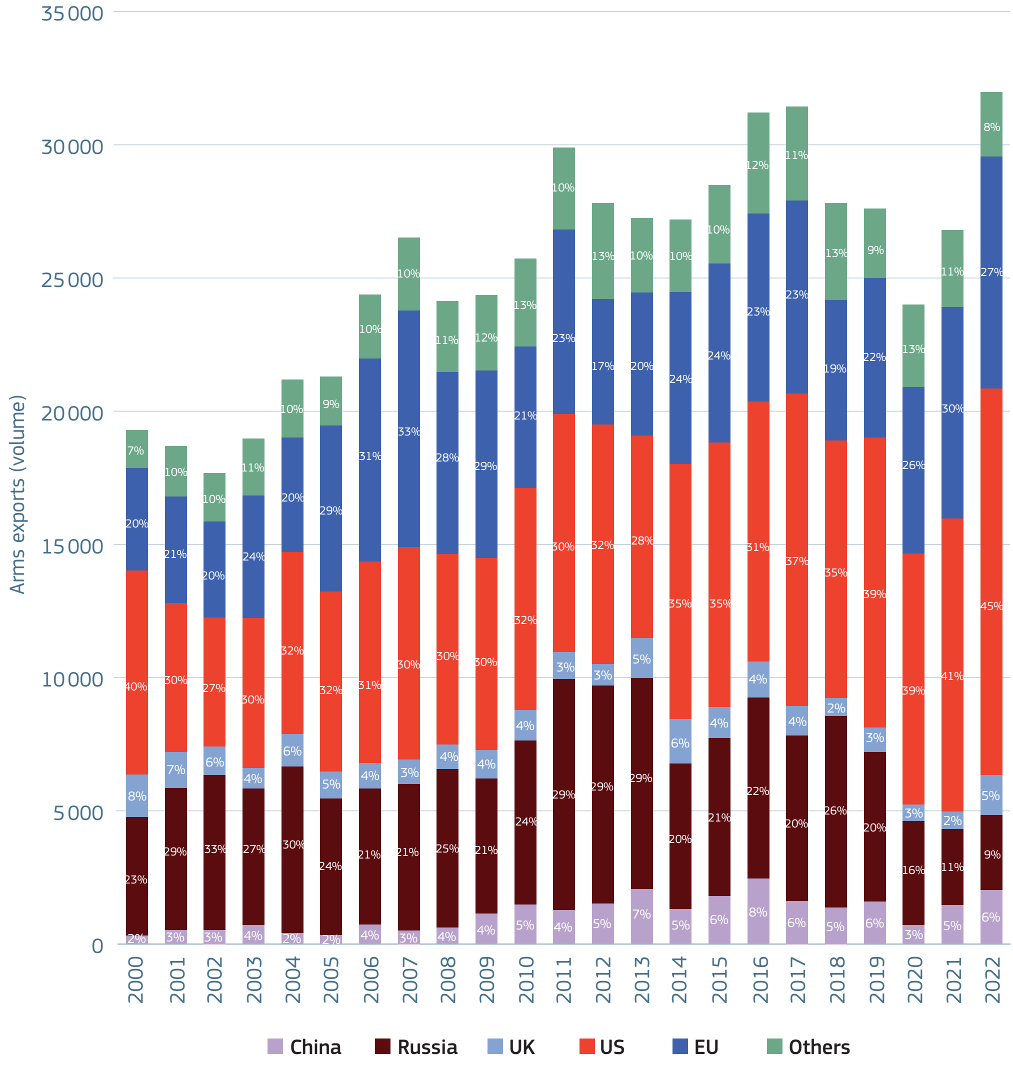
Table 2.3-2 Main exporters and importers of arms by country (2018-2022)

Rank	Exporter	Global share in %	Importer	Global share in %
1	United States	40.2	India	11.2
2	Russia	16.2	Saudi Arabia	9.6
3	France	10.8	Qatar	6.4
4	China	5.2	Australia	4.7
5	Germany	4.2	China	4.6
6	Italy	3.8	Egypt	4.5
7	United Kingdom	3.2	South Korea	3.7
8	Spain	2.6	Pakistan	3.7
9	South Korea	2.4	Japan	3.5
10	Israel	2.3	USA	2.7
11	Netherlands	1.4	UAE	2.7
12	Turkey	1.1	Kuwait	2.4
13	Sweden	0.8	United Kingdom	2.3
14	Switzerland	0.7	Ukraine	2
15	Australia	0.6	Norway	2
16	Canada	0.5	Israel	1.9
17	Ukraine	0.5	Netherlands	1.9
18	UAE	0.4	Algeria	1.8
19	Poland	0.4	Turkey	1.3
20	Belarus	0.3	Singapore	1.3

Science, research and innovation performance of the EU 2024
Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit's own elaboration based on the SIPRI Arms Transfers Database.
Note: EU Member States' global share is 24.7%.

Examining historical patterns from 2000 to 2022 reveals a notable increase in the global share of arms exports by both the EU and the US. Conversely, Russia and the United Kingdom have experienced a decline in their share of the global arms export market. China's arms exports, however, have shown a significant rise, increasing from 2% of the global share in 2000 to 6% in 2022. Focusing on the destinations of these arms, the Middle East and Asia have consistently been the primary importers, accounting for the vast majority of arms imports throughout the period 2000-2022. Notably, arms imports from European non-EU countries witnessed a threefold increase in 2022, largely as a result of Russia's unprovoked invasion of Ukraine (Figures 2.3-5 and 2.3-6).

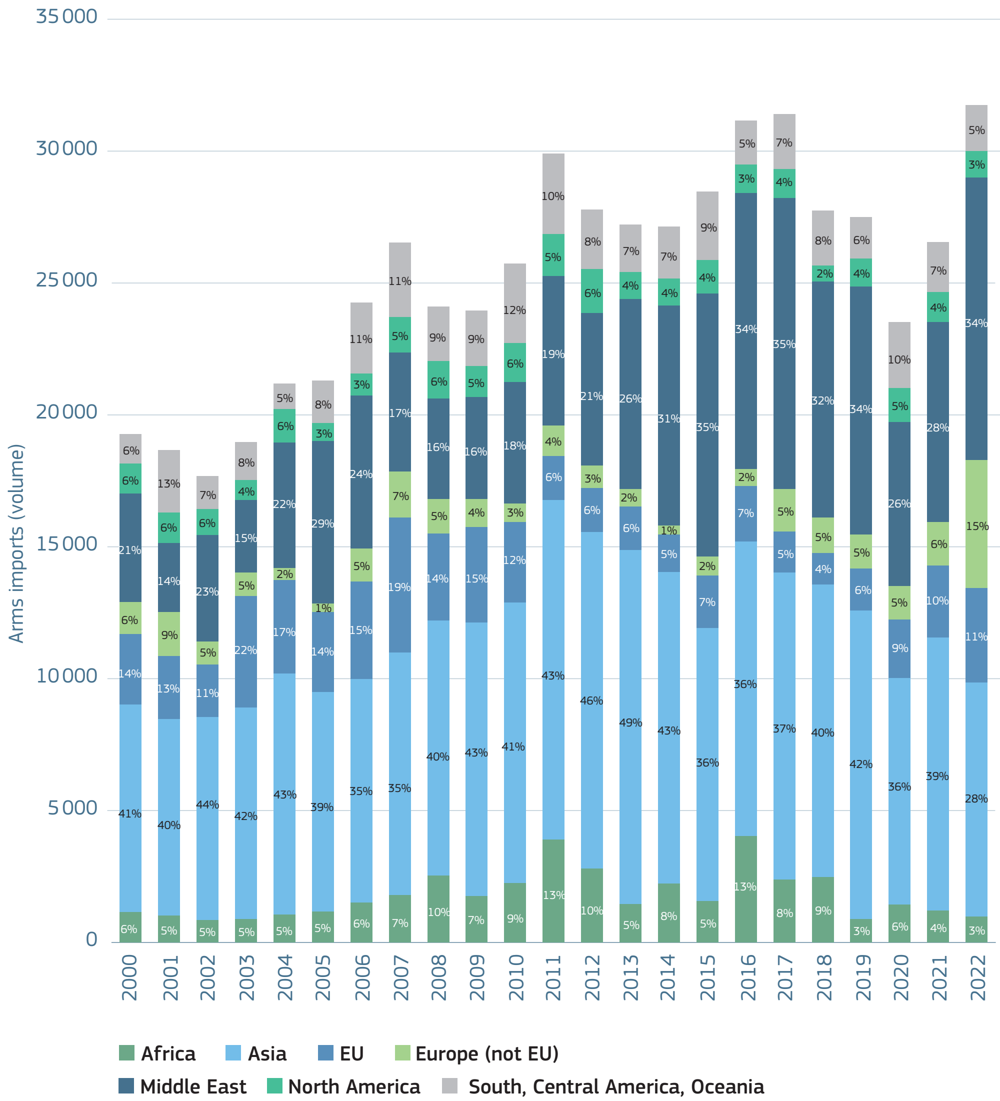
Figure 2.3-5 Arms exporters trend



Science, research and innovation performance of the EU 2024

Source: DG Research and innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit's own elaboration based on the SIPRI Arms Transfers Database.

Figure 2.3-6 Arms importers trend



Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit's own elaboration based on the SIPRI Arms Transfers Database.

Note: Imports classified as being from NATO and the United Nations are excluded.

2. Investments in dual-use technologies and socioeconomic returns

The concept of dual-use technology encompasses a wide range of products, services and technologies that are inherently versatile, serving both civilian and military purposes. This versatility is evident in fields like advanced materials, nano-electronics, biotechnology, advance robotics and autonomous systems, and information and communication technologies (ICT). These areas demonstrate the fluidity with which research, technology development and manufacturing can pivot between civil and defence applications (European Commission, 2014).

Dual-use technology represents a crucial frontier with profound implications for the future of innovation and national security. Transfer in the context of dual-use refers to the adaptation of technologies developed in one sector for use in the other. This adaptability not only fosters innovation but also promotes economic efficiency by maximising the utility of technological investments. As the divide between civil and military applications continues to diminish, dual-use technologies are poised to become a cornerstone of socioeconomic growth, driving both industrial innovation and national defence capabilities (European Commission, 2021a,b).

The North Atlantic Treaty Organization (NATO) aligns with this perspective, as evidenced by its comprehensive strategy[3] aimed at promoting the development and adoption of dual-use technologies. This strategy involves collaborative efforts with public and private sector entities, academic institutions, venture capital and civil society. Together, they work towards the development and adoption of new technologies, while also establishing international principles for their responsible use. This collaborative approach is key to maintaining NATO's technological superiority, which is crucial for the defence and security of its member countries (Reding, D.F. and Eaton, J., 2020; NATO, 2021). To effectively support these objectives and foster the advancement of (dual-use) emerging and disruptive technologies, NATO leaders agreed at the 2021 Brussels Summit to establish a NATO Innovation Fund. The EUR 1 billion venture capital fund will provide strategic investments in start-ups developing dual-use emerging and disruptive technologies in areas that are critical to allied security. The fund will be the world's first multi-sovereign venture capital fund.[4] In 2023, NATO doubled down on dual-use technologies with the launch of DIANA (Defence Innovation Accelerator for the North Atlantic). DIANA is an acceleration programme and test centre network to bring start-ups together with operational end users, scientists and system integrators to advance compelling deep tech with dual-use solutions for the Alliance.

3 Exemplified by the recent NATO 2022 Strategic Concept and NATO 2030 Agenda.

4 NATO – Topic: Emerging and disruptive technologies.

The history of dual-use technologies is a fascinating journey from government-led innovation to a more private-sector-driven landscape of today. During the height of the Cold War, the US Federal Government was the primary conductor of technological R&D. This era witnessed the birth of numerous technologies initially intended for military use but later found critical applications in civilian life (Ruttan, 2006; Mazzucato, 2013). Some of the most groundbreaking innovations include:

- ***The internet***: initially developed as ARPANET by the US Department of Defence, the internet revolutionised global communication and information sharing.
- ***Global Positioning System (GPS)***: initially developed by the US Department of Defence for military navigation, GPS is now integral to civilian navigation systems, location-based services, and various applications across transportation, agriculture and emergency response services.
- ***Radar technology***: originally developed for military use during World War II, radar technology is now used in civilian air traffic control, meteorology and even automotive safety systems.
- ***Scanning machines***: technologies like MRI and CT scanners have roots in technologies developed for military purposes, significantly advancing medical diagnostics.
- ***Semiconductors and integrated circuits***: much of the early development in semiconductor technology was driven by defence needs. These components are now fundamental to almost all modern electronics, including computers, smartphones and household appliances.
- ***Material sciences***: many advanced materials, such as Kevlar and carbon fibre, were initially developed for military applications but are now widely used in civilian industries, including automotive, aerospace and sports equipment.
- ***Space exploration technologies***: rocket technology, initially developed for military purposes, played a crucial role in launching humans to the moon and continues to be vital in space exploration.

Government defence R&D can foster the speed of innovation and ultimately promote productivity growth (Moretti, E et al., 2023). However, as highlighted by different case studies of US post-war military R&D, the effectiveness of defence R&D hinges on the scale of investment and the programme structure. Large-scale programmes are influential in guiding firms' strategic decisions and allow for exploring a variety of technological avenues. The programme structure is also key, particularly in the IT sector, where US military R&D has historically encouraged new firms and facilitated inter-firm knowledge sharing, thus nurturing a competitive industry. These factors – investment scale, technological diversity and a structure promoting innovation – are essential for delivering the economic and civilian advantages of defence R&D (Hall et al., 2010).

In today's tech-driven landscape, dominated by major corporations, military transformation increasingly focuses on the challenge of quickly adopting and adapting civilian-developed technologies for military use. This shift signifies a major change in the dynamics of defence innovation. Rather than originating primarily from military-driven R&D, many cutting-edge technologies are now emerging from the commercial sector and are being repurposed for defence uses. Such increased synergies between civilian innovation and military application are fostering a new era of defence capabilities, where the rapid pace of technological change in the private sector directly informs and enhances military effectiveness and strategic superiority (Reding and Eaton, 2020).

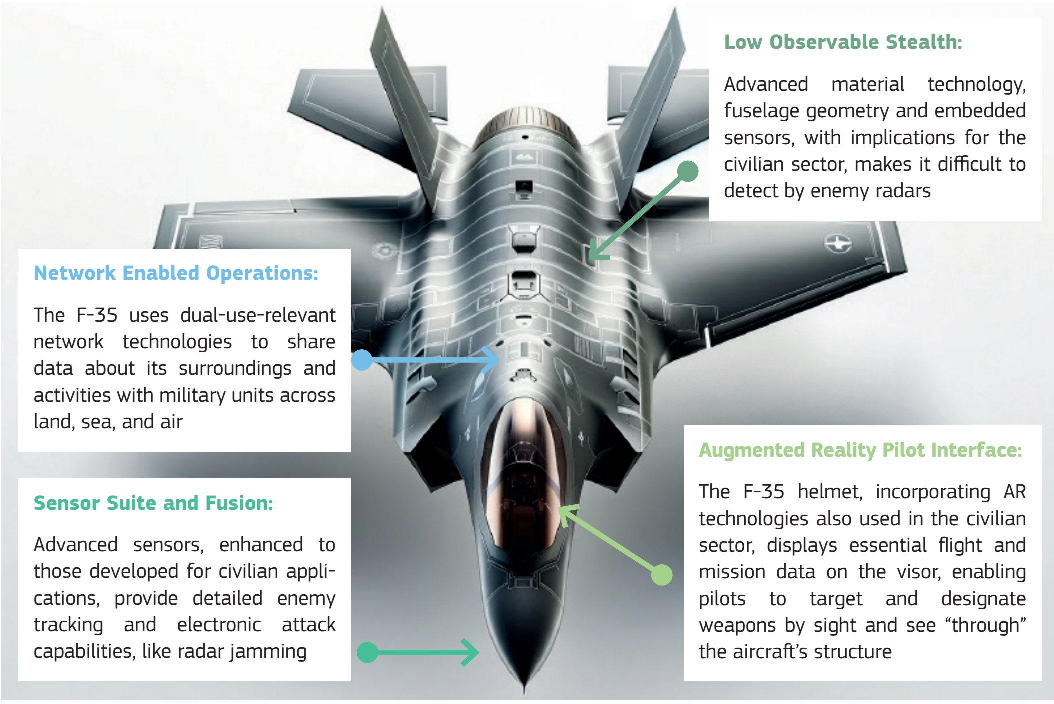
The F-35 Lightning II fighter jet stands as a premier example of collaborative, public-private-led innovation, encapsulating an array of dual-use technologies. Developed by Lockheed Martin, following their victory over Boeing in a competitive bid for a US Government contract, it has been described by the US Air Force's Chief of Staff as a 'computer that happens to fly'. The jet exemplifies cutting-edge technology in aerial warfare, encompassing electronic warfare technologies, advance sensor and network systems, stealth capabilities and augmented reality interface. Its development is a global endeavour, involving suppliers and companies from the US, Australia, Belgium, Denmark, Germany, Italy, Japan, the Netherlands, Norway, Switzerland and the UK. These international collaborators engage in the production, technological development and sustainment of what is considered the most technologically advanced fighter jet in the world. Significantly, over 25 % of the F-35's components are manufactured in Europe by European firms, reflecting its global production footprint and the extensive international cooperation driving its innovation.[5]

Advanced features that endow the NATO fighter jet with airspace superiority stem from the integration of many dual-use technologies, such as advanced materials, network systems, sensors, communication and digital technologies. Figure 2.3-7 shows how such technologies have impacted the jet performance capabilities, as well as how its production fosters their diffusion and expertise across NATO member industries.

The European Defence Agency (EDA) has identified a set of technologies, most of them dual-use, that will define the future of military capabilities. Such technologies are the Internet of Things (IoT), biotechnology and human enhancement, advance materials and manufacturing, hypersonic weapon systems, new space technologies, quantum technologies, blockchain, robotic and autonomous systems, and AI (see Figure 2.3-8).

5 Lockheed Martin website.

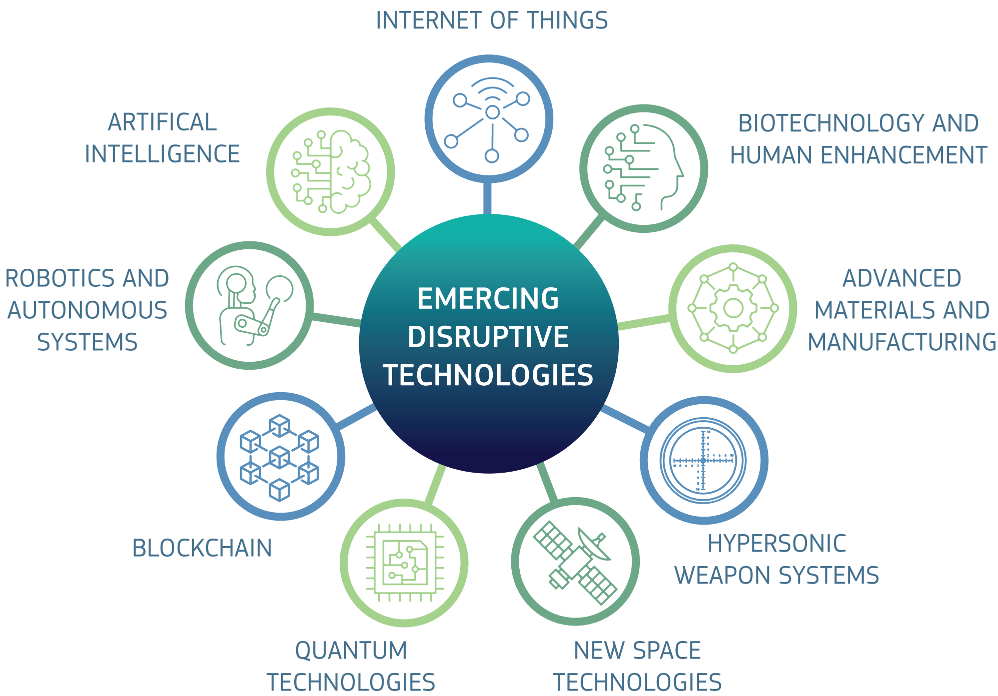
Figure 2.3-7 **F-35 Lightning II features derived from dual-use technologies**



Science, research and innovation performance of the EU 2024
Source: Human-AI generated. Author’s own elaboration based on Lockheed Martin specifics.

Figure 2.3-9 depicts the military applications of the EDA’s emerging disruptive technologies with high dual-use potential. Interestingly, all these technologies are part of the technological classes with higher complexity and long-run economic return (see Chapter 2.2). IoT enhances situational awareness and streamlines operations but raises cybersecurity and interoperability concerns. AI automates decisions and improves autonomy in systems, requiring strict validation and ethical considerations. Biotechnology advances health monitoring and training for soldiers, with long-term prospects for brain-computer interfaces but mindful of ethical implications. Robotics increase operational efficiency and safety, necessitating careful integration regarding autonomy and ethics. Advanced materials offer new protective and stealth capabilities, with additive manufacturing poised to transform logistics. Quantum technologies promise superior computing and secure communications, though integration with existing systems remains a challenge.

Figure 2.3-8 Technologies for future military capabilities



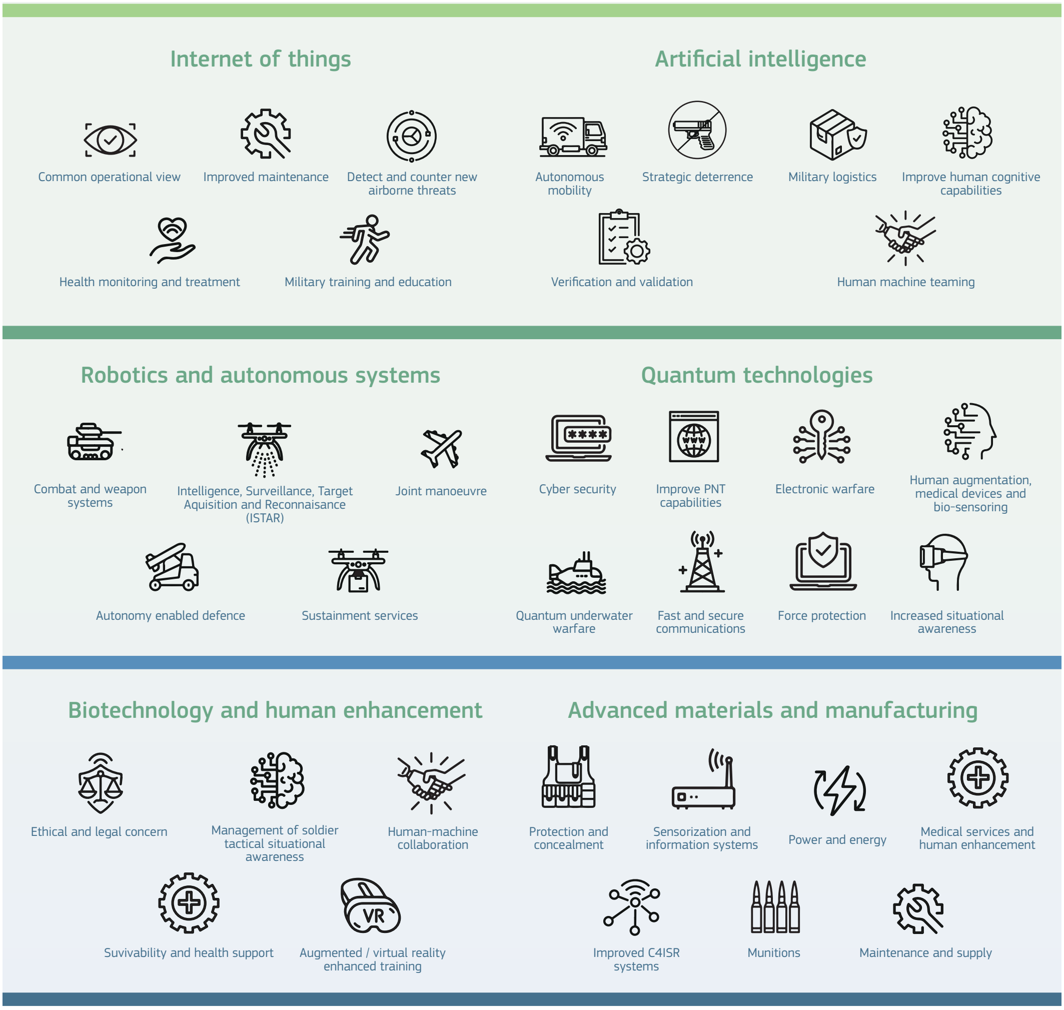
Source: European Defence Agency, (2023).

The main part of European Commission's EU framework programme for R&I does not allow for the financing of defence R&D projects.[6] Under the current EU Framework Programme for R&I (Horizon Europe), activities carried out under the European Defence Fund should have an exclusive focus on defence research and development, while activities carried out under the 'civilian' specific programme and the EIT should have an exclusive focus on civil applications. However, if research is intended to develop or improve dual-use technologies or goods, it can qualify for funding, as long as the goods or technologies are intended for civil applications (EC, 2021c). This opens up support for dual-use technologies, particularly at a lower level of technology readiness levels (TRL), where the spillovers and overlaps between civilian and military interests are larger.

Indeed, Horizon 2020 has already funded many projects with dual-use technology potential. Hristova et al. (2019) studied potential dual-use projects within Horizon 2020. A total of 349 projects related to security and defence research were identified, with ICT and cybersecurity as the main areas, of which almost 90% (311 projects) have dual-use potential, meaning that the civil application outputs could be used for defence purposes. Figure 10 shows the number of Horizon 2020-funded projects related to security and defence classified by a thematic focus.

6 Under the current EU Framework Programme for R&I (Horizon Europe), activities carried out under the European Defence Fund should have an exclusive focus on defence research and development, while activities carried out under the 'civilian' specific programme and the EIT should have an exclusive focus on civil applications.

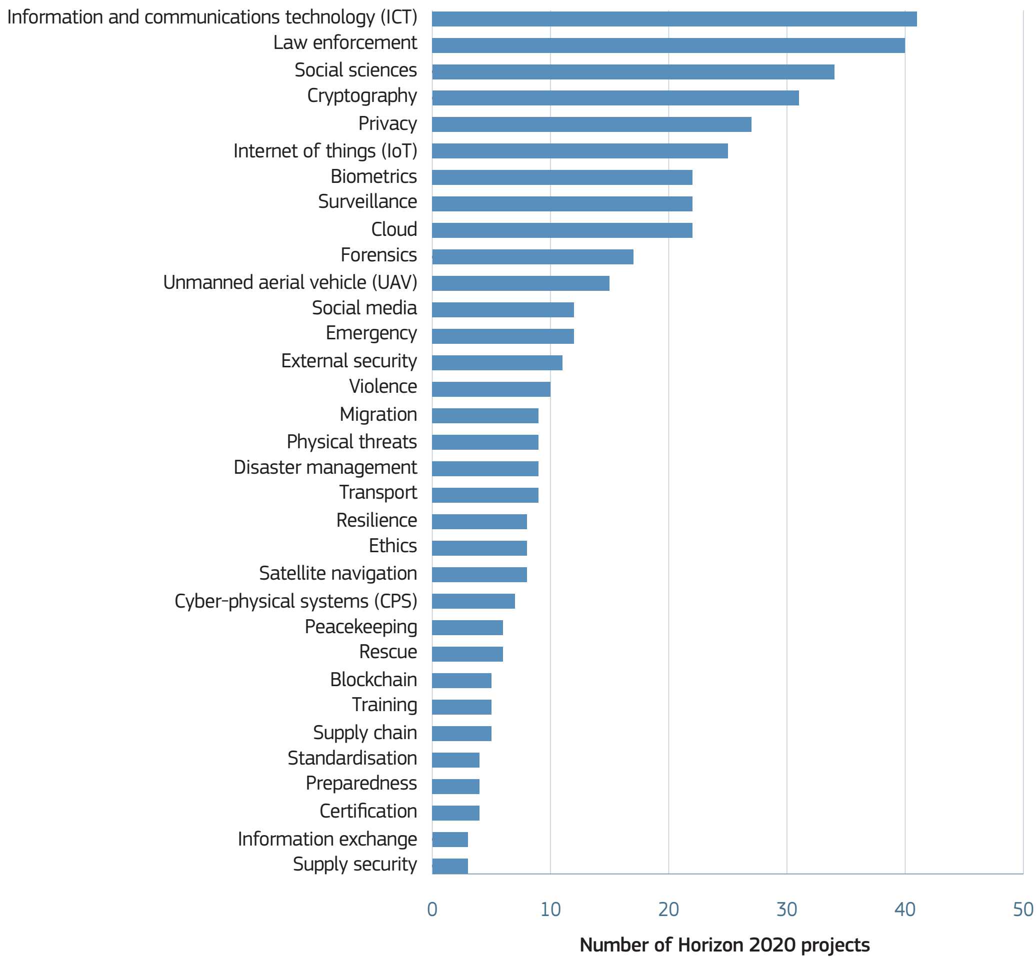
Figure 2.3-9 Defence applications of emerging disruptive dual-use technologies



Science, research and innovation performance of the EU 2024

Source: European Defence Agency, (2023).

Figure 2.3-10 Horizon 2020 projects related to security and defence, by topic

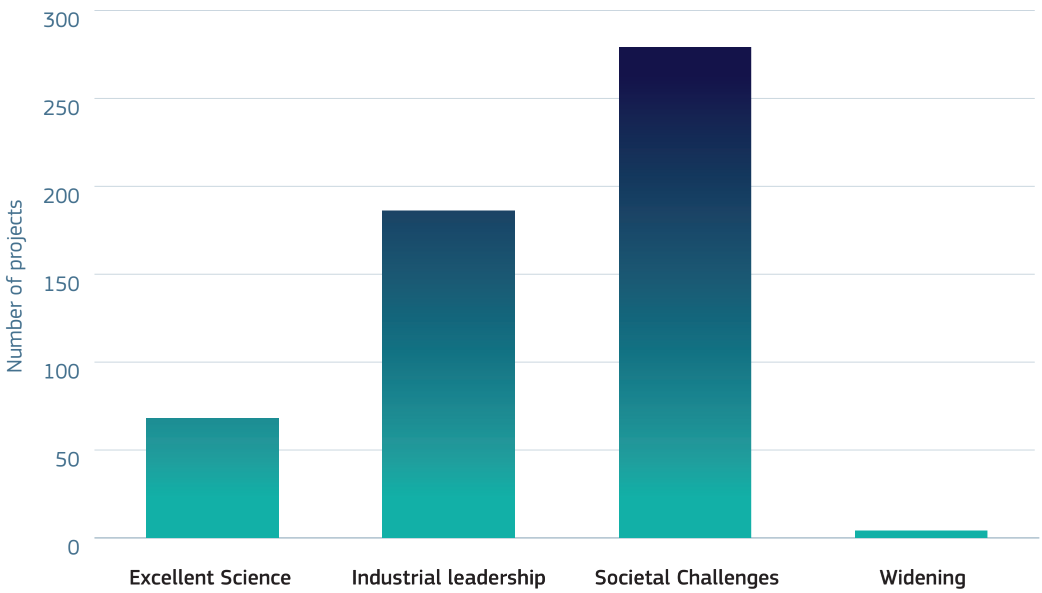


Science, research and innovation performance of the EU 2024

Source: Hristova et al. (2019).

Only 60% of the Horizon 2020 projects related to security were financed through the security-dedicated programme section; the remainder received funding through other channels. Figure 2.3-11 depicts the distribution of such security-related projects across all of Horizon 2020's programme parts, showing the broad spectrum of objectives of modern dual-use technologies.

Figure 2.3-11 **Horizon 2020 projects related to security and defence by programme pillars**



Source: Hristova et al. (2019).

3. Defence R&I and current global challenges

Russia's unprovoked invasion of Ukraine has sharply underscored the critical importance of defence R&D and technological superiority, not only for deterring aggressions but also in safeguarding peace and prosperity, and upholding the fundamental principles of freedom and democracy.

The convergence of climate change, demographic shifts, political polarisation and geopolitical changes presents unprecedented challenges to global security. Innovation in defence and security technologies is not only essential but imperative to address these multifaceted threats and ensure stability and peace in an increasingly complex world (European Defence Agency, 2023).

Such dimensions can be clustered as follows:

- **Climate change is accelerating, presenting long-term security risks**, such as rising sea levels, extreme weather events and natural disasters. These environmental shifts necessitate enhancements in military capabilities for operating in increasingly hazardous conditions. Furthermore, climate-induced scarcities of resources like water, agricultural land and essential raw materials will likely heighten global competition and could be exploited by adversaries to destabilise economies and incite unrest.

- **Significant demographic transitions**, including aging populations, declining middle-class influence and uncontrolled migration, pose security challenges. These changes are poised to increase the need for responsive and adaptable security strategies. First, ageing necessitates a re-evaluation of national defence and public safety strategies to cater to an older population's unique needs. Second, a weakened middle class could heighten the risk of radicalisation and civil unrest, requiring nuanced and socially sensitive security approaches. Third, uncontrolled migration, fuelled by conflict, economic disparities and climate change, places significant strain on host countries' infrastructure, social services and communal harmony. This leads to humanitarian issues and increased tensions, necessitating effective border control and migrant integration strategies.

- **The COVID-19 pandemic** has highlighted the vulnerability of densely populated, interconnected societies to contagious diseases. The potential use of health threats as weapons by state and non-state actors adds a new dimension to national and global security, necessitating innovative defence solutions.

- **The increasing use of tactics like social engineering, misinformation** and unconventional warfare broadens the spectrum of security threats. Innovations in defence technology are essential to address these challenges, including cyber threats, hybrid warfare tactics and new biological weapons. Future conflicts are likely to see an increase in the misuse of social media and information control to destabilise societies. Defence strategies must therefore evolve to counter misinformation and social polarisation effectively.

- **In the context of the evolving international landscape**, characterised by a multipolar order, EU defence capabilities are important for global stability. Regions such as Africa, the Middle East and the Asia-Pacific can be pivotal with a higher degree of volatility. Consequently, this necessitates the consideration and development of adaptive and proactive defence strategies that are responsive to the changing geopolitical environment.

4. EU policies related to defence and security R&D

The unprovoked invasion of Ukraine by Russia, along with the ongoing conflict, has sharply focused attention on the EU's security and defence needs, placing them at the forefront of the EU's policy discussions. Even before the full-scale invasion, the EU had begun to broaden its role in these areas. This expansion was initially triggered by Russia's annexation of Crimea, as well as increasing threats in terrorism, cybersecurity and security. In response, the EU launched several policy initiatives aimed at strengthening its defence capabilities. These initiatives included the Permanent Structured Cooperation (PESCO), the establishment of the Directorate-General for Defence Industry and Space (DG DEFIS) and the creation of the European Defence Fund (EDF). These efforts build upon the foundational pillars of EU defence and security policy, specifically the common foreign and security policy (CFSP) and the common security and defence policy (CSDP), detailed in Box 2.3-2.

The Strategic Compass for Security and Defence, approved by the European Council in 2022, prioritises boosting investments in technology, research and disruptive innovations to strengthen the EU's security and defence by 2030. Its main goal is to ensure the EU's decisive action in crises and the protection of its citizens. Key focuses include enhancing technological and industrial sovereignty, investing in innovative and dual-use technologies, and building capacities to defend EU interests. Additionally, it emphasises the importance of international cooperation, particularly with NATO, which is essential for collective defence among EU Member States.

During the last couple of years, the NATO-EU cooperation has been strengthened and deepened, with NATO and the EU currently having 23 Member States in common. The renewed cooperation materialised with the Third Joint Declaration on EU-NATO Cooperation at the beginning of 2023, which states that the organisations want to further strengthen the cooperation in existing areas, and expand and deepen the cooperation in other areas to address the growing geostrategic competition and emerging and disruptive technologies, among other things. On this aspect, a relevant difference to highlight is that the EU does not have a permanent military command structure along the lines of NATO.

The EU's key instrument to support competitive and collaborative defence projects throughout the entire cycle of R&D is the European Defence Fund (EDF). Its focus is on strengthening the European defence capability and industrial landscape, encouraging SME participation and emphasising breakthrough innovations. With the EDF, for the first time, the EU budget is used to fund multinational defence projects, with the fund as a key initiative under the CSDP. The EDF has an initial budget of almost EUR 8 billion for 2021-2027, with EUR 2.7 billion to fund collaborative defence research and EUR 5.3 billion to fund collaborative capability development projects, with national contributions.[7] Recently, a Defence Innovation Hub within the European Defence Agency was announced to develop cutting-edge innovations for defence (European Council, 2022).

7 European Defence Fund, https://defence-industry-space.ec.europa.eu/system/files/2022-05/Factsheet%20-%20European%20Defence%20Fund.pdf

Box 2.3-2 EU's main pillars of security and defence policy

Common foreign and security policy[8]

The common foreign and security policy (CFSP) is the EU's joint foreign and security policy. The CFSP was first established in 1993 under the Maastricht Treaty. It has been progressively reinforced by subsequent treaties, particularly the Treaty of Lisbon. The main objectives of the CFSP are to preserve peace; reinforce international security; and promote international cooperation, democracy, the rule of law and respect for human rights and fundamental freedoms. The European External Action Service (EEAS) is the diplomatic service of the EU and in charge of the CFSP (and the CSDP). For the 2021-2027 period the actions are financed via the CSDP programme with a total budget of EUR 2.68 billion. Actions include civilian stabilisation missions, the Kosovo Specialist Chamber and the European Security and Defence College.

Common security and defence policy[9]

The common security and defence policy (CSDP) is the part of the CFSP that relates to defence and crisis management. An important part of the CSDP is the possibility of setting up military or civilian missions to preserve peace, prevent conflict and strengthen international security.

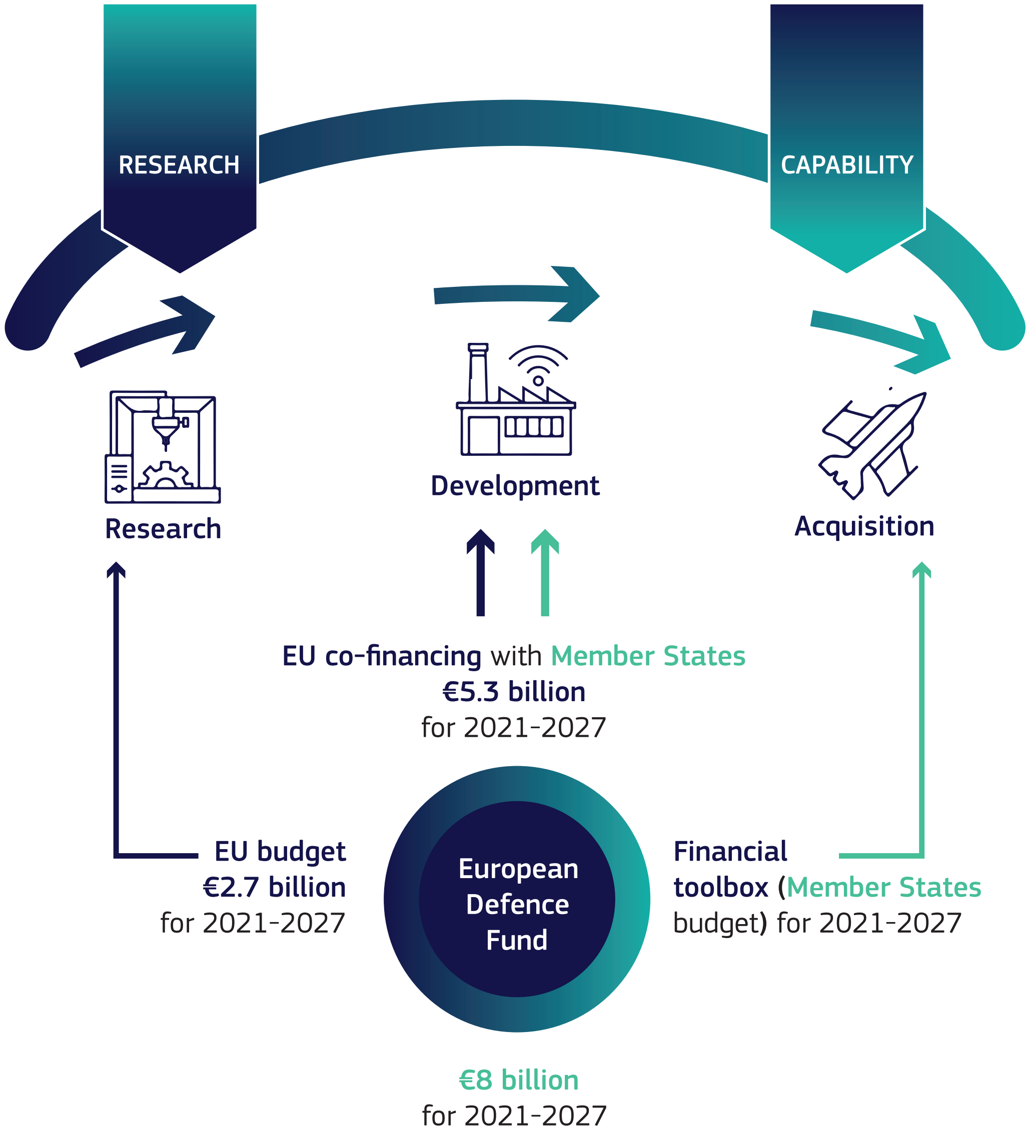
PESCO

To strengthen cooperation on defence matters by EU Member States, the Treaty of Lisbon provides a provision to set up permanent structured cooperation between Member States (PESCO). Currently, 26 of the 27 EU Member States' armed forces are cooperating on a few projects via PESCO (with the exception of Malta) to pursue structural integration. The European Defence Agency was established in 2004 to facilitate the integration of EU Member States within the CSDP.

8 Common foreign and security policy (europa.eu).

9 The Diplomatic Service of the European Union | EEAS (europa.eu).

Figure 2.3-12 Overview and budget distribution of the European Defence Fund



Source: European Defence Fund.

Horizon Europe, particularly the European Innovation Council and the clusters *Civil Security for Society* and *Digital, Industry and Space* in Pillar 2 on 'Global challenges and European industrial competitiveness', can play a role in the EU's R&D initiatives focused on defence and security (Hristova et al., 2019). Additionally, other programmes like the European Regional Development Fund, the Connecting Europe Facility, the Digital Europe Programme, InvestEU and the Space Programme are also crucial. They contribute not only through direct funding but also through related policies that facilitate the integration, adoption and dissemination of new technologies and innovations, as reported by the European Commission in 2022.

In 2022, the European Investment Bank (EIB) launched the Strategic European Security Initiative (SESI), allocating up to EUR 6 billion for projects on dual-use research and civilian security infrastructures. SESI aims to tackle security challenges across cybersecurity, the New Space industry, AI and quantum technologies, building on its predecessor's foundation. By June 2023, in response to changing geopolitical dynamics and increased funding needs, the EIB's Board of Directors raised its security and defence financing cap to EUR 8 billion. This expansion not only increases funding but also broadens support within the sector, maintaining a strict policy against financing weapons, ammunition and core military or police infrastructure.

To prepare a coherent EU future defence and security landscape, jointly investing in cutting-edge defence technologies is essential. At the same time, to maximize the potential of dual-use technologies, it's crucial to enhance collaboration and bridge the gap between civilian and defence research, technology, and innovation (RTD&I) across the EU and its member states.

The recently published European Commission's White Paper reignited a comprehensive discussion on enhancing support for research and development in technologies with dual-use potential (European Commission, 2024). It proposes three strategic directions for future advancement: (1) extending and building upon the existing framework, (2) diversifying the focus beyond solely civilian applications in specific segments of the programme succeeding Horizon Europe, and (3) establishing a specialised entity devoted exclusively to R&D in dual-use technology areas.

Launched in March 2024, the European Defence Industrial Strategy (EDIS) by the European Commission and EU High Representative aims to enhance the EU defence industry's efficiency and competitiveness. The strategy focuses on decreasing the industry's fragmentation and lowering weapon imports. Key goals include boosting intra-EU defence trade to 35% of the EU defence market by 2030, ensuring that 50% of defence procurement is sourced from within the EU, and promoting that at least 40% of defence equipment purchases are made collaboratively by EU countries (European Commission, 2024).

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CHAPTER 2.4

RESILIENCE AND PREPAREDNESS

Key questions

- What types of risks are currently affecting Europe and its partners?
- How has Europe drawn lessons from past crises to effectively tackle current challenges?
- How does R&I contribute to enhancing resilience and preparedness, and what potential future scenarios does it enable us to anticipate?

Highlights

- Geopolitical risk has significantly intensified over recent years. Europe also faces the compounding effects of the aftermath of recent crises, where risks are complex and interconnected.
- The EU and other economies in Europe have demonstrated considerable resilience, adapting swiftly to acute challenges and new realities. Indeed, 70% of EU citizens believe it is a place of stability in uncertain times.
- Private R&D investments have proven more stable compared to capital expenditure, remaining resilient in the face of economic crises. This trend suggests that businesses perceive R&I as a strategic tool for mitigating the impacts of crises. R&I is therefore a vital component for ensuring economic resilience and fostering long-term competitiveness.
- R&D can play a key role in addressing global risks. Global Risks Perception Survey (GRPS) respondents find that R&D has a strong potential for ensuring risk reduction and preparedness, especially for infectious diseases (81%), adverse outcomes of frontier technologies (58%) and extreme weather events (56%).

Policy insights

- In navigating present challenges, it is essential to maintain a forward-looking, strategic perspective. Embracing the power of R&I can help spearhead a new European drive towards a more adaptive, resilient and innovative future.
- Strengthening global research networks that link researchers, institutions, and industries across the world can help achieve preparedness through R&I.

The recent crises have ushered in a new era of 'polycrisis' or 'permacrisis', whose key feature is a high level of uncertainty. The COVID-19 pandemic, the Russian invasion of Ukraine, the energy crisis and its broader inflationary consequences, and the increased frequency of climate-related extreme events cannot be seen as one-off crises but rather a manifestation of a new reality to which policies need to adapt. Dealing with 'black swan' or 'grey rhino' events requires building resilience, strengthening adaptability, and promoting anticipation.[1]

Faced with higher degrees of uncertainty, policymaking may require a comprehensive rethink in order to ensure continued progress towards long term objectives across a range of scenarios, while also addressing the short-term impact of crises. Recently, the Expert group on the economic and societal impact of research and innovation (ESIR) stressed the need for policies to avoid falling into the trap of 'short-termism', and instead adopt a "protect, prepare and transform" approach[2]: 'protect' through a timely and coordinated response in cases of emergency; 'prepare' for a broad set of future risks, through coordination, foresight, community involvement and re-skilling; 'transform' the economy and society towards a competitive, green and fair Europe.

1. How Europe shows resilience in uncertain times

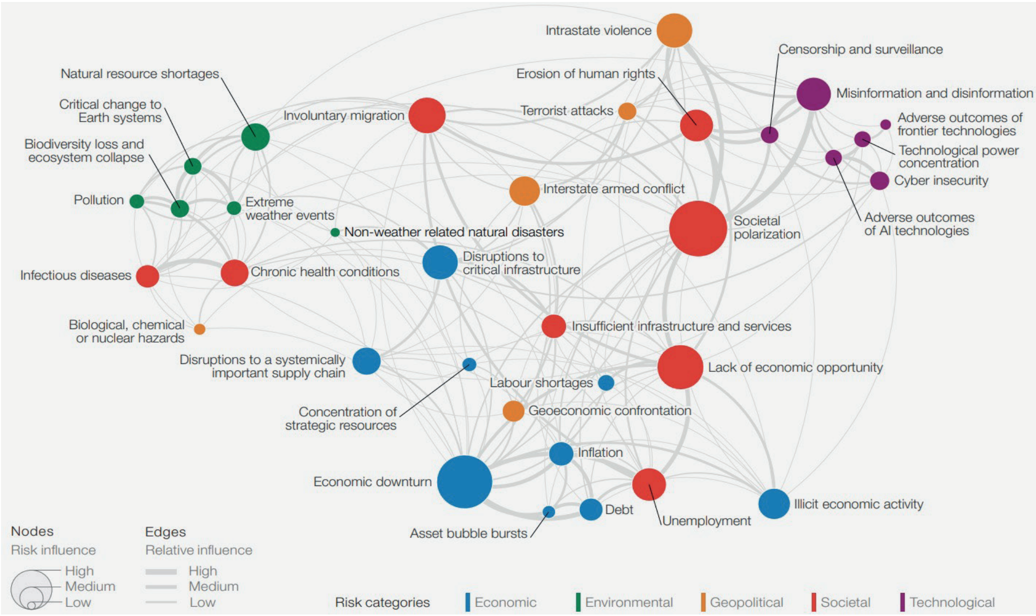
Europe continues to be exposed to the cumulative effects of recent crises. Despite a heightened awareness of the interconnectedness of global risks, disorderly dynamics have contributed to a very high level of perceived uncertainty in Europe (World Economic Forum, 2023). The world in 2024 is facing major crises related to climate and conflict, and, within the global risk landscape (Figure 2.4-1; World Economic Forum, 2024), the most interconnected risks are societal polarisation and economic downturn. While the scientific understanding of the distinct threats giving rise to these crises is extensive, a more general awareness of the causal links among these factors remains limited (Homer-Dixon et al., 2022). Hence, while individual crises may have been contained thus far, the simultaneous shocks to Europe's economic, environmental, geopolitical, societal, and technological systems have created unprecedented challenges, whose aggregate effects on the risk landscape are multifaceted and complex (World Economic Forum, 2023).

Conflicts outside of Europe perpetuate an ongoing state of uncertainty in the region. The Gaza conflict and its spillover potential, coupled with the Russian invasion of Ukraine, poses an acute challenge for the EU.

1 Black swan and grey rhino events were also key concepts in the previous edition of this report, the Science, research and innovation performance of the EU 2022 report (European Commission, 2022). Black swan events are very rare, unpredictable and have very high impact, while grey rhino events can be observed from afar, but are difficult to stop once in motion.

2 European Commission (2023), Research and innovation to thrive in the poly-crisis age, Directorate-General for Research and Innovation, Publications Office of the European Union, Luxembourg https://data.europa.eu/doi/10.2777/92915.

Figure 2.4-1 Global risks landscape

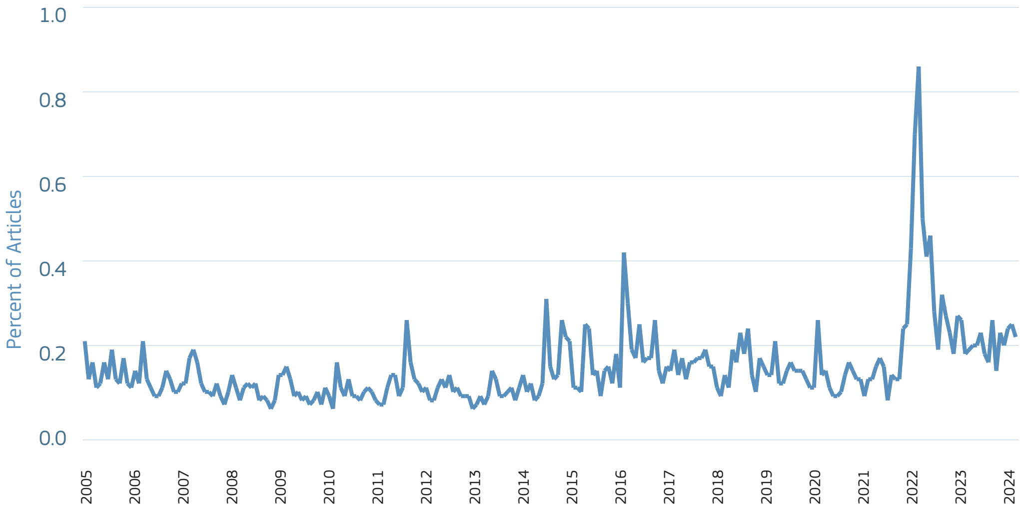


Source: World Economic Forum, Global Risks Report 2024

These events may result in a renewed spike in energy prices causing another economic slump and tighter financial conditions, as well as increased geopolitical risks — most dramatically illustrated by the two ongoing wars in Europe's neighbourhood. Further risks relate to the persistence of inflation, vulnerabilities in trade relations and energy markets, as well as risks associated with climate change and the degradation of natural capital (European Commission, 2024a). Broader global factors, such as geopolitical tensions in the US and China, technological shifts, and environmental threats, add complexity to the 2024 outlook (Economist Intelligence Unit, 2024). Measuring the extent of geopolitical risk associated with these events is a challenge as there is a shortage of robust indicators to quantify these phenomena (Caldara et al. 2022). The geopolitical risk (GPR) index is an attempt to provide such a quantitative measure (Figure 2.4-2).[3] Although the index is measured based on English-speaking newspapers (US, UK, Canada), it provides a proxy for the level of uncertainty in other regions, such as the EU and specific countries.

3 The Geopolitical Risk (GPR) index utilised in this study is constructed from a sample comprising approximately 25 million news articles sourced from the print editions of prominent English-language newspapers spanning the period from 1900 to the present day. This dataset comprises approximately 30,000 and 10,000 articles per month in the recent and historical samples, respectively. The index is derived by quantifying, on a monthly basis, the proportion of articles discussing adverse geopolitical events and associated threats. For the recent GPR index, starting from 1985, automated text searches were conducted on the electronic archives of ten newspapers: the Chicago Tribune, the Daily Telegraph, the Financial Times, the Globe and Mail, the Guardian, the Los Angeles Times, the New York Times, USA Today, the Wall Street Journal, and the Washington Post. The selection of six newspapers from the US, three from the United Kingdom, and one from Canada was deliberate, aiming to encompass events of global significance. The index computation involves tallying the monthly count of articles addressing escalating geopolitical risks, divided by the total number of articles published.

Figure 2.4-2 Average of Geopolitical Risk Indexes for available EU countries over the last 20 years



Science, research and innovation performance of the EU 2024

Source: World Bank Group (2024), Global Economic Prospects, January 2024.

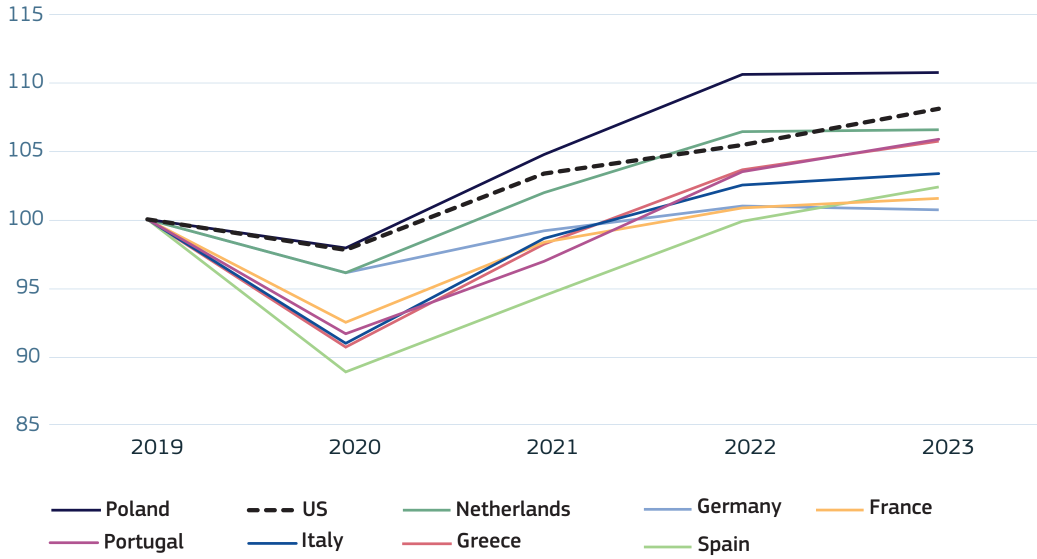
Note: Unweighted average of Country-Specific GPR Indexes for available EU countries (Belgium, Germany, Denmark, Spain, Finland, France, Hungary, Italy, Netherlands, Poland, Portugal, Sweden). Labels for years are positioned on the 1st of January.

A key foundation to containing the risk of a 'polycrisis' is a thorough understanding of the interconnectedness of individual crises. For example, viewing the war in Ukraine as an isolated interstate conflict, ignores the strong effect it has on the instability of the global food supply chain, which has been a major driver of the increase in the cost of living. As the short-term ramifications of the invasion on e.g. agricultural production compounded longer-term trends of more volatile crop yields, policymaking needs to be aware of the interrelations between cyclical developments and structural trends. The perceived uncertainty resulting from these crises is further amplified by the spread of misinformation and societal polarisation.

As a recent illustration of countries' capacity to deal with a crisis, the economic impact of COVID-19 shows strong heterogeneity among member states (Figure 2.4-3). While some member states, such as Spain, Greece, and Italy, were among the hardest-hit economies, others, such as Ireland, Denmark, and Poland have been able to maintain positive growth rates. This regional disparity might be related to varying effectiveness and stringency in governmental reactions, market dynamics, and the inherent resilience of different economies. The sectoral composition of economies was also an important determinant, as tourism- and services-intensive countries were particularly hard-hit. However, many affected EU economies — including those most affected by the pandemic — have leveraged the crisis to drive digitalisation and foster new opportunities for start-ups, particularly in the online trade sector (European Commission, 2022). Tourist-dependent economies were also able to rebound (Figure 2.4-3), driven by a recovery in tourism activity in 2023 as well as a shift towards spending by residents on services like restaurants (International Monetary

Fund, 2023). Moreover, the positive perception of the EU among its citizens underscores this resilience. The 100th Standard Eurobarometer survey shows that seven EU citizens out of 10 (70 %) believe that the EU is a place of stability in a troubled world. This is the case for the majority of respondents in all Member States (European Commission, 2023d).

Figure 2.4-3 Economic impact of COVID-19 (real GDP levels, 2019 = 100)



Science, research and innovation performance of the EU 2024

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

Utilising the Economic Resilience Index (ERI)[4] **to examine the individual dimensions of resilience also reveals conceptual differences among the EU countries**. In Table 2.4-1, which shows the composite score[5] of the 25 measured EU countries in the six resilience dimensions of the ERI, it becomes evident that the ability of EU economies to absorb, recover from, and adapt to shocks reveal great disparities. Notably, of the 25 EU countries, some of Europe's largest economies such as France, Spain and Italy are positioned in the middle or lower ranks. While Scandinavian countries such as Sweden, Denmark, and Finland score highly across all categories, France and Italy struggle to produce comparable composite scores, due to low scores across categories such as Education & Skills, Financial Resilience, and Social Progress & Cohesion.

4 ZOE, the Institute for Future-Fit Economies has developed the Economic Resilience Index (ERI), which assesses the future-preparedness of economies to thrive when faced with continuous crises. The index considers in total 27 different indicators, divided into six dimensions: Economic Independence, Education & Skills, Financial Resilience, Governance, Production Capacity and Social Progress & Cohesion (See Hafele et al., 2023).

5 The composite score can be understood as both the average of all 27 indicators as well as the average of the six dimensions. Each country score can take on a value between zero and one ranging from worst to best performance.

Table 2.4-1 Economic Resilience Index ranking

Rank	Country	Composite score	Economic independence	Education & Skills	Financial Resilience	Governance	Production Capacity	Social Progress & Cohesion
1	Sweden	0.78	0.74	0.9	0.73	0.79	0.78	0.75
2	Denmark	0.74	0.59	0.88	0.63	0.9	0.62	0.81
3	Finland	0.74	0.6	0.92	0.59	0.9	0.69	0.75
4	Netherlands	0.67	0.49	0.86	0.77	0.79	0.6	0.61
5	Germany	0.65	0.75	0.6	0.7	0.75	0.62	0.53
6	Austria	0.64	0.41	0.67	0.69	0.82	0.61	0.7
7	Ireland	0.63	0.42	0.76	0.66	0.62	0.74	0.66
8	Belgium	0.63	0.46	0.62	0.67	0.75	0.63	0.69
9	Estonia	0.62	0.56	0.72	0.6	0.61	0.78	0.53
10	Slovenia	0.62	0.66	0.58	0.73	0.44	0.45	0.76
11	France	0.56	0.72	0.49	0.55	0.69	0.56	0.38
12	Czechia	0.51	0.44	0.48	0.71	0.37	0.7	0.43
13	Cyprus	0.49	0.35	0.47	0.35	0.43	0.61	0.66
14	Hungary	0.45	0.44	0.25	0.61	0.29	0.56	0.53
15	Lithuania	0.41	0.42	0.3	0.47	0.4	0.42	0.45
16	Latvia	0.41	0.45	0.32	0.46	0.3	0.45	0.46
17	Croatia	0.4	0.46	0.22	0.47	0.23	0.46	0.52
18	Spain	0.39	0.53	0.45	0.34	0.44	0.16	0.4
19	Italy	0.39	0.67	0.34	0.3	0.38	0.28	0.34
20	Slovakia	0.38	0.44	0.19	0.67	0.29	0.24	0.42
21	Portugal	0.35	0.17	0.55	0.24	0.37	0.37	0.39
22	Poland	0.32	0.34	0.39	0.34	0.22	0.32	0.31
23	Bulgaria	0.29	0.53	0.1	0.32	0.12	0.41	0.22
24	Greece	0.28	0.47	0.2	0.09	0.35	0.25	0.28
25	Romania	0.25	0.56	0.06	0.22	0.07	0.4	0.17

Science, research and innovation performance of the EU 2024

Source: ZOE Institute for Future-fit Economies, The Economic Resilience Index 2023 (Hafele et al., 2023).

Furthermore, there doesn't seem to be a strong link between economic resilience and CO_2 emissions per capita, suggesting that, in the search for the formula of economic resilience, factors beyond GDP and elevated levels of material consumption play a role (Hafele et al., 2023).

The Recovery and Resilience Facility (RRF) continues to be a powerful instrument in the face of uncertainty. Since its start of operation in 2021 it has become a central element in the EU's efforts to enhance the economic resilience of its Member States (European Commission, 2023c) while supporting the economic recovery and twin transitions. An amount of EUR 233 billion have already been disbursed under the RRF and around 75 % of the milestones and targets planned to be achieved by end 2023 either have already been assessed by the Commission as satisfactorily fulfilled or are reported as completed by Member States. Furthermore, through their RRPs, Member States have made significant progress in addressing the CSRs issued in the context of the European Semester (European Commission, 2024b).

2. R&I for resilience and preparedness

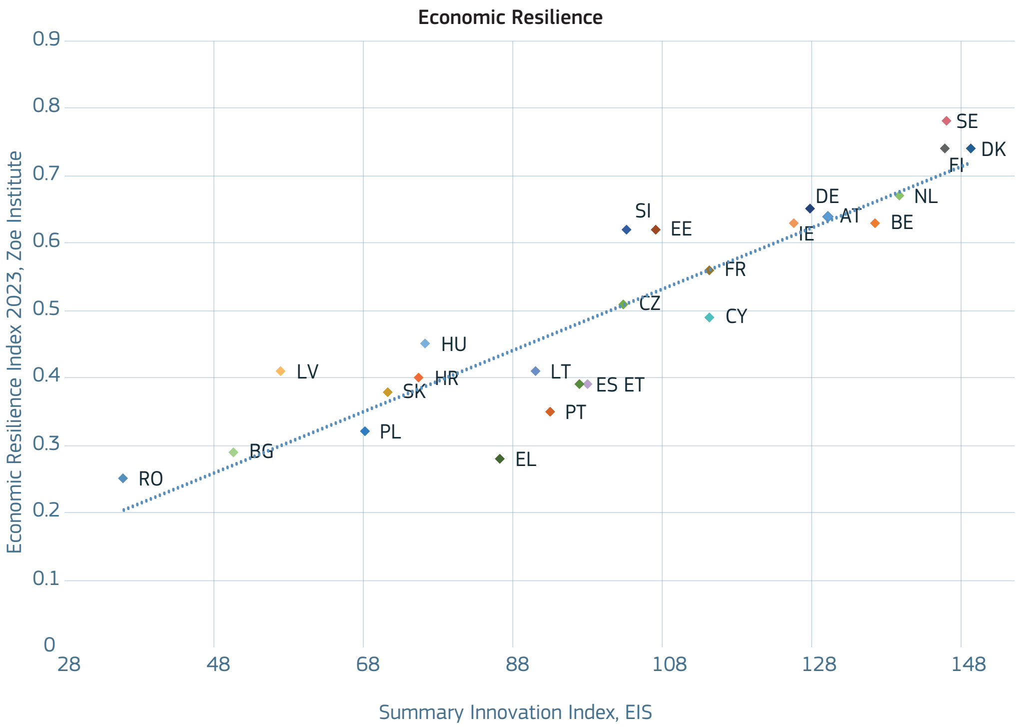
The recent geopolitical shifts stress the critical role of R&I in strengthening the resilience of the EU economy. Promoting technological sovereignty in strategic sectors can contribute to economic security and shield the EU from geopolitical fallout. New technologies can also provide ways of substituting necessary critical materials, e.g. for the green transition, where important dependencies on single countries exist. Furthermore, innovation fosters the economic resilience of firms and innovative firms contribute significantly to the dynamism of the EU economy. Novel products and services not only stimulate competitive markets, but also foster resilience by diversifying economic activities and reducing dependency on traditional industries. Innovation also helps firms cushion the negative impact of economic disturbances. Figure 2.4-4 illustrates the high degree of correlation between innovation and resilience. [6]

R&I enhances preparedness for unavoidable environmental hazards like extreme weather events and non-weather-related natural disasters. The escalating impacts of climate change, combined with strained planetary boundaries, are introducing unprecedented disruptions to key societal systems – be they water supply, energy, health, transport, or product markets. R&I can help accelerate the de-risking of key systems and infrastructures, scale up civil protection capabilities and facilitate the medium- to long-term financial and economic transition for climate change adaptation and/or mitigation. Additionally, it can help improve resource efficiency and promote the development of circular economies. For instance, technological breakthroughs in nuclear fusion power generation would represent a game-changer; it would offer clean energy, accelerating the shift towards achieving net zero, while concurrently mitigating the risk of pollution and contamination.

6 For resilience, the aforementioned Economic Resilience Index (ERI) was used, and for innovation, the Summary Innovation Index. The Summary Innovation Index measures the performance of the EU national innovation systems and is referenced from the the annual European Innovation Scoreboard (EIS), which provides a comparative assessment of the research and innovation performance of EU Member States and selected third countries, and the relative strengths and weaknesses of their research and innovation systems (European Commission, 2023a).

The power of R&I to strengthen preparedness is further acknowledged by GRPS respondents, who emphasise the pivotal role of research and development in addressing health, environmental, and technological risks (Figure 2.4-5) (World Economic Forum, 2024).

Figure 2.4-4 **Innovation capacity and economic resilience**

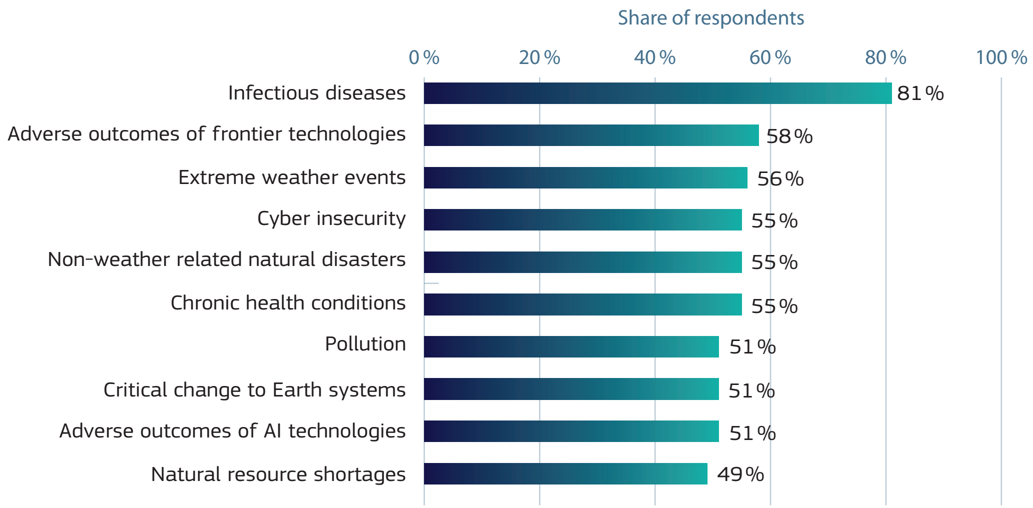


Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on the European Innovation Scoreboard (European Commission, 2023a) and the Economic Resilience Index (Hafele et al., 2023).

Private R&D investments have proven more stable compared to capital expenditure, remaining resilient in the face of economic crises. This trend was observed both during the Global Financial Crisis of 2009 and the COVID pandemic (Figure 2.4-6), suggesting that businesses perceive R&D as a strategic tool for mitigating the impact of crises; it may also reflect a preference of companies — typically larger ones — to not jeopardise their future growth potential by shelving R&D projects. Unlike

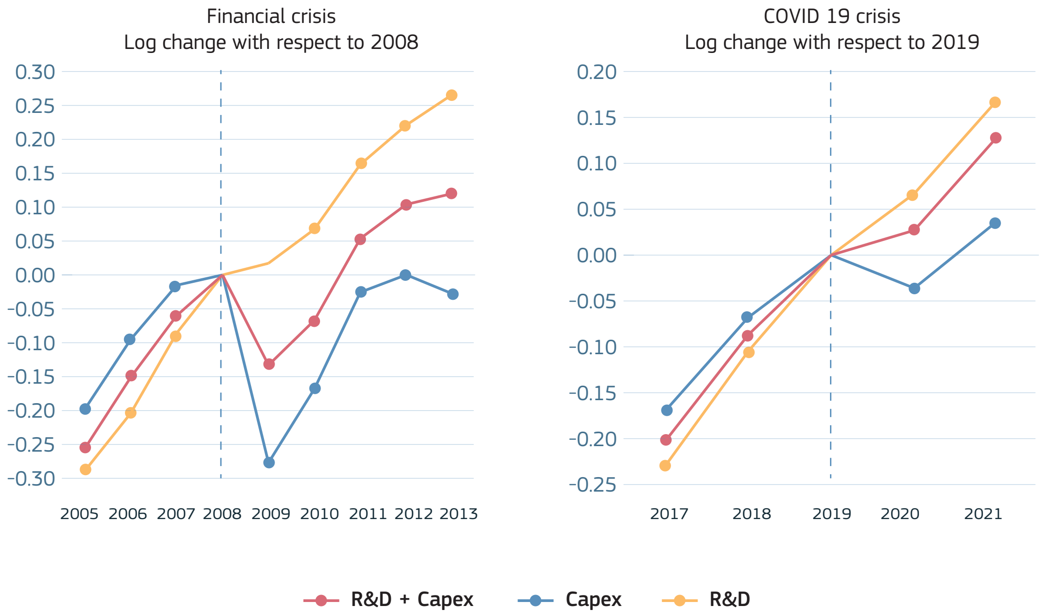
Figure 2.4-5 Top global risks addressed by research and development



Science, research and innovation performance of the EU 2024
Source: World Economic Forum Global Risks Perception Survey 2023-2024.
Note: To the question “Which approach(es) do you expect to have the most potential for driving action on risk reduction and preparedness over the next 10 years?” related to each item, respondents could select up to three responses from nine options, including research and development.

more traditional forms of capital investment, R&D tends to be seen as a vital component for ensuring economic resilience and fostering long-term competitiveness. This resilience of R&D investment could be attributed to the recognition that innovation and technological advancement are key drivers of sustainable growth, especially in turbulent times (European Commission, 2023b).

Figure 2.4-6 R&D and Capex before and after major crises, by investment type



Science, research and innovation performance of the EU 2024

Source: The 2023 EU Industrial R&D Investment Scoreboard, European Commission (2023b).

Notes: The graph plots coefficients of year indicator variables from regressions controlling for net sales and firm fixed effects. All values are in 2015 PPP USD, except for net sales, which are in 2015 USD. Values x100 are % changes compared to the base year (2008 or 2019).

In the wake of the 2009 financial crisis and the COVID-19 pandemic, R&D investment by leading firms has significantly contributed to their economic recovery. A positive correlation between R&D spending and key performance indicators can be seen, for instance concerning turnover growth and productivity gains (European Commission, 2023b).

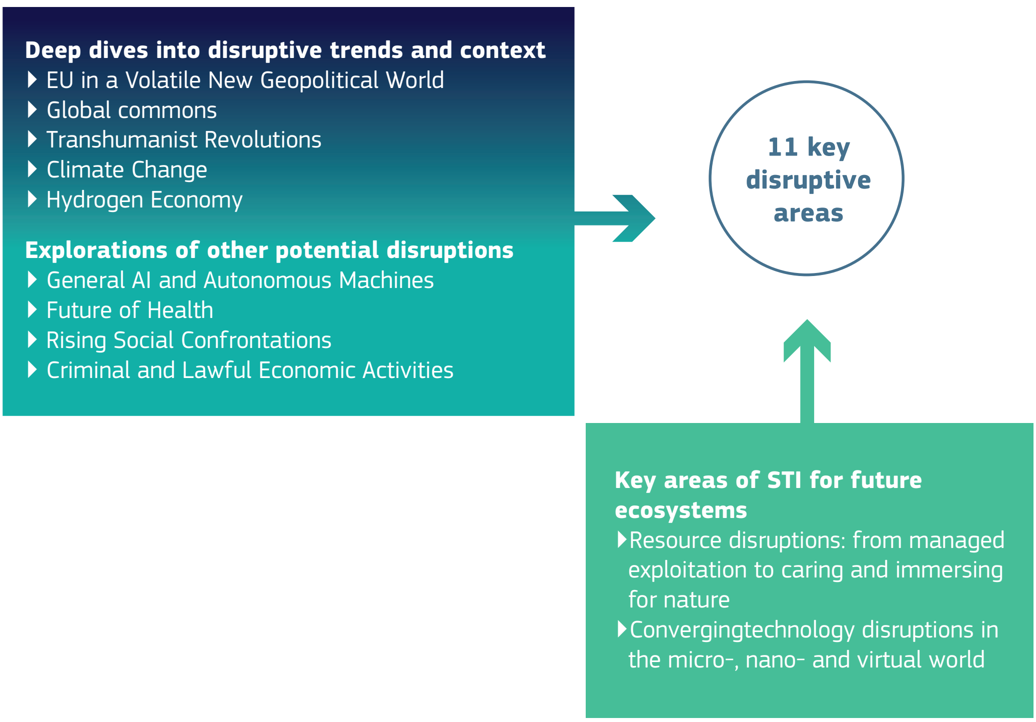
However, this trend is not uniform across regions. For instance, American and Chinese firms saw a more rapid recovery in their R&D and capital expenditures than their European counterparts. This regional disparity might be influenced by varying governmental policies, market dynamics, and the inherent resilience of different economies.

3. What the future may bring for Europe and the role of R&I

Europe's green transition efforts aim to achieve carbon neutrality and significantly increase sustainability in the coming decades. A successful transformation can be defined as limiting the existential risks of climate change and the environmental crisis. It will also be crucial in strengthening the EU's strategic autonomy and economic security, and in reinforcing Europe's long-term competitiveness, social model and resilience. However, to succeed, Europe will have to address and overcome some key social and economic challenges. This will require making difficult political choices and confronting acute trade-offs that are expected to have an immense impact on our societies and economies.

Foresight studies on European R&I have identified 11 key disruptive areas over a time perspective of 20–30 years (Box 2.4-1 and Figure 2.4-7). These potential key areas of change are divided into three subsections: 1. World of global tensions; 2. Technology and society; and 3. R&I for future ecosystems.

Figure 2.4-7 Exploring potential futures in key areas of change



Source: European Commission, Directorate-General for Research and Innovation (2023): Horizon Europe Strategic Plan 2025-2027 Analysis

Box 2.4-1: R&I foresight in the EU

In today's rapidly changing world, the use of strategic foresight exercises is more relevant than ever. Foresight enables groups, leaders and organisations to prepare, shape, anticipate future trends and increase the robustness of policy to future risks. It is becoming an increasingly important tool contributing to better-informed political processes, governance and decisions based on the best possible understanding of drivers of future trends and resulting scenarios. The interest in foresight has grown at both national and European level as part of a response to current - and potentially forthcoming - challenges. Harnessing the power of collective intelligence through strategic knowledge exchange and dialogue is key to reach a new shared understanding of the bigger picture of tomorrow. By distilling new insights across different horizons, and encouraging development of collaborative and anticipatory strategies, collective foresight can inform decisions affecting the future in a structured way. One particular strength of collective foresight comes from engaging with a wide spectrum of relevant actors, such as experts and stakeholders. Appreciating diversity and embracing differences can lead to a more critical understanding of the whole system and to more dependable solutions.

The metaphor of the Fox and Hedgehog[7] bridges the gap between risk and foresight. The Fox and the Hedgehog represent two distinct views of the world (Berlin, 1953). The Hedgehog has a single and broad understanding of the world and uses it as a framework for interpretation. In contrast, the Fox, knows many small details and uses a broad range of experiences and knowledge to navigate complexity. Both strategies have advantages when it comes to making decisions under uncertainty (Logan et al., 2024). However, in foresight, the Hedgehog's possibly rigid and singular approach might be surpassed by the Fox's flexible and varied way of thinking (Tetlock, 2005). In R&I policy, integrating the flexibility and openness of the Fox with the strategic focus and coherence of the Hedgehog can help to promote R&I and address challenges with wisdom and agility.

The EU has played an important role in driving foresight for decades, working hand-in-hand with Member States and associated countries. The European Commission's growing efforts to embed strategic foresight into EU policymaking was reflected in the appointment of Executive Vice-President Maroš Šefčovič in 2019 as the first ever member of the College of Commissioners in charge of strategic foresight. Since then, the EU has developed a set of initiatives and processes across its institutions, including the publication of annual strategic foresight reports as well as a Future

7 The metaphor stems from poet Isaiah Berlin, who elaborates on a fragment by the Greek poet Archilochus, who wrote 'The fox knows many things, but the hedgehog knows one big thing.' It should be noted that this metaphor can be interpreted in different ways.

of Europe (Ministers of Future) conference, signalling its attention to resilience, the EU's ability to act in the world — the decline of which has been a core concern for the EU since the Gonzales report of 2010 — and the EU's pursuit of the twin green and digital transition in line with the EU's sustainability objectives.

The EU has also increased the use of foresight exercises and activities in various policy areas. R&I foresight under the Horizon Europe programme has aimed at exploring future trends, opportunities and challenges in key disruptive sectors. Its objective has been to inform political processes by using both possible and plausible predictions of future developments. In the context of more traditional R&I policy, where there is considerable uncertainty about both the directions and the expectations of R&I, key questions concern the significance of the objectives, the extent to which there are trade-offs between them, and the extent to which such trade-offs are determined by current structures and technologies.

The Russian invasion of Ukraine dramatically underscored that the world system is at a crossroads and may evolve towards a new bipolar or multipolar configuration, with important implications for global governance and its institutions. The EU's relationship with the US and the extent to which the US engages with global issues and in global governance institutions are critical for the EU's future. The EU's foresight activities have explored scenarios with high and low levels of global engagement from the United States, and high and low levels of global agency for the EU.[8] These scenarios put the EU's pursuit of digital leadership into context, as the US is the de facto leader in many such technologies, followed by China. The EU faces a critical investment gap – in which, for example, the annual R&D budget of Amazon is more than four times that of the annual budget for the EU framework programme for research and innovation.

The indispensable digital transition of the EU economy and society could be framed as a battle for leadership, or as participation in a global digital and sustainable transition. The choice of strategic framing affects the chosen approach to key policy directions for R&I, especially as regards international cooperation and global regulatory frameworks. Framing the EU as – at least partly – a follower, rather than a global leader, could make the strategic orientations more conducive to global collaborations for global challenges.

8 European Commission (2023e), Reference foresight scenarios: Scenarios on the global standing of the EU in 2040, Publications Office of the European Union, Luxembourg. https://publications.jrc.ec.europa.eu/repository/handle/JRC132943

The internal coherence of the EU is significant for its ability to act in the global scene, and promoting this internal coherence is a very important function of R&I policy. In addition, recognising the significance of the relationship with the US has important implications for the extent and forms of R&I cooperation with the US. Recognising the importance of R&D for defence and security raises important concerns about the security of the R&I process, as well as the possibility of the leakage of strategically important capabilities through R&I projects.

Building resilience cannot happen when operating in silos. Instead, a collaborative approach that fosters global scientific communication is crucial (Homer-Dixon et al., 2022). As the past has shown, enhancing global research networks that link researchers, institutions, and industries across the world, is fundamental for achieving preparedness through R&I, as it leads to effective communication and facilitates resource-sharing. For instance, during COVID-19, co-funding from the public sector was essential for healthcare companies to rapidly deploy an effective vaccine (World Economic Forum, 2024). Implementing science, technology and innovation (STI) policies can play a pivotal role by providing incentives to strengthen and expand networks in 'normal times', along with continued support for investments in critical infrastructures and technologies (OECD, 2022).

Leveraging the potential of R&I requires a multifaced perspective. When tackling current challenges, maintaining a forward-looking perspective is crucial and can lead to more durable and beneficial outcomes. Committing to groundbreaking initiatives typically represents a prolonged and somewhat risky investment (World Economic Forum, 2024). Furthermore, investing in R&I can also result in possibilities for future growth and adaptability (Atanassov et al., 2019), thereby strengthening resilience and preparedness. The effectiveness of this dual approach also becomes evident when looking at COVID-19. While nations rebuild health systems post-COVID-19, emphasis lies also on addressing workforce challenges and strengthening resilience against future pandemics. In the same vein, investing in R&I emerges as one practical and strategic approach for a more adaptive future (OECD, 2024).

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CHAPTER 3

SCIENTIFIC KNOWLEDGE PRODUCTION

CHAPTER 3.1

SCIENTIFIC PERFORMANCE

Key questions

- How is the EU positioned compared to its global competitors in terms of scientific output and excellence[1]? Have there been any significant changes over the past 20 years, including within the EU?
- How is the EU contributing to science related to the Societal Grand Challenges (SGCs) and Sustainable Development Goals (SDGs)?
- What are the trends in terms of gender representation in science?

Highlights

- The EU has a solid research base and is ranked second globally in terms of scientific output. It is stronger in less technological domains, whereas the US leads in health sciences, and China is more focused on natural and applied sciences.
- China is the global leader, not only in terms of volume of scientific publications but also in terms of share of the top 10 % of most cited publications. Recently, its share of the top 1% of most cited publications overtook that of the US.
- The number and quality of publications vary significantly across EU countries. Southern and eastern European countries continue to make positive progress in terms of scientific output and quality.
- The EU produces a large number of international co-publications, which corresponds to 56 % of all its publications. However, these collaborations are mainly within Europe.
- The EU is ahead of its global competitors in terms of sharing of scientific output. In 2020, around 80 % of all EU peer-reviewed publications were available through at least one open access pathway.
- Women's participation in scientific publications continues to increase both globally and at EU level, but there is still work to be done to address gender disparities, particularly in STEM fields.

1 Scientific excellence is measured by the share of the top 1 % and top 10 % of the most cited publications. In addition, qualitative judgments are important for improving the assessment of research systems. Ongoing projects to reform research assessment aim to support interdisciplinarity, mobility between sectors, and promote young talents and new players in Europe. See the Coalition for Advancing Research Assessment (CoARA), https://coara.eu/

Policy insights

- To stay competitive in the global knowledge economy and address key challenges, the EU needs to enhance the efficiency and efficacy of its public research systems. This will entail boosting investment in R&I while implementing strategic policy reforms to retain and attract top-tier scientists.

- To succeed in the green and digital transitions, Europe must boost its research system in more technological fields, in which it is lagging behind.

- EU programmes that foster cooperation and mobility are essential to narrow current knowledge gaps between EU countries and ensure that the EU plays an active role in global science.

- Given the rapid adoption of AI across various domains, including science, the EU must support the European research community in responsible use of generative AI, respecting the principles of research integrity.

- Targeted actions, such as those implemented in the framework programme for R&I, are necessary to address persistent gender gaps and inequalities, particularly in STEM fields.

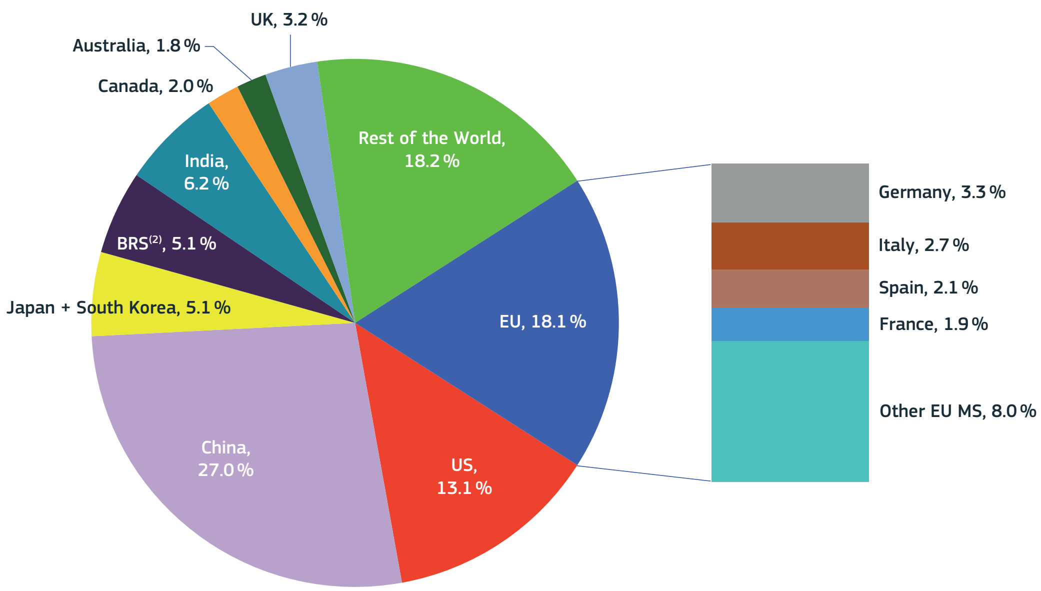
1. Scientific output

In 2022, the EU ranked second globally and contributed to 18.1 % of all scientific publications, amounting to approximately 650 000 publications[2]. China led the way in terms of scientific output, with a share of 27 %, equivalent to 965 000 publications. The US followed in third place with a 13.1 % share, corresponding to approximately 470 000 publications. Other significant contributors included India, with a 6.2 % share; Brazil, Russia and South Africa, with a joint share of 5.1 %; Japan and South Korea, which together also accounted for 5.1 %; the UK with 3.2 %; Canada with 2 %; and Australia with 1.8 % (Figure 3.1-1).

Within the EU, the largest countries are the most significant contributors to scientific publications. Germany led the way in 2022, accounting for 3.3 % of the total number of publications, followed by Italy with 2.7 %, Spain with 2.1 % and France with 1.9 % (Figure 3.1-1).

In 2022, the EU, the US and China together accounted for nearly 60 % of global scientific output. China has seen a significant increase in its contribution, which rose from 5.7 % in 2000 to 27 % in 2022. It surpassed the US in 2016 and the EU in 2019 to become the leading contributor to scientific publications (Figure 3.1-2). From

Figure 3.1-1 Global share of scientific publications(1), 2022



Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on Science-Metrix using data from Scopus (Elsevier).

Note: (1) Fractional counting was used to assign publications to countries/aggregates. (2) BRS: Brazil, Russia and South Africa.

2 The computation of bibliometric indicators for several countries included in this analysis is limited by the coverage of the Scopus database. Specifically, Scopus' coverage of Asian countries, including China, Japan and South Korea, is known to be limited. Consequently, the publication counts reported for these countries may be underestimates (source: Science-Metrix).

2000 to 2022, the annual number of scientific publications worldwide more than tripled, growing from 1.1 million to 3.6 million.

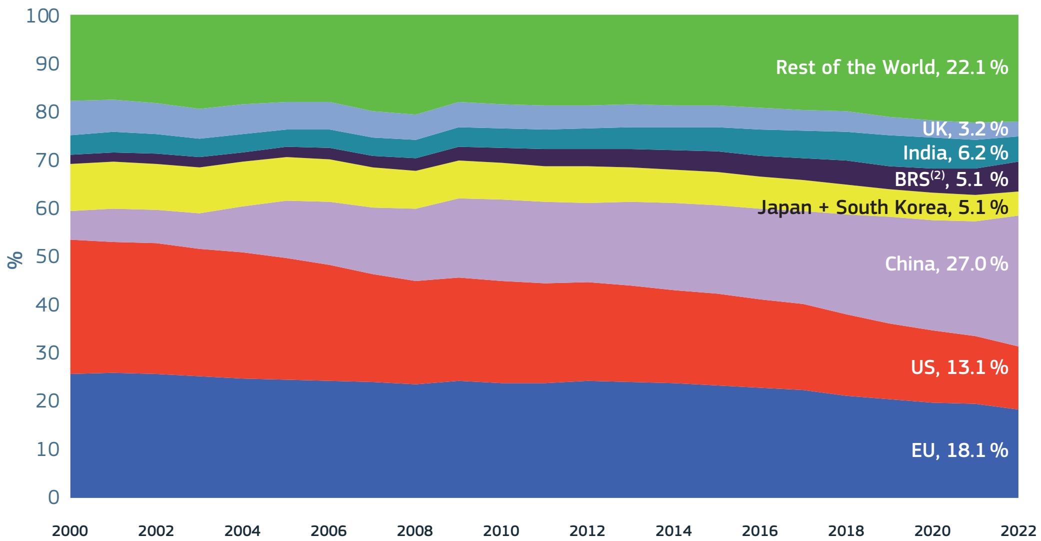
China's emergence as a leading scientific nation can be attributed to several factors, such as an increase in international collaborations and scientific mobility, as well as increased funding. Mobility is supported by programmes designed to encourage scientists working abroad to return to China. These returning scientists have contributed significantly to China's most impactful publications and have engaged extensively in international collaborations (Cao et al., 2020). International mobility has been proven to be key for knowledge diffusion and can positively affect research productivity by improving matching of researchers with research environments. Publications in China were also encouraged through a monetary reward system designed to incentivise publication in high-impact journals. The impact of this system has already been captured in most large-scale bibliographic databases, such as Scopus. However, the implementation of the system had unintended consequences, including an increase in production of fraudulent papers, plagiarism and inappropriate citation practices, resulting in its discontinuation in 2020 (Mallapaty, 2020). Finally, government priorities and increased funding through the National Natural Science Foundation of China have significantly contributed to China's scientific advances (Ahlers and Christmann-Budian, 2023).

Over the past two decades, the EU's contribution to global scientific publications has declined, dropping from 25.5% in 2000 to 18.1% in 2022, despite sustained growth in absolute terms. Although this represents a significant decrease, it is less pronounced than that observed in the US, where the share of global scientific publications fell from 27.9% to 13.1% during the same period (Figure 3.1-2). This disparity in rates of decline can partly be attributed to the EU's specialisation in less technological fields, in which it faces less competition from emerging scientific powerhouses. However, changes in the EU's specialisations in some technological fields were also observed. For example, the EU's specialisation index (SI) fell less than that of the US in applied sciences (especially in enabling and strategic technologies), which experienced strong growth overall in emerging countries (the EU SI went from 0.83 in 2000 to 0.76 in 2022; that of the US from 0.89 to 0.57). In engineering, the EU SI actually increased (from 0.75 to 0.79), whereas that of the US fell from 1.01 to 0.64. Similar declining trends were noted for Japan and the UK. In contrast, Brazil, Russia and South Africa saw a slight increase in their share of global scientific publications.

From 2020 to 2022, the number of publications grew by more than 30% in China. In the EU, it increased by only 2.6%, and in the US, it decreased by 2.3%. These trends have contributed to widening the gap in terms of shares of scientific publications.

Publications within the EU remain concentrated, with four countries (Germany, Italy, Spain and France) producing 56% of EU publications in 2022 (Figure 3.1-3). This concentration is partly due to the large size of these countries. However, a noticeable shift has occurred, as larger countries like France and Germany have seen their publication shares decrease, while some countries, especially in southern and eastern Europe, have become increasingly active in scientific publication production. Notably, Spain, Italy, Portugal and Poland show the highest increases in publication share among EU Member States. In relative terms, the most significant increases in shares of EU publications between 2000 and 2022 are observed in Luxembourg (+843%), Malta (+618%) and Cyprus (+452%). To account for the disparities in country size, Box 1 on research productivity provides an alternative analysis. By normalising the number of publications against other indicators, it takes account of the different sizes of R&I systems across the EU.

Figure 3.1-2 Global share of scientific publications(1), 2000-2022

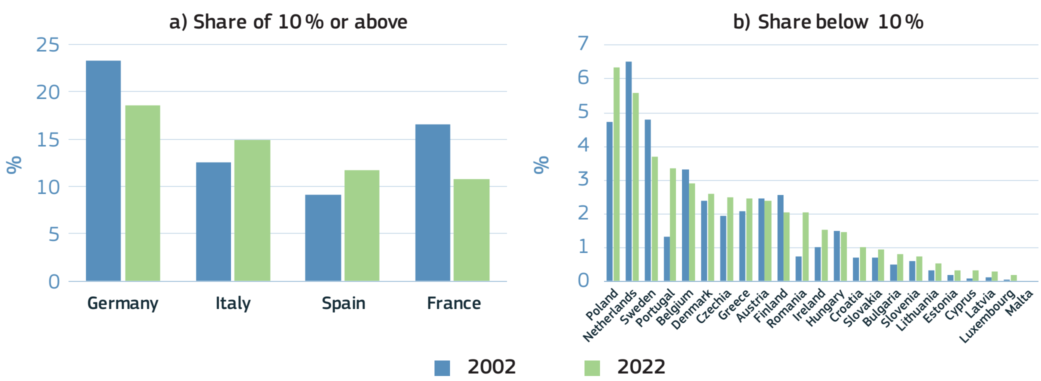


Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on Science-Metrix using data from Scopus (Elsevier).

Note: (1) Fractional counting was used to assign publications to countries/aggregates. (2) BRS: Brazil, Russia and South Africa.

Figure 3.1-3 Share of each EU Member State of EU scientific publications(1), 2002-2022



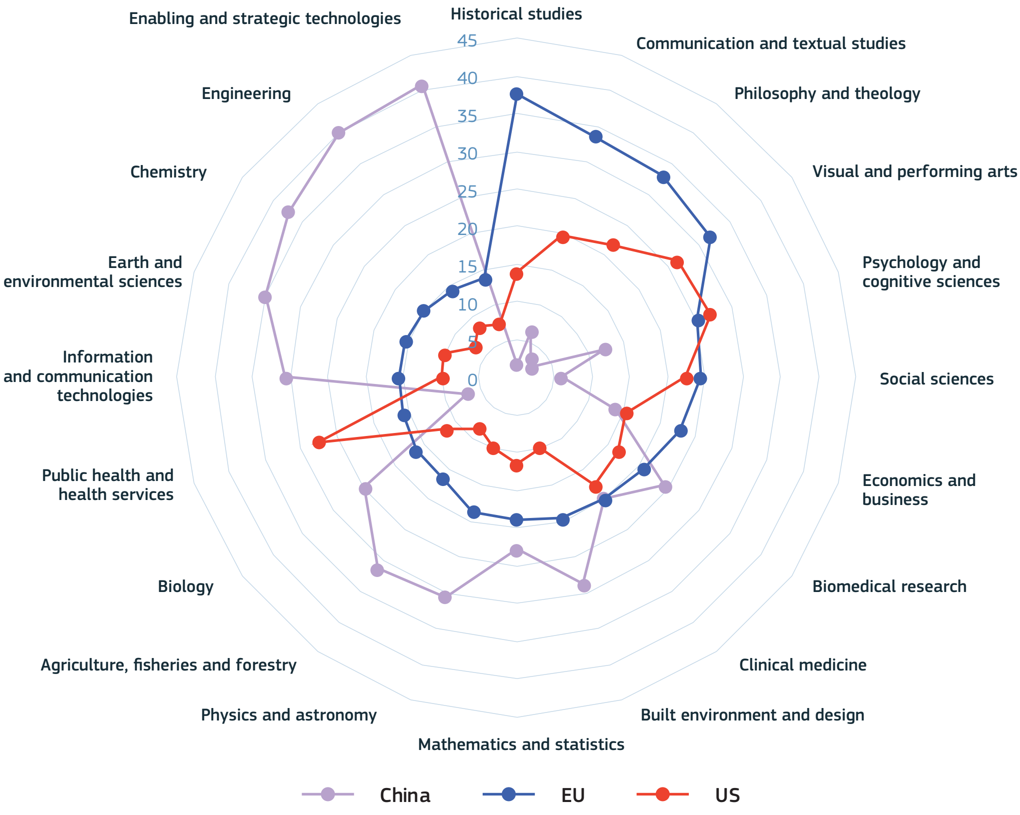
Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on Science-Metrix using data from Scopus (Elsevier).

Note: (1) Fractional counting was used to assign publications to countries/aggregates.

The distribution of publications across scientific fields[3] offers insights into the relative strengths and research priorities of different countries. **In 2022, the EU led the world in the share of publications within the non-technological domains of economics and social sciences, and arts and humanities**. Specifically, the EU had the largest shares in historical studies, communication and textual studies, and philosophy and theology. The EU's pre-eminence in these fields, although they account for only a small share of publications, underscores its distinctive research focus. Additionally, in 2022, the EU's share of world output was larger than that of the US in all fields except two: psychology and cognitive sciences, and public health and health services. In 2000, this was true for only 6 out of 20 fields. **In the broader health sciences category, the US maintains a strong presence**. Meanwhile, **China's publications are predominantly concentrated in the domains of applied sciences and natural sciences**, with significant contributions in enabling and strategic technologies, engineering, and chemistry (Figure 3.1-4).

Figure 3.1-4 Global shares (%) of scientific publications by country and scientific field(1), 2022



Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on Science-Metrix using data from Scopus (Elsevier).

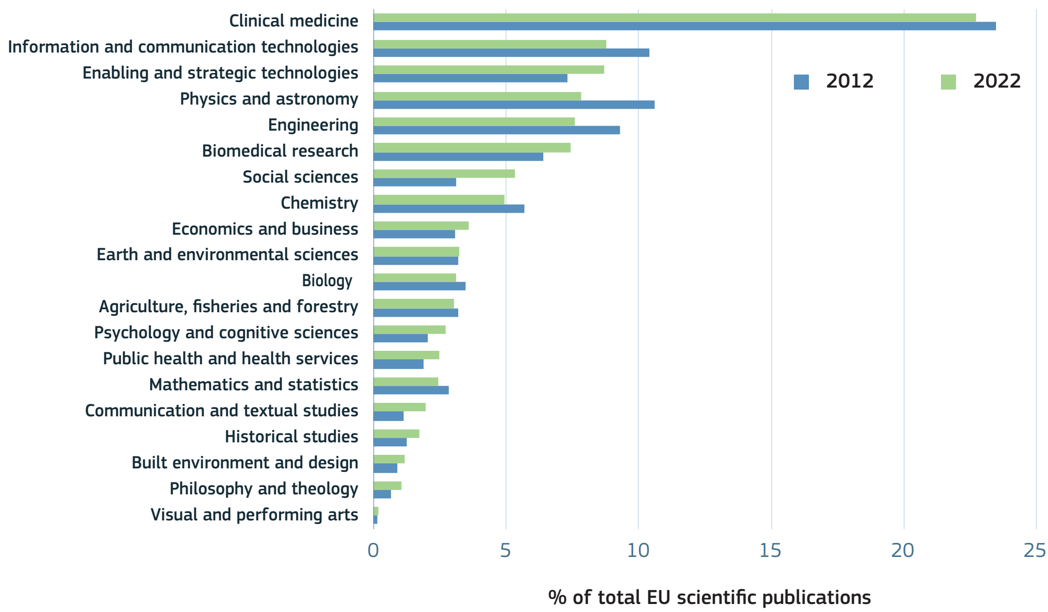
Note: (1) Fractional counting was used to assign publications to countries/aggregates.

3 The classification developed by Science-Metrix, which is used here, encompasses five domains: applied sciences, arts and humanities, economics and social sciences, health sciences, and natural sciences, and 20 scientific fields reported in figure 3.1-4.

The relatively low scientific productivity of the EU in the natural and applied sciences may be linked to the share of STEM graduates, which in the EU varies from 11 % to 35 %[4], whereas in Asian countries, such as India and South Korea, it is above 30 % of all graduates. The role of STEM graduates in advancing scientific knowledge is further discussed in Chapter 5.2.

The distribution of scientific publications in the EU has undergone slight changes over the past decade. Approximately 23 % of publications in the EU were in the field of clinical medicine in 2022. Information and communication technologies (8.8 %) and enabling and strategic technologies (8.7 %) also accounted for substantial shares of EU publications (Figure 3.1-5). In the US, a strong emphasis on health sciences is evident, with significant shares of publications on clinical medicine (27.9 %) and biomedical research (8.3 %), followed by information and communication technologies (7.6 %). Additionally, a considerable share of publications in the US (6.8 %) is in the field of social sciences (Figure 3.1-6). In contrast, publications in China are predominantly on enabling and strategic technologies, which account for 17.3 %, with a significant increase observed over the past decade (Figure 3.1-7).

Figure 3.1-5 EU share of publications[(1)] by scientific field, 2012 and 2022



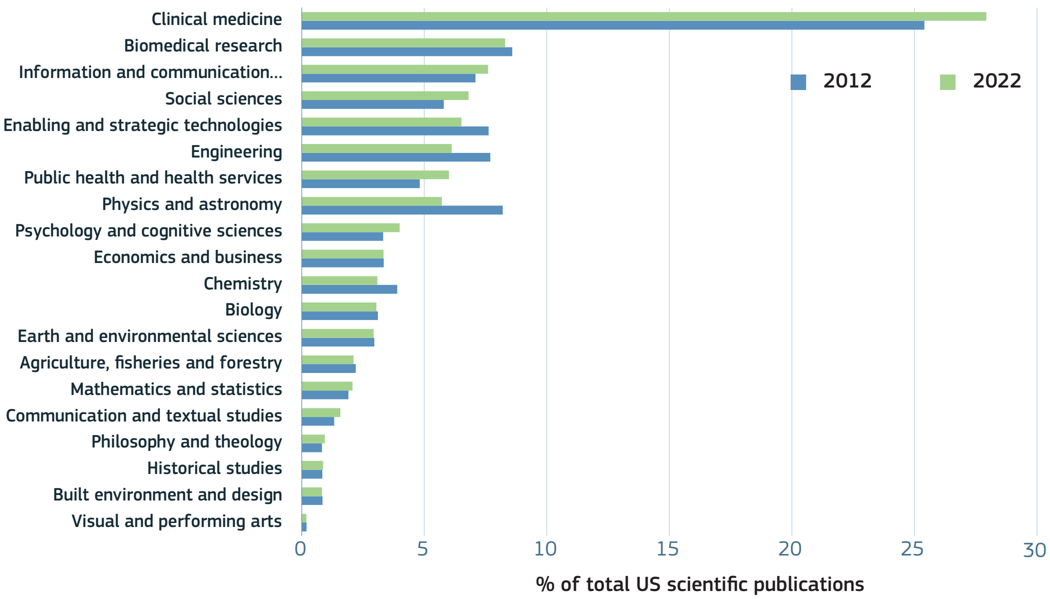
Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on Science-Metrix using data from Scopus (Elsevier).

Note: (1) Fractional counting was used to assign publications to countries/aggregates.

4 UNESCO datafile 'Other policy relevant indicators': http://data.uis.unesco.org/

Figure 3.1-6 US share of publications(1) by scientific field, 2012 and 2022



Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on Science-Metrix using data from Scopus (Elsevier).

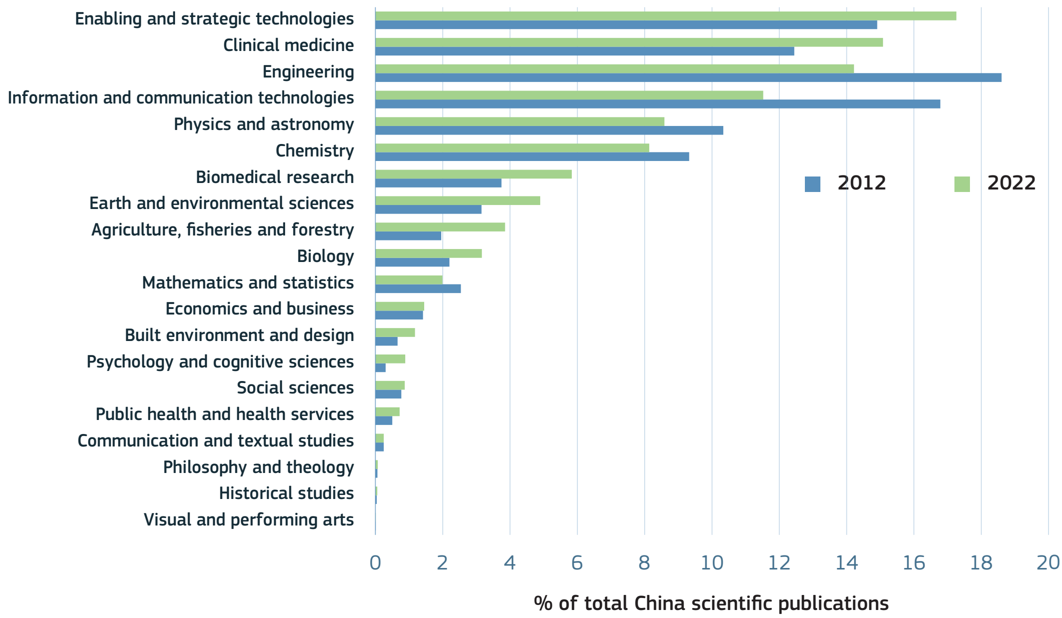
Note: (1) Fractional counting was used to assign publications to countries/aggregates.

The EU is a global leader in the adoption of open access[5] practices. In 2020, around 80 % of all EU peer-reviewed publications were available through at least one open access pathway (gold, green, both or unknown open access), surpassing the rates observed in the US and China. However, the adoption of open access varies among EU Member States, with most of them reporting rates of between 70 % and 90 % (Figure 3.1-8).

Open access is recognised for its potential to enhance scientific performance by broadening access to knowledge and increasing research visibility. However, it also presents challenges, including transfer of publication costs to authors, potential compromises on quality and creation of financial disparities within the research community. The open access community acknowledge these challenges and various measures have been proposed and implemented to address them such as funding support, quality assurance, fee waivers, transparency and collaboration. These issues are discussed in more detail in Chapter 3.2.

5 Open access refers to the practice of providing online access to scholarly information that is free of charge to the user and reusable.

Figure 3.1-7 China's share of publications[1] by scientific field, 2012 and 2022

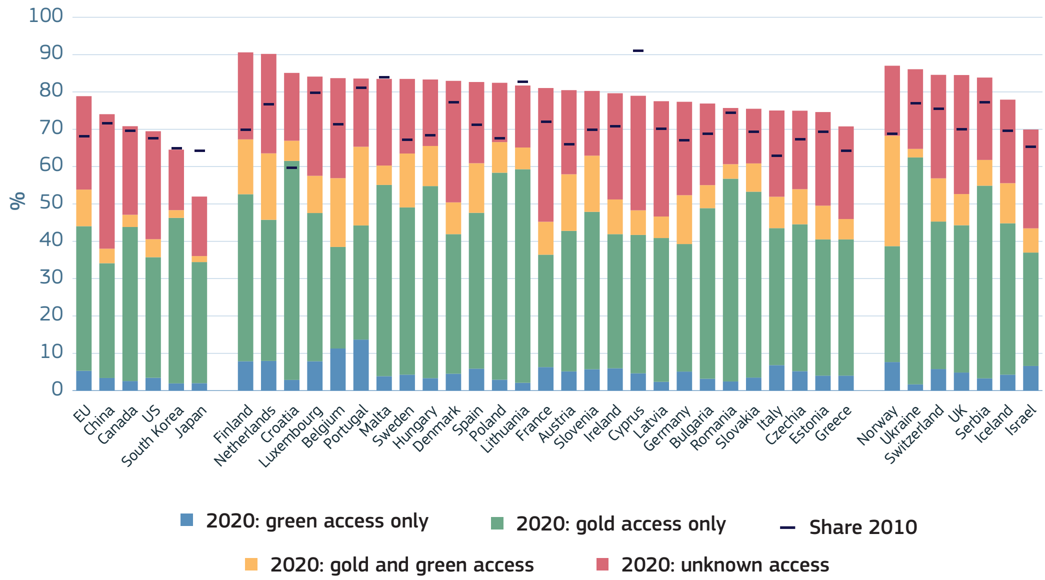


Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on Science-Metrix using data from Scopus (Elsevier).

Note: (1) Fractional counting was used to assign publications to countries/aggregates.

Figure 3.1-8 Open-access peer-reviewed publications(1) with DOI as % of total peer-reviewed publications with DOI, 2010 and 2020



Science, research and innovation performance of the EU 2024

Source: Powered by the OpenAIRE Graph, a global scholarly knowledge graph: https://graph.openaire.eu

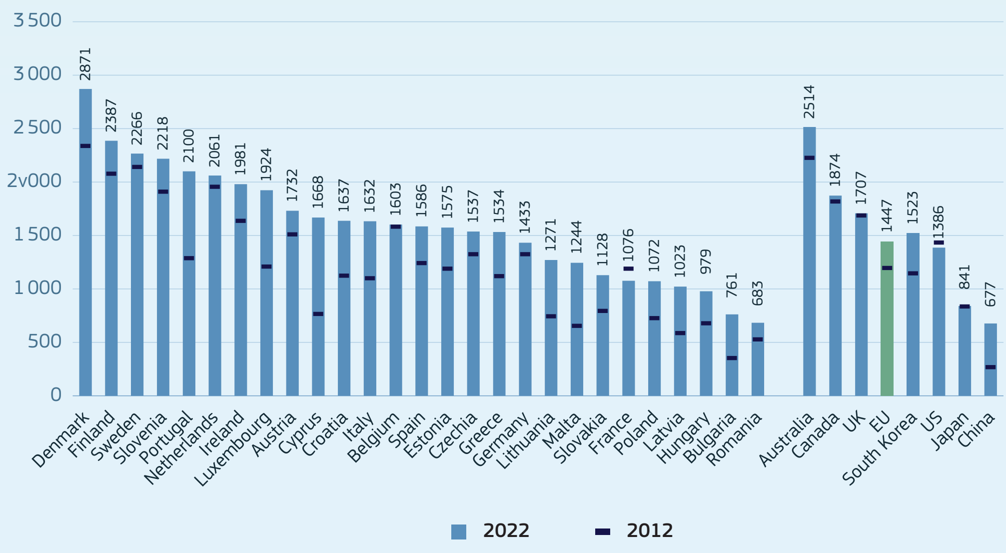
Note: (1) Full counting used. OpenAIRE has adopted Unpaywall's approach to defining open access types. Gold open access involves publishing in fully open access journals, which are defined by one or more of the following criteria: the journal is in the Directory of Open Access Journals (DOAJ); it has a known fully open access publisher (curated list); it only publishes open access articles. Green open access involves self-archiving of the article in a freely accessible repository after a publisher-determined embargo period, or as a pre-print, making the article immediately available. Hybrid open access involves publishing in subscription journals that offer some open access articles but are not fully open access. For the purposes of this report, both gold and hybrid open access are categorised as gold. The term 'unknown open access' refers to peer-reviewed publications with DOIs that are openly accessible, but whose specific type of open access is not identified. The open access rates presented here may vary from those published in the 2022 SRIP report due to discrepancies in the coverage of the publication database and variations in the definition of open access.

Box 3.1: Research productivity

To account for differences in country size, indicators on publications can be normalised by different metrics. Dividing the number of publications by population size, number of researchers or GDP in purchasing power standards (PPS) can capture the effectiveness of countries in producing publications relative to the size of their economies or the scale of their R&I systems. Each metric allows for comparison from different perspectives.

In 2022, the EU produced, on average, 1 447 publications per million population, indicating a slight improvement since 2012 (Figure 3.1-9). In terms of publications relative to the number of researchers, the EU recorded 311 publications per thousand. This figure ranks below the UK and China but above the US and South Korea (Figure 3.1-10). The decrease in publications per researcher in the EU suggests a decline in research productivity. Recent works provide empirical evidence of declining research productivity in the US over time, attributing this trend to the increasing difficulty in finding new ideas. For instance, Bloom et al. (2020) observed a decline in R&D productivity across various sectors, including the semiconductor industry, agriculture, healthcare and US manufacturing. Similarly, Boeing et al. (2023) reported a decline in average research productivity in Germany and China.

Figure 3.1-9 Publications per million population, 2012 and 2022

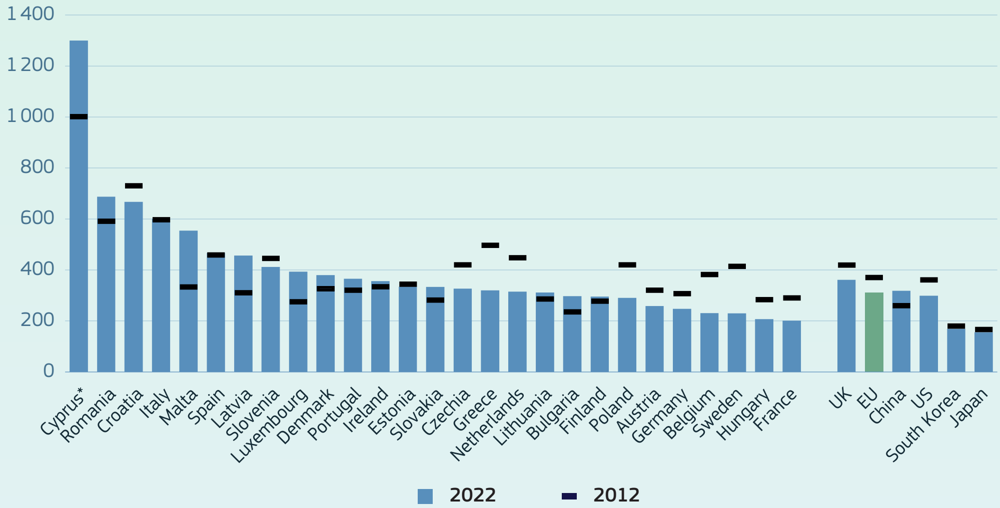


Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on Eurostat and Science-Metrix data.

Note: Fractional counting was used to assign publications to countries/aggregates.

Figure 3.1-10 Publications per thousand researchers, 2012 and 2022



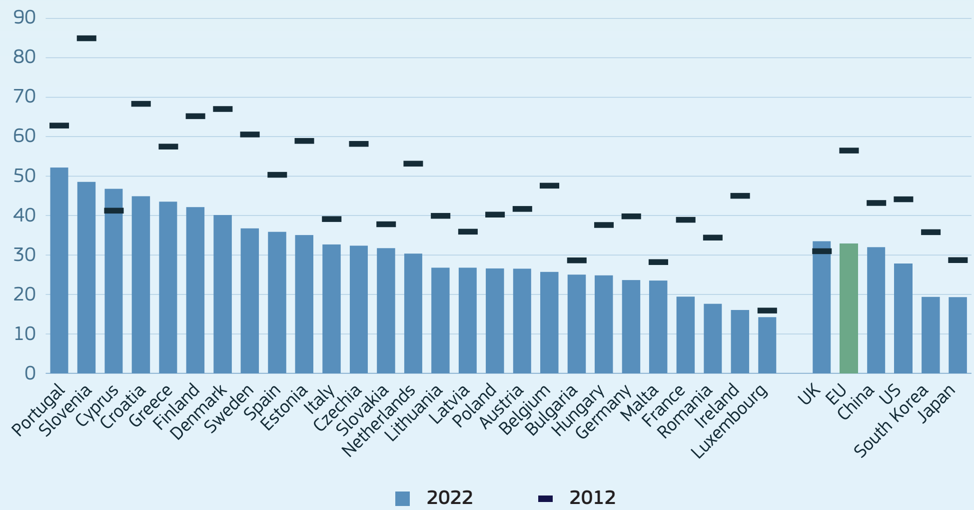
Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on Eurostat and Science-Metrix data.

Note: Due to missing data, results for Denmark, China and the UK are for 2021, results for the US are for 2020, and results for Japan and South Korea are for 2019. Fractional counting was used to assign publications to countries/aggregates.

*For Cyprus, the number of publications per thousand researchers is inflated because the count includes publications from both the Turkish and non-Turkish sides of the island, while the number of researchers only includes the non-Turkish side.

Figure 3.1-11 Number of publications per billion EUR of GDP, 2012 and 2022



Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on World Bank indicators (GDP in purchasing power parity (PPP) in current international dollars) and OECD (period average EUR-USD exchange rate) and Science-Metrix data.

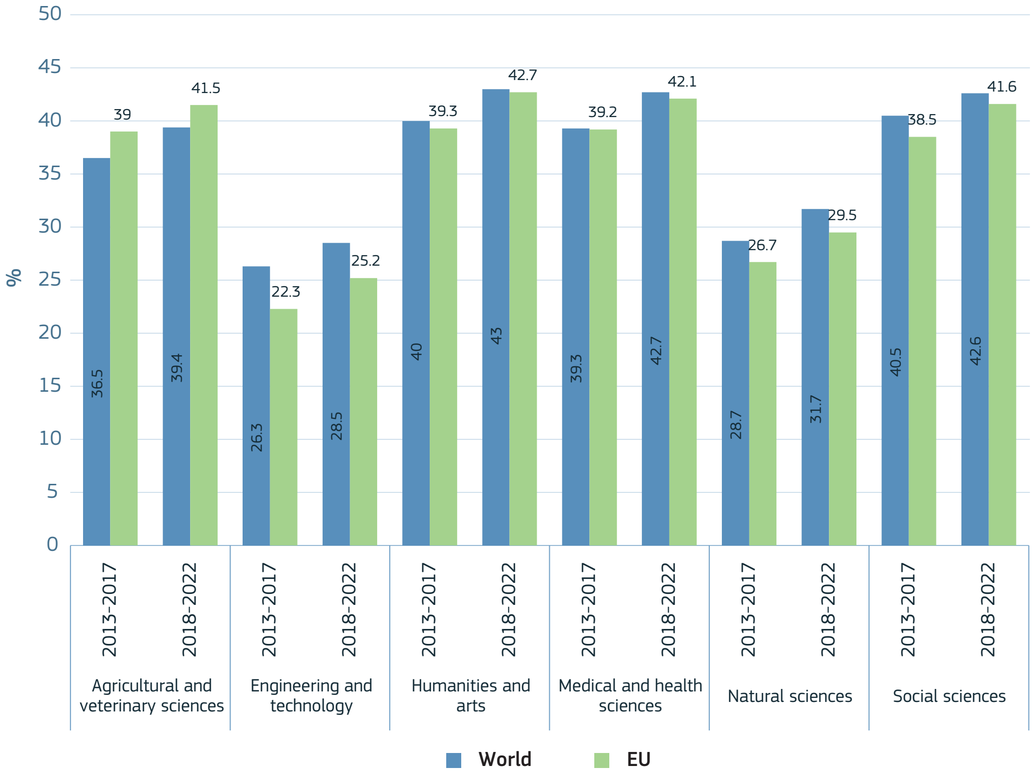
The gender dimension in scientific authorship

Women remain under-represented in scientific publications. At EU level, the average share of female authors for publications with at least one EU author was 34 % for the period 2018-2022, but it varied significantly between R&D fields. Engineering and technology had the lowest proportion (25.2 % in 2018-2022), followed by natural sciences with 29.5 % in the same period. In these two fields, the EU was below the global averages of 28.5 % and 31.7% respectively. Humanities and arts, and medical and health sciences had the highest levels of female authorship, with roughly 42 % in each (Figure 3.1-12).

Female authorship of scientific publications is continually increasing, both globally and at EU level. Figure 3.1-12 shows that the average shares of female authors increased in the period 2018-2022 compared to the period 2013-2017 in all R&D fields. Several positive developments in recent years contributed to this growth. They include increased access to education, diversity and inclusion initiatives to promote gender equality, awareness campaigns and flexible work arrangements. However, there is still work to be done to address gender disparities, particularly in STEM fields.

Why do women publish less than men in STEM fields? Empirical evidence indicates notable gender disparities in both the overall productivity and impact of academic careers across STEM fields (Huang J. et al., 2020). Various factors contribute to this trend, including less favourable working environments for women, greater family responsibilities, differing roles within laboratories or fewer resources at women's disposal. However, it is important to recognise that the productivity gap may not reflect a relative lack of scientific contributions by women, but rather a disparity in how their contributions are acknowledged. Studies have shown that women in research teams are significantly less likely than men to receive credit for authorship (Ross M.B. et al., 2022). Additionally, a significant part of the gender gaps observed as regards research careers can be attributed to gender-specific dropout rates. Women are less likely to be recognised for their contributions and may consequently be less likely to advance in their careers, indicating that efforts that are solely focused on junior scientists may not adequately address the gender imbalance observed throughout STEM fields.

Figure 3.1-12 Average share of female authors for publications with at least one EU author, by R&D field, 2013-2017 and 2018-2022

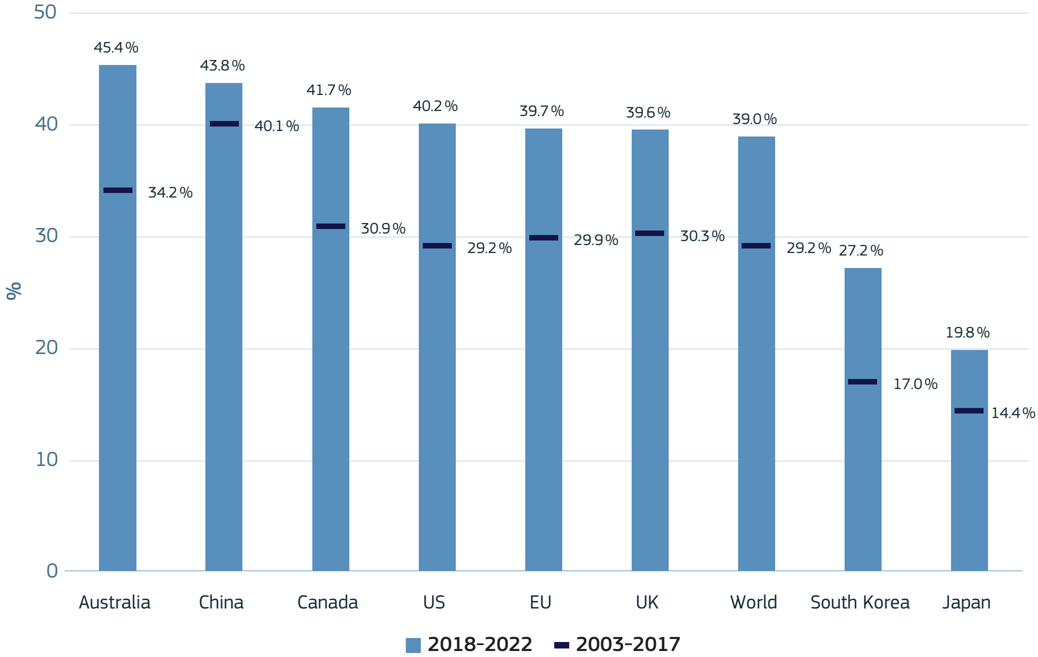


Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on data from Scopus (Analytical and Data Services, Elsevier) as they will be featured in the She Figures 2024.

The share of female first authors has also increased worldwide, but it varies between countries, from about 45% in Australia to less than 20% in Japan. Despite a significant increase since 2007 (about 10 percentage points), the share of female first authors in the EU is less than 40%, just ahead of the UK and below the US and China (Figure 3.1-13). The difficulty in identifying the gender of Asian authors must be taken into consideration.

Figure 3.1-13 Share of female first authors

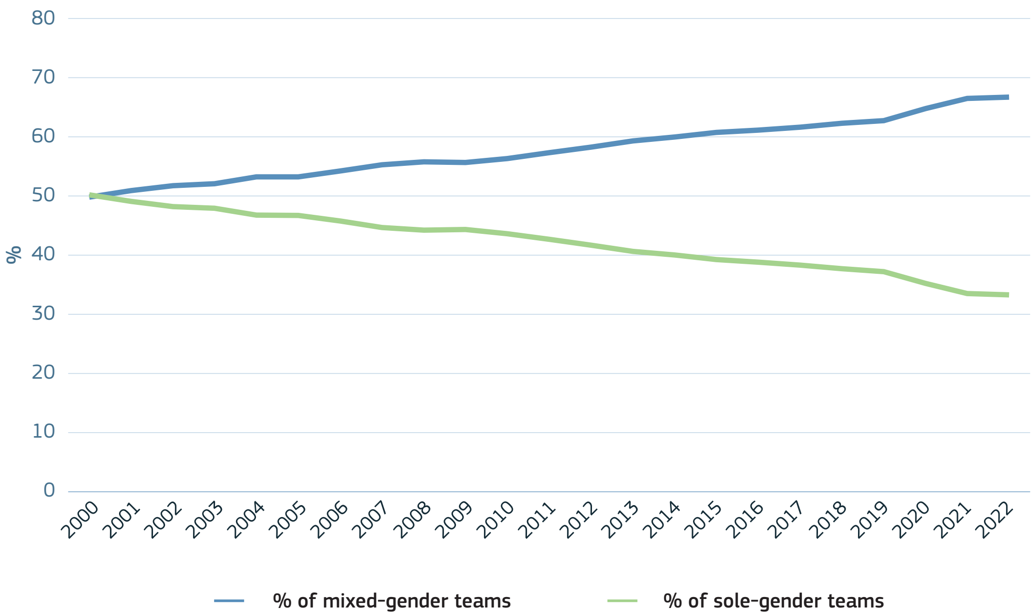


Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on data from Scopus (Science-Metrix, Elsevier).

Note: The shares are calculated from the total number of publications for which the gender of the author could be identified.

Figure 3.1-14 Composition of teams over time, EU



Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on data from Scopus (Science-Metrix, Elsevier).

Note: The shares are calculated from the total number of publications for which the gender of the author could be identified.

Over the last 20 years, mixed-gender research teams have become more common than single-gender teams[6] (Figure 3.1-14). Evidence shows that mixed-gender teams produce more novel and more widely cited papers than single-gender teams and stimulate creativity and innovation, (Yang Y. et al., 2022), (Reardon S., 2022). A small share of mixed-gender teams may reflect research environments in which women receive less credit for their work than their male colleagues, which inhibits the formation of mixed-gender teams and hinders women's careers. At the same time, publications with only one author are not very common and are mainly produced by men (57 % in 2022), despite a significant increase in the percentage of female sole authors (32 % in 2022).[7]

AI technologies are spreading rapidly among scientific communities. **The integration and use of AI in science and innovation has had a positive impact on knowledge production, but it has also brought challenges** (European Commission, 2023a) of which scientific integrity and public trust are just two. Further analysis of the impact of AI on science can be found in Chapter 3.3.

6 This may not apply to all scientific fields.

7 The remaining 11 % correspond to scientific papers for which the gender of the authors could not be identified.

Box 3.2: Use of ChatGPT in scientific publications

Since its launch in 2022, ChatGPT has gained millions of users worldwide across various disciplines and for multiple purposes, including scientific writing. Academics have expressed different opinions about using this technology (Meyer et al., 2023; Stokel-Walker, C, 2023). The main debate is on how ChatGPT and its variants should be referenced in scientific publications. While ChatGPT has the potential to enhance research productivity and academic output by assisting in precise citation identification and formatting, its use gives rise to ethical considerations. These include uncertainties about whether ChatGPT can be considered an author and the necessity of adhering to copyright regulations and providing proper attribution when incorporating external materials, such as quotes or data, in order to avoid plagiarism (Lund et al., 2023). Hence, efforts to balance the utilisation of AI to accelerate knowledge generation with the implications for human potential and autonomy within the research process may lead to controversy (van Dis et al., 2023).

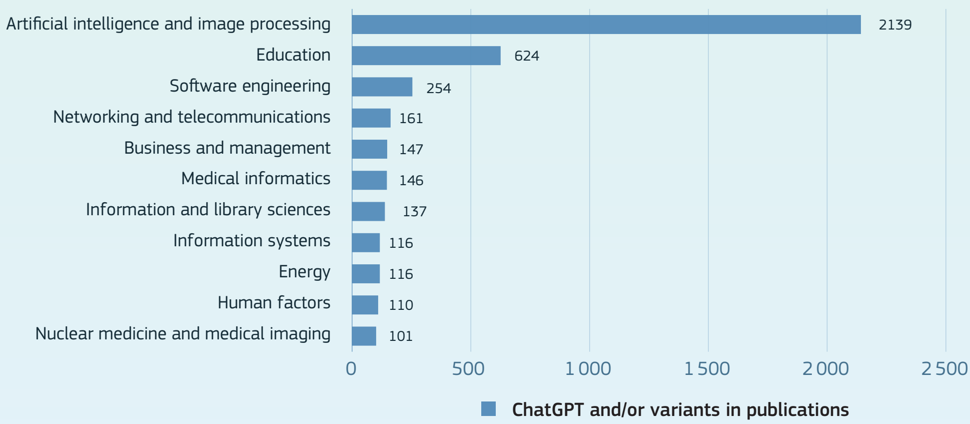
In 2023, 7 023 publications (0.2 % of all Scopus publications) refer to ChatGPT for various purposes. About 34.4 % of these publications directly mentioned ChatGPT in their title, abstract or keywords. In addition, 72 % of papers referencing ChatGPT did so through references to other publications that mentioned ChatGPT in their title. In a random sample of about 150 publications mentioning ChatGPT, 54.9 % applied it to research, 12.2 % focused on tool development, 19.5 % evaluated ChatGPT, 11.6 % used it for language enhancement and 1.8 % used it for various purposes. Recently, publications have begun crediting ChatGPT as a co-author in cases where its contribution is substantial (eight such cases were identified). Regarding subfields with at least 100 publications, AI and image processing accounted for close to one third of all publications that referenced/mentioned ChatGPT. It was followed by education, software engineering, networking and telecommunications, business and management, and medical informatics (Figure 3.1-15).

In 2023, based on the overall fractional count, the countries with the largest volumes of scientific publications referencing/mentioning ChatGPT in Scopus were the US, China, Germany, the UK and India. The US recorded the highest fractional count of such publications, which represented close to 0.4 % of the overall fractional count of publications from the US. Among European countries, Germany, the UK, Italy, Spain and the Netherlands stand out as the top contributors to publications mentioning ChatGPT and its variants.

Among countries that contributed to a minimum of 20 papers mentioning or referencing ChatGPT and its variants, Singapore, Qatar, the United Arab Emirates, Jordan and Slovenia have the highest shares of such publications.

To make sure that researchers use the technology in the best possible way, efforts are underway to introduce guidelines for its ethical use in research. For instance, Elsevier has introduced guidelines for use of AI in scientific writing[8] and responsible AI principles[9], while the European Commission has developed guidelines for Horizon Europe projects (European Commission, 2021). Furthermore, the European Commission, together with the European Research Area (ERA) and stakeholders, has put forward a set of guidelines to support the European research community, including researchers, research organisations and funding organisations, in responsible use of generative AI.[10]

Figure 3.1-15 Subfields with at least 100 publications referencing/ mentioning ChatGPT and/or variants, 2023



Science, research and innovation performance of the EU 2024
Source: Science-Metrix using data from Scopus (Elsevier).

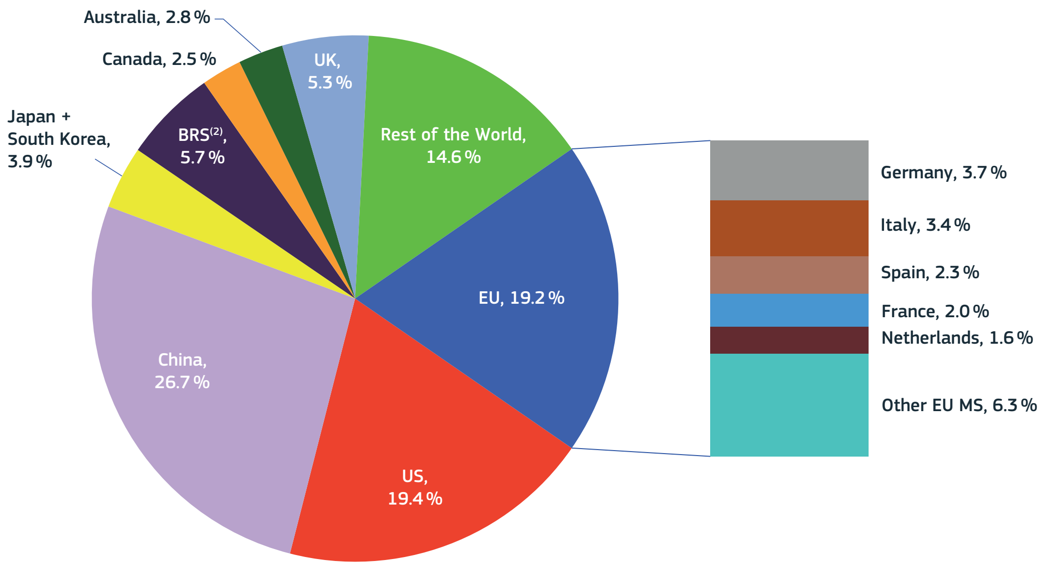
8 https://www.elsevier.com/about/policies-and-standards/the-use-of-generative-ai-and-ai-assisted-technologies-in-writing-for-elsevier
9 https://www.elsevier.com/about/policies-and-standards/responsible-ai-principles
10 https://research-and-innovation.ec.europa.eu/news/all-research-and-innovation-news/guidelines-responsible-use-generative-ai-research-developed-european-research-area-forum-2024-03-20_en

2. Scientific excellence

As China steadily increases the influence of its publications, the EU has fallen to third place globally in terms of contributions to widely cited publications, close behind the US. In 2020, China accounted for 26.7% of the top 10% of most cited publications – the largest share worldwide, followed by the US (19.4%) and the EU (19.2%). Within the EU, Germany (3.7%), Italy (3.4%), Spain (2.3%) and France (2.0%) led the way (Figure 3.1-16).

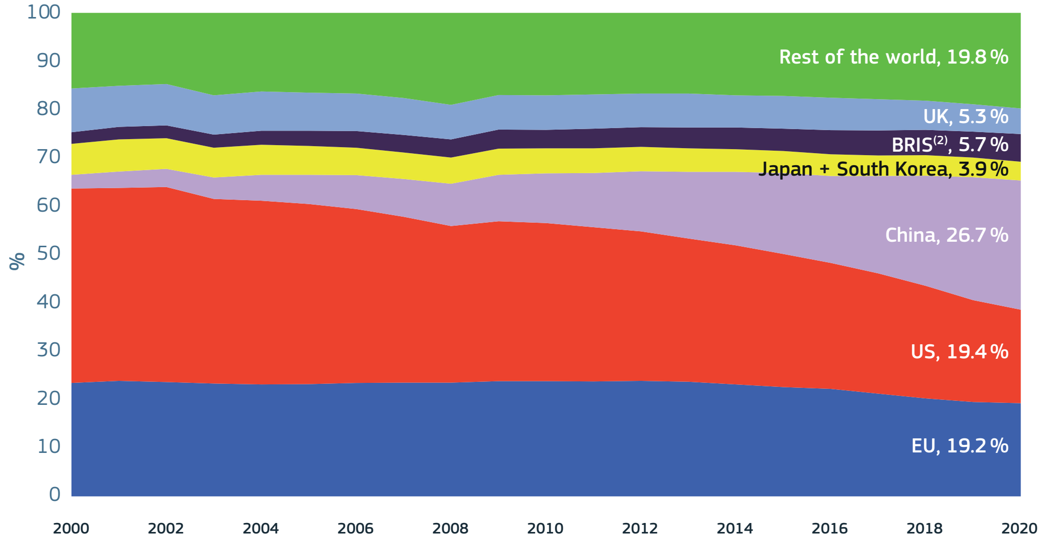
Over the past 20 years, China's significant growth in terms of both the number and the influence of its publications has been primarily at the expense of the US and, to a lesser extent, the EU. The share of the top 10% of most cited publications originating from China has increased significantly, from 2.8% in 2000 to 26.7% in 2020. During the same period, the US's share decreased from 40.2% to 19.4%, while that of the EU decreased from

Figure 3.1-16 Global share of the top 10% of most cited scientific publications[1], 2020 (citation window: 2020-2022)



Science, research and innovation performance of the EU 2024
Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on Science-Metrix using data from Scopus (Elsevier).
Note: (1) Scientific publications within the top 10% of most cited scientific publications worldwide. Fractional counting was used to assign publications to countries/aggregates. (2) BRIS: Brazil, Russia, India and South Africa.

Figure 3.1-17 **Global share of top 10% of most cited scientific publications[1], 2000 (citation window: 2000-2002) - 2020 (citation window: 2020-2022)**



Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on Science-Metrix data using the Scopus database.
Note: (1) Scientific publications within the 10% most cited scientific publications worldwide. Fractional counting was used to assign publications to countries/aggregates. (2) BRIS: Brazil, Russia, India and South Africa.

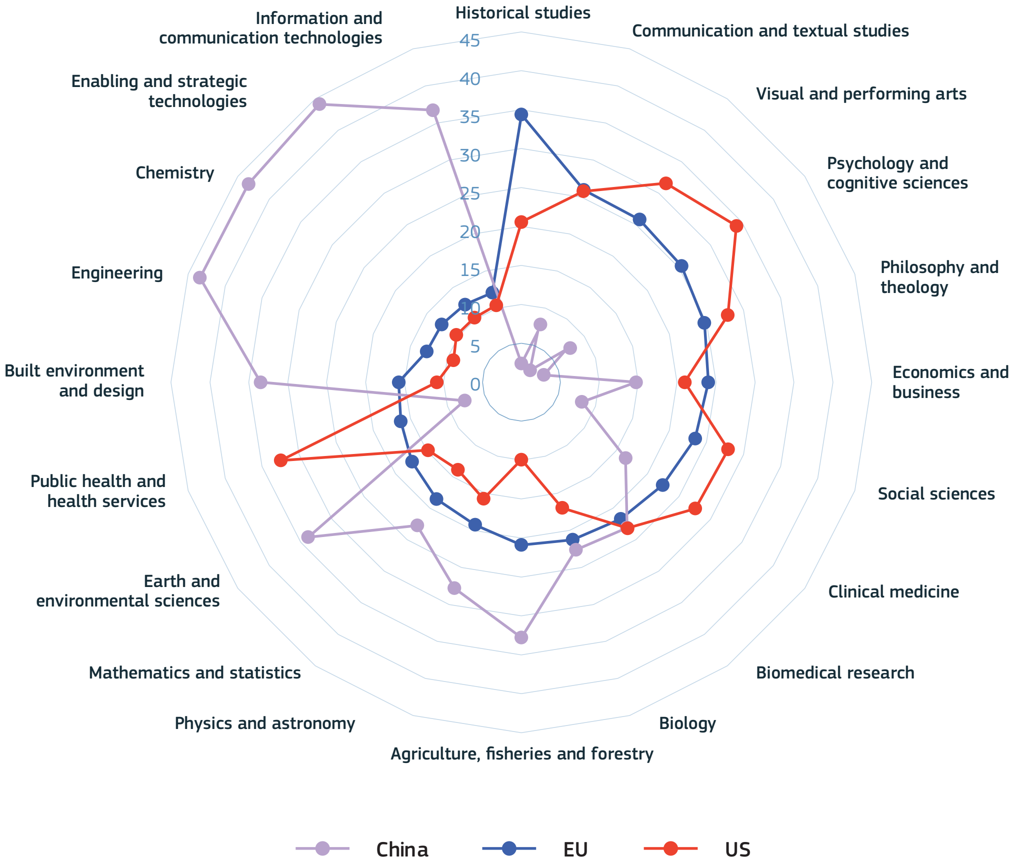
23.4% to 19.2%. China overtook the EU in 2018 and the US in 2019. Another significant trend is the growing importance of the BRIS group[11] in the global share of most cited publications, driven mainly by an increase in high-quality publications from India. Nevertheless, the EU, the US and China together still account for approximately 65% of the top 10% of most cited publications (Figure 3.1-17).

Similarly to the total volume of scientific output, when examining the most cited publications across different scientific fields, the EU holds the highest shares in less technological fields such as historical studies, economics and business, and communication and textual studies.

China leads in applied sciences, notably in enabling and strategic technologies, engineering, and information and communication technologies, as well as in natural sciences, particularly chemistry, physics and astronomy, and earth and environmental sciences. The US leads in health sciences across all scientific fields, including clinical medicine and biomedical research (Figure 3.1-18).

11 Brazil, Russia, India and South Africa

Figure 3.1-18 **Global shares of the top 10% of most cited publications by country/ region and scientific field(1), 2020**



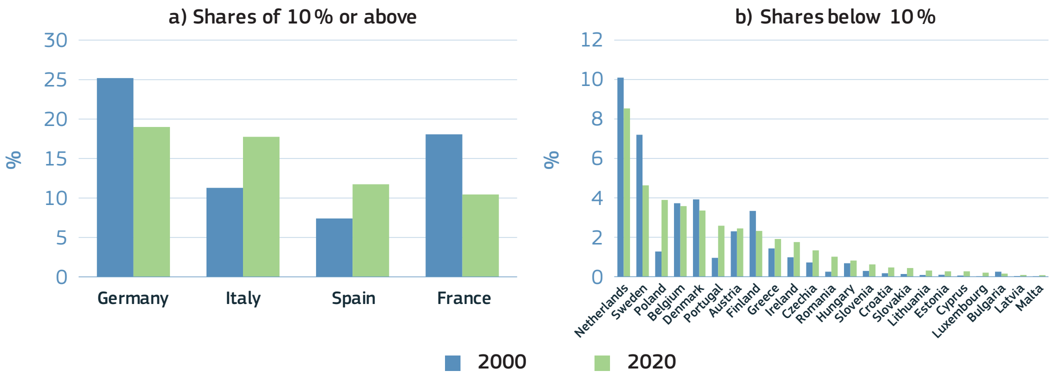
Science, research and innovation performance of the EU 2024

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

Note: (1) Scientific publications within the top 10% of most cited scientific publications worldwide. Fractional counting was used to assign publications to countries/aggregates.

Within the EU, eastern and southern European countries are catching up in terms of production of influential publications. Conversely, larger economies, such as Germany and France, have seen a decrease in their share within the EU since 2000. Nevertheless, the production of widely cited publications in the EU remains concentrated, with four countries (Germany, Italy, Spain and France) accounting for 59% of the EU's top 10% of most cited publications, compared to 62% in 2000 (Figure 3.1-19).

Figure 3.1-19 Share of each EU Member State of the top 10 % of most cited EU scientific publications(1), 2000 and 2020



Science, research and innovation performance of the EU 2024

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

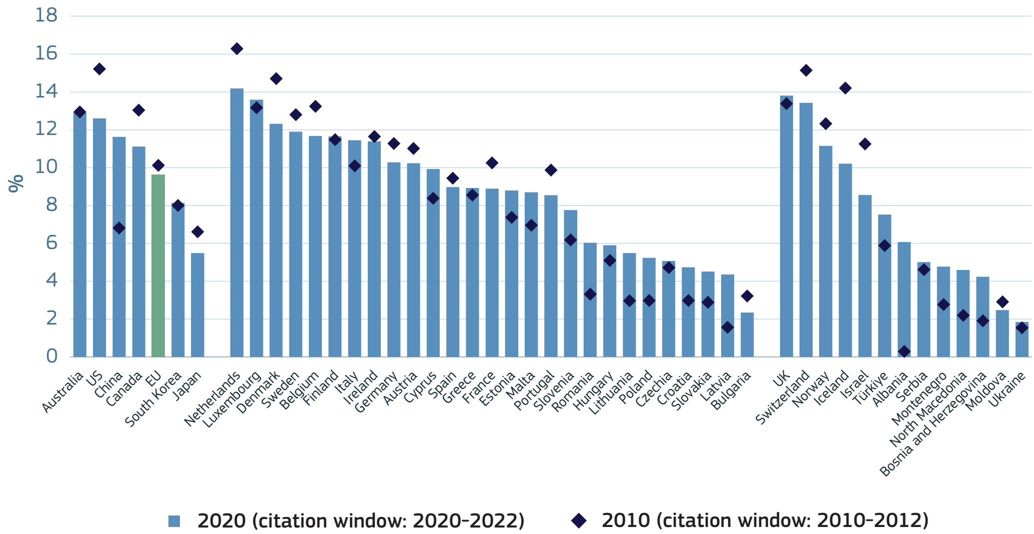
Note: (1) Fractional counting was used to assign publications to countries/aggregates.

The percentage of EU publications in the top 10 % most cited worldwide may be lower than those of a few other global players such as the US, China, Canada and Australia, but it is relatively stable over time. The US, which ranks second after Australia, saw a decrease of 2.6 percentage points between 2010 and 2020, whereas the EU experienced only a slight decline (0.5 percentage points). The improvement in the quality of Chinese publications is striking, with the share of publications in the top 10 % at 11.6 %, compared to only 6.8 % in 2010 (Figure 3.1-20).

Within the EU, there is significant heterogeneity in percentages of publications in the top 10 % of most cited publications, which range from 2.3 % for Bulgaria to 14.2 % for the Netherlands – the highest percentage of all analysed countries. Germany, the largest European contributor to the top 10 % of most cited publications, scores above the EU average (10.3 %). There has been an improvement in eastern and southern countries, which had previously scored low but increased their percentages in the last decade. Despite these improvements, significant disparities persist within the EU. Large countries like Germany, Italy, Spain and France are scientific powerhouses and dominate in terms of numbers of publications among the 10 % most cited. However, the contribution of smaller European countries is gradually becoming more significant (Figure 3.1-20).

The EU has the third largest share of scientific publications in the top 1 % most cited worldwide (17.8 %). China comes first with 27.3 %, and the US follows with 21.7 %. China overtook the EU in 2018 and the US in 2020. Since 2000, the share of the US has decreased by 25.5 percentage points (Figure 3.1-21).

Figure 3.1-20 Percentage of publications in the top 10% of most cited publications worldwide[(1)], 2010 and 2020



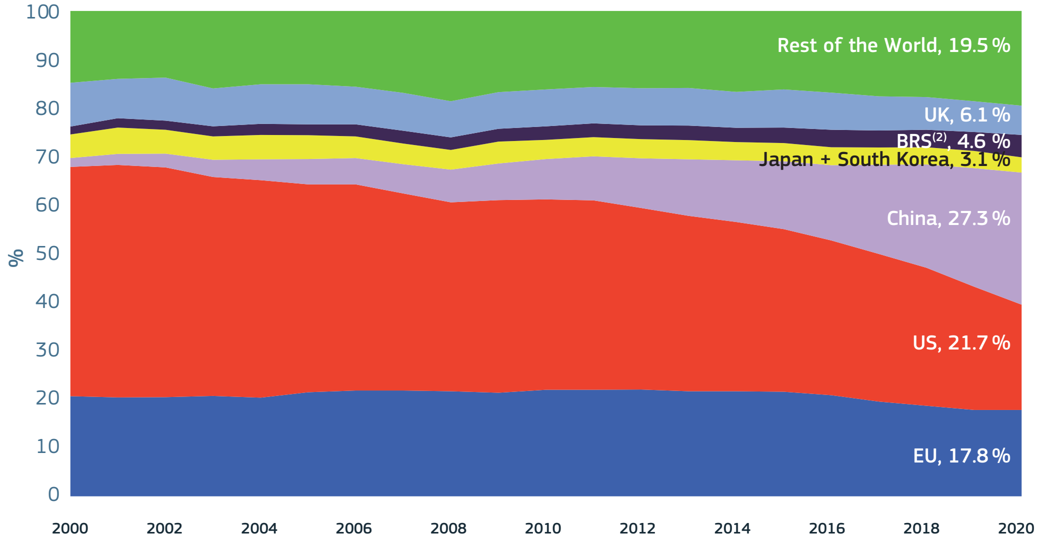
Science, research and innovation performance of the EU 2024

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

Note: (1) Scientific publications within the top 10% of most cited scientific publications worldwide as a share of the country's total number of scientific publications. Fractional counting was used to assign publications to countries/aggregates. The top 10% most cited scientific publication percentage measures the quality of publications for a given country and year. It is calculated as the ratio of the number of publications in the top 10% most cited worldwide to the total number of publications from that country in the same year.

Another evidence of the average, yet consistent, impact of EU publications is the percentage of total EU publications that belongs to the top 1% of most cited publications worldwide, which has remained slightly below 1%. In contrast, both the US and Canada, which enjoy higher shares, have experienced a notable decline in this metric, while China's share has doubled, confirming once more the rapid and continuous increase in influence of Chinese publications (Figure 3.1-22).

Figure 3.1-21 Global share of the top 1 % of most cited scientific publications[1], 2000 (citation window: 2000-2002) - 2020 (citation window: 2020-2022)



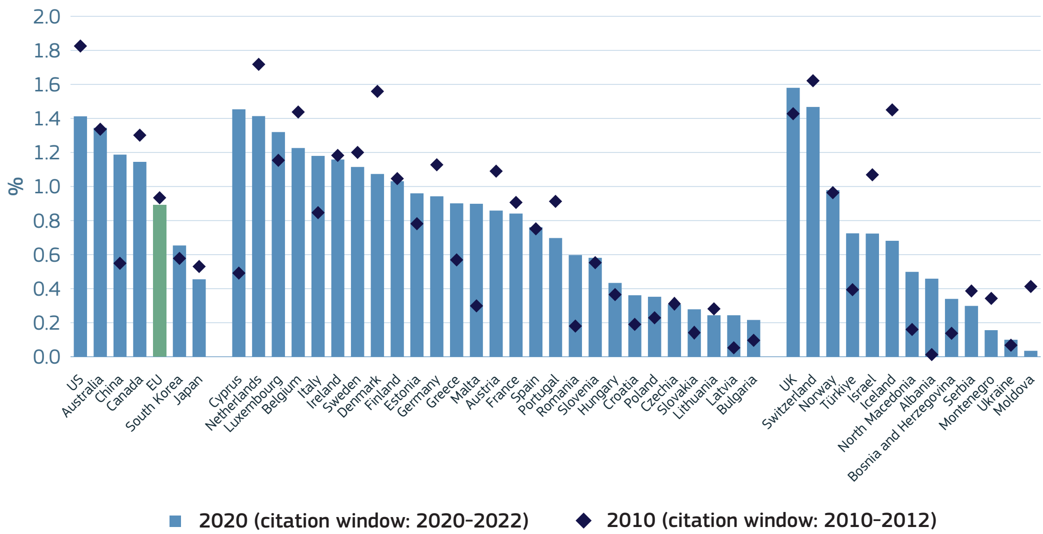
Science, research and innovation performance of the EU 2024

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

Note: (1) Scientific publications within the top 1 % of most cited scientific publications worldwide as a share of the country's total number of scientific publications. Fractional counting was used to assign publications to countries/aggregates.

The citation impact of EU publications has been quite stable since the mid-2000s, remaining just above the world average, which is indexed at 0, and below some of the EU's main global competitors such as Australia, the UK, the US and Canada. The EU saw a slight increase in 2018-2020, following a drop in 2016-2017. The most significant progress in citation impact is that of China. Since 2005, the country has consistently increased its citation impact performance, which reached the world average in 2017 and caught up with the EU in 2018. It is safe to conclude that Chinese publications are now widely read and used by researchers throughout the world. The stability of the citation impact of EU publications is a positive result when compared with the declines in performance of some of the EU's competitors, such as the US and Canada. These countries' citation impact scores have declined since the early 2010s. The gains in citation impact by China may have come at their expense (Figure 3.1-23).

Figure 3.1-22 Percentage of publications in the top 1 % of most cited publications worldwide[(1)], 2010 and 2020

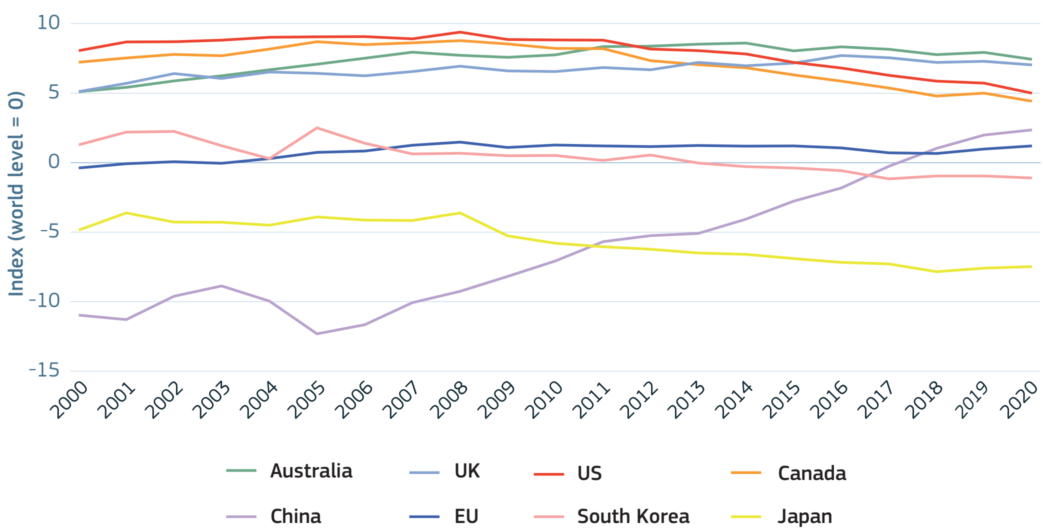


Science, research and innovation performance of the EU 2024

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

Figure 3.1-23 Citation distribution index (CDI), 2000-2020



Science, research and innovation performance of the EU 2024

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

China's comparative advantage in the natural sciences (physical science, chemistry and earth and environmental science) and the US advantage in biological and health sciences are confirmed by the Nature Index 2023[12]. In 2022[13], for the first time, China led the world in the natural sciences, with a Share[14] of 19 373, an increase of more than 21 % from the previous year, well ahead of the US Share of 17 610. In the same period, the Share of both the UK and Germany fell by about 9 %. China also dominated at institutional level. Half of the 20 institutions with the highest Share scores for natural science articles in 2022[15] were based in China. Predictions that China's rise will slow due to the national policy introduced in 2020, which encourages publication in domestic journals, have not yet been vindicated.

The EU framework programmes for R&I play an important role in ensuring scientific production, excellence and collaborations at European level. Evidence from the latest ex-post evaluation of Horizon 2020 (European Commission, 2024a) showed that in the period 2014-2022, Horizon 2020 produced a total of 276 784 peer-reviewed publications (about 4 % of all EU publications in that period), an increase of more than 57 000 compared to the previous framework programme. In addition, 3.9 % of these publications are among the top 1 % of most cited publications worldwide (European Commission, 2024a).

12 The Nature Index is an indicator of global high-quality research output. As such, it tracks contributions to research articles published in high-quality natural science and health science journals. The Nature Index 2023 was calculated based on 146 selected journals.

13 Reference year for the Nature Index 2023.

14 Share is the Nature Index's key metric. It measures each nation's or institution's contribution to the Index from the proportion of its affiliated researchers named as authors on each article.

15 https://www.nature.com/nature-index/annual-tables/2023/institution/all/natural-sciences/global

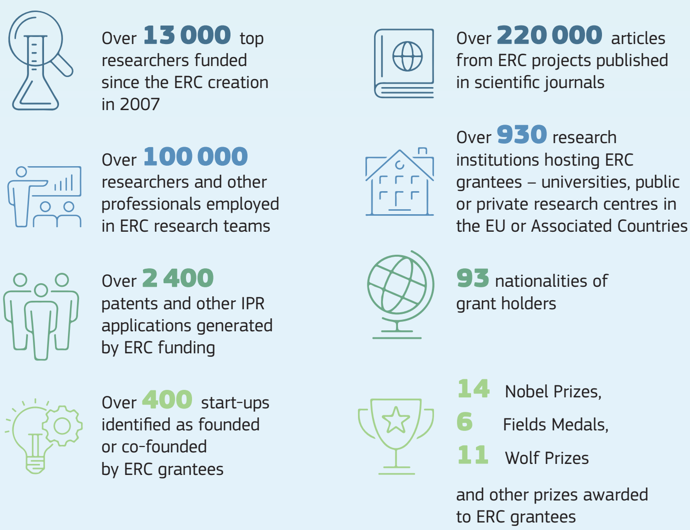
Box 3.3: The European Research Council

Established in 2007, the European Research Council (ERC) has been highly effective in supporting curiosity-driven frontier research across all fields, based only on scientific excellence. The ERC has added a new dimension to the EU framework programmes, which complements traditional top-down approaches and provides a benchmark for excellence in European science.

The ERC has demonstrated the amazing creativity and talent of Europe's best researchers when they are given the freedom to propose their best ideas. Between them, ERC grantees have won 14 Nobel Prizes, 6 Fields Medals, 11 Wolf Prizes and many other awards[16].

ERC-funded researchers have advanced knowledge and contributed to achieving many wider EU goals[17] in terms of the green and digital transitions, as well as societal challenges such as improving health or addressing demographic trends. They have made breakthroughs in critical technologies such as AI and quantum information and stand out as innovation leaders. In all, 40 % of ERC projects have produced results that have subsequently been cited in patents, and about 400 ERC-funded researchers have founded start-up companies[18]. ERC researchers are also training the next generation of excellent scientists and have employed over 100 000 other researchers, mainly PhD candidates and postdocs, in their teams (Figure 3.1-24).

Figure 3.1-24 ERC facts and figures



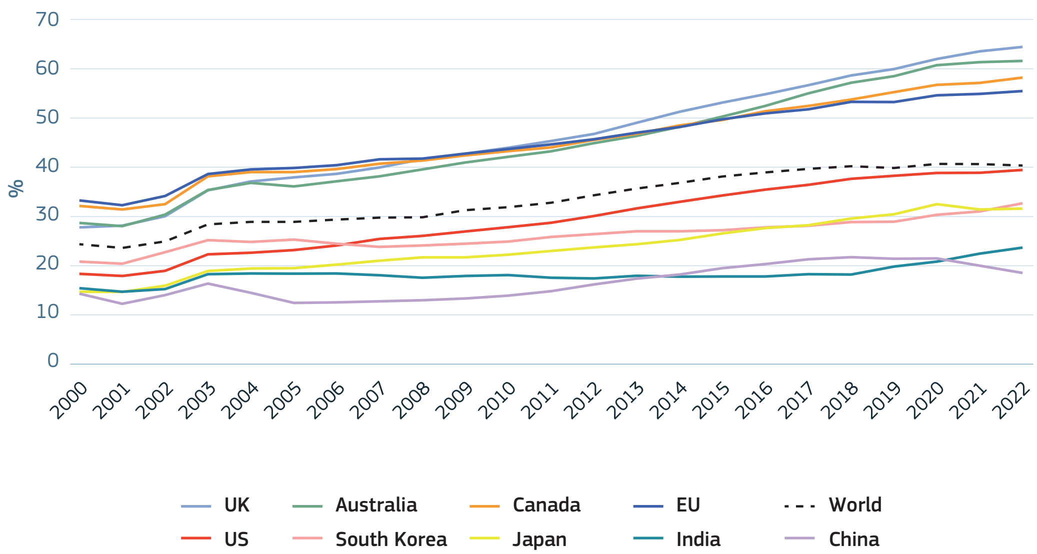
Source: ERC.

16 https://erc.europa.eu/projects-statistics/scientific-prizes
17 https://erc.europa.eu/projects-statistics/mapping-erc-frontier-research-an-overview
18 https://erc.europa.eu/news-events/news/new-study-reveals-how-frontier-research-spurs-patented-inventions

International scientific collaborations, measured by share of scientific co-publications, involving the EU and some of its global competitors have continued to increase. In 2022, the EU recorded a share of international co-publications of 55%, surpassed only by the UK (64%), Australia (62%) and Canada (58%) among the countries analysed. The remaining countries recorded shares of international co-publications below the world average of 40%. China is not only well below the world average but its share has declined since 2019 (Figure 3.1-25). Analysis of the Nature Index 2023 confirms this finding. Although China is making a progressively larger contribution to high-quality research, the proportion of that research conducted with collaborators from other countries is falling, most likely due to policy changes in Chinese academia, which have made international collaborations less important for researchers' careers, (Owens B., 2023). Recent studies also suggest that this decline is driven by political tensions and the effect of the COVID-19 pandemic on international mobility (Cai et al., 2021).

Within the EU, shares of international co-publications vary between the 27 Member States, from 80% to 40% in 2022 (Figure 3.1-26). **The EU has a high share of international co-publications, but its collaborations are mainly intra-European**. This is due to a strong emphasis on building and sustaining an integrated internal market for research (the European Research Area, ERA) and removing barriers to intra-EU mobility of researchers.

Figure 3.1-25 Trends in international co-publication rates, 2000-2022

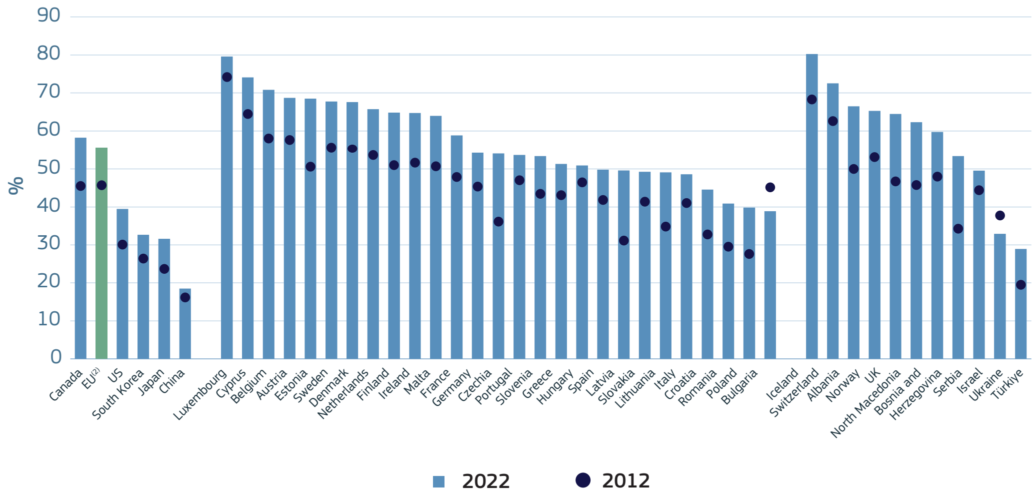


Science, research and innovation performance of the EU 2024

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

Note: Full counting method used. The EU average includes intra-EU international co-publications, which account for 59% of international co-publications in the EU.

Figure 3.1-26 Share of international scientific co-publications in total scientific publications(1), 2012 and 2022



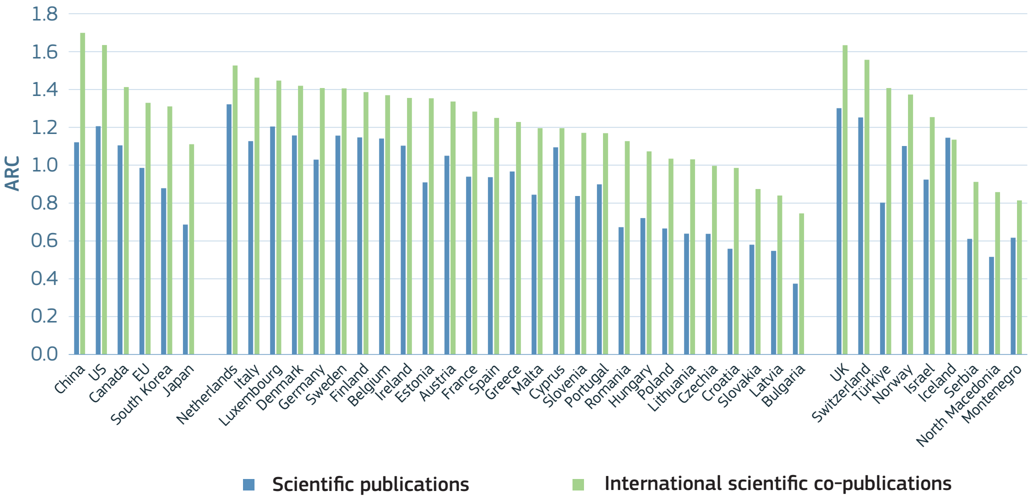
Science, research and innovation performance of the EU 2024
Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on Science-Metrix data using the Scopus database.
Note: (1) Full counting method used. (2) The EU average includes intra-EU international co-publications, which account for 59% of EU international co-publications.

International scientific co-publications yield greater citation impact. As demonstrated in Figure 3.1-27, the average of relative citations (ARC)[19] for international co-publications is consistently higher than that of all scientific publications. This difference underscores the significance of global partnerships in enhancing the influence of a country's scientific output. In 2020, China had the highest ARC for international co-publications, after overtaking the US, which was leading until 2018. The US still leads in the overall ARC, but the gap with China is narrower. The EU comes after the US and Canada, but ahead of South Korea and Japan. Within the EU, the Netherlands, Italy and Luxembourg stand out as leaders in this regard.

Collaborations with EU researchers are attractive for many researchers worldwide. Co-publications with EU researchers account for a significant share of total publications for the UK, Australia and Canada and to a lesser extent for the US. Collaborations with Asian countries are less frequent, except in the case of Japan (Figure 3.1-28).

19 The ARC used by Science-Metrix is an indicator of the scientific impact of papers produced by a given entity (e.g. a country or an institution) which takes into consideration the fact that citation behaviour varies between fields. For a paper in a given subfield, the citation count is divided by the average count of all papers in the relevant subfield (e.g. astronomy and astrophysics) to obtain a relative citation (RC) count. The ARC of a given entity is the average of the RC count of papers belonging to it (source: Science-Metrix).

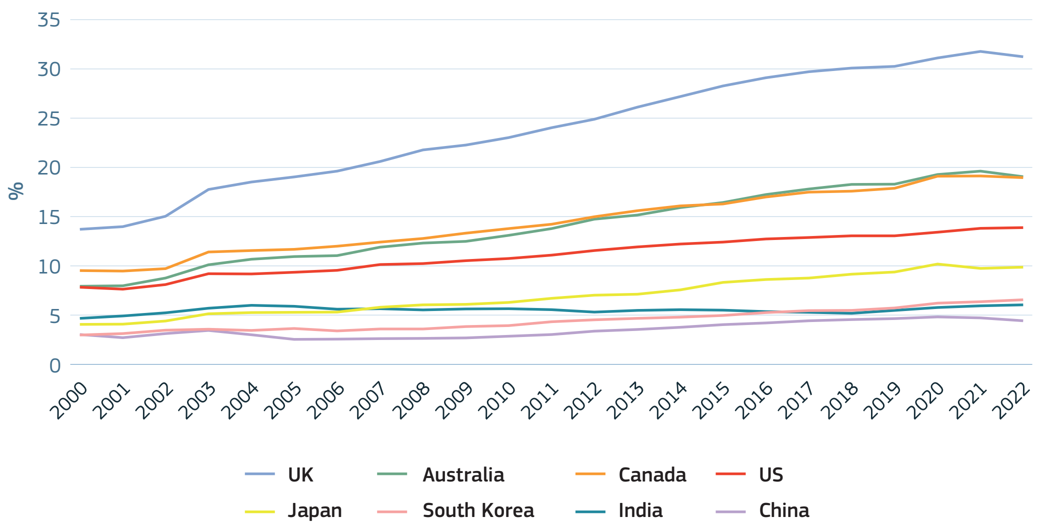
Figure 3.1-27 Average of relative citations (ARC), 2020 (citation window: 2020-2022)



Science, research and innovation performance of the EU 2024

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

Figure 3.1-28 Share of international publications co-authored with the EU

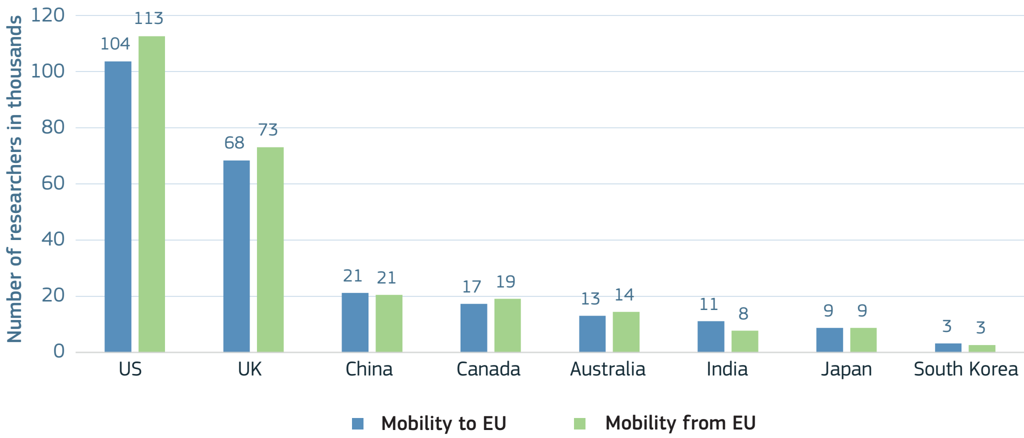


Science, research and innovation performance of the EU 2024

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

International mobility for researchers is key for knowledge diffusion and can positively affect research productivity by improving matching between researchers and research environments. Empirical studies suggest that mobility is an important mechanism in the spread of ideas and technology transfer (Veugelers and Van Bouwel, 2015). In the past decade, researcher mobility from and to the EU has increased, with outflows of researchers from the EU to the US and the UK slightly higher than inflows to the EU from those countries (brain drain) (Figure 3.1-29).

Figure 3.1-29 **Researcher mobility to and from the EU (in thousands)**



Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on OECD database of bibliometric indicators of implied bilateral mobility flows. Data are based on the main country/regional affiliation for authors captured in at least two documents published and indexed in the Scopus database over the 2007-2021 period. Counts are based on the number of authors with distinct country affiliations in their first and last recorded publications within this period. Flows to and from interim affiliations are not taken into account in this figure. In cases of multiple country affiliations (approximately 2% of documents), the most recurrent (modal) affiliation is used.

3. Societal Grand Challenges, Sustainable Development Goals and Key Emerging Technologies

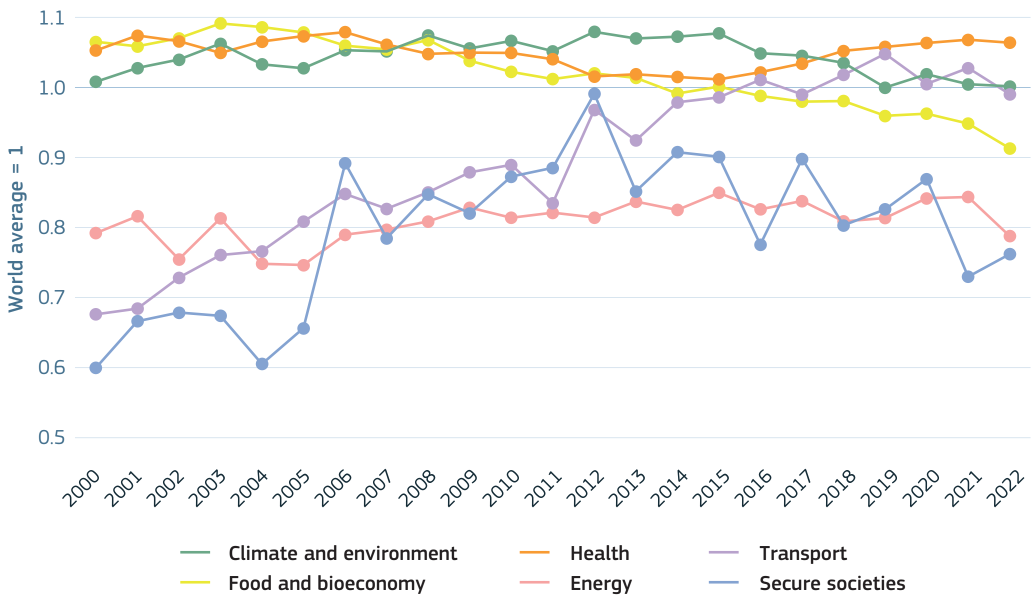
The EU is committed to addressing the societal grand challenges. It contributes significantly to the body of research into SGCs[20], accounting for 14-19% of publications worldwide, a percentage that has decreased over a 10-year period. In 2022, China led the world in the share of scientific publications across all six Horizon 2020 SGCs, while the US has seen a significant decline in its publication share for all SGCs over the last 10 years. One noteworthy finding is the increased contribution of the BRIS countries on all SGCs, particularly in the 'secure societies' category. This rise in the secure societies group is primarily attributed to a large number of publications from India and Russia.

Overall, the EU is more specialised in publications related to health and less specialised in publications on secure societies and energy. Over the last two decades, the EU has significantly increased its specialisation in publications related to transport (Figure 3.1-30). In comparison to the US, the EU is more specialised in energy, climate and environment, and food and bioeconomy, and less specialised in health (Figure 3.1-31). In contrast, the specialisation level of the EU relative to China has decreased or stagnated for all SGCs but the EU is still more specialised in health publications than China (Figure 3.1-32). China's strong shift towards addressing environmental challenges is also evident in the Nature Index, where it overtook the US as the leading nation in earth and environmental sciences in 2022. This trend is explained by the increased funding and resources the country has allocated to atmospheric sciences, geology and materials science but also the greater number of Chinese scientists returning to China after training abroad.[21]

20 The Horizon 2020 Societal Grand Challenges are: health, demographic change and well-being (health); food security, sustainable agriculture and forestry, marine, maritime and inland water research, and the bioeconomy (food and bioeconomy); secure, clean and efficient energy (energy); smart, green and integrated transport (transport); climate action, environment, resource efficiency and raw materials (climate), and secure societies – protecting the freedom and security of Europe and its citizens (security).

21 https://www.nature.com/articles/d41586-023-02159-7

Figure 3.1-30 EU Specialisation Index[1] (SI), 2000-2022

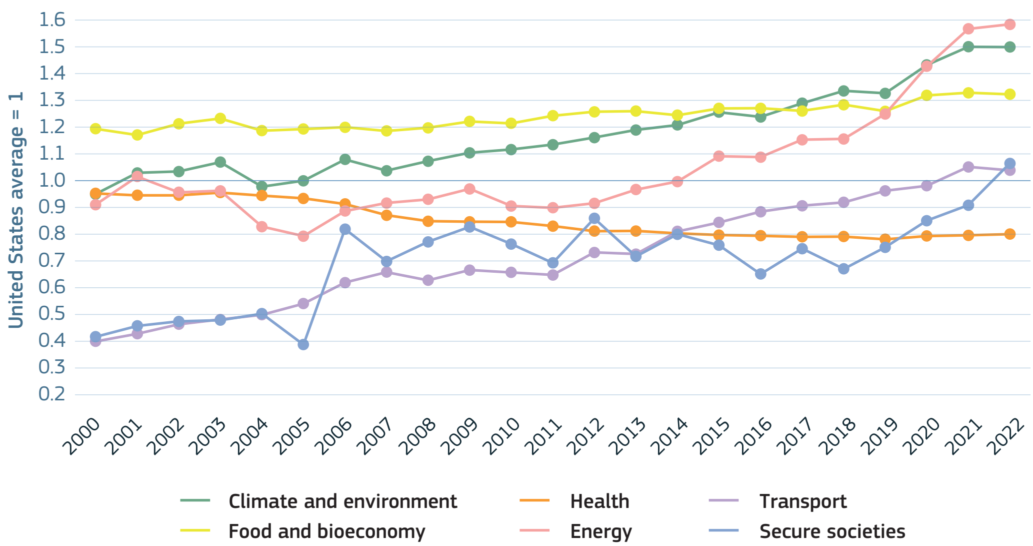


Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on Science-Metrix data 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. a 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 shows how much emphasis that country places on research in that domain relative to overall global emphasis. Comparisons are meaningful only between countries of similar size.

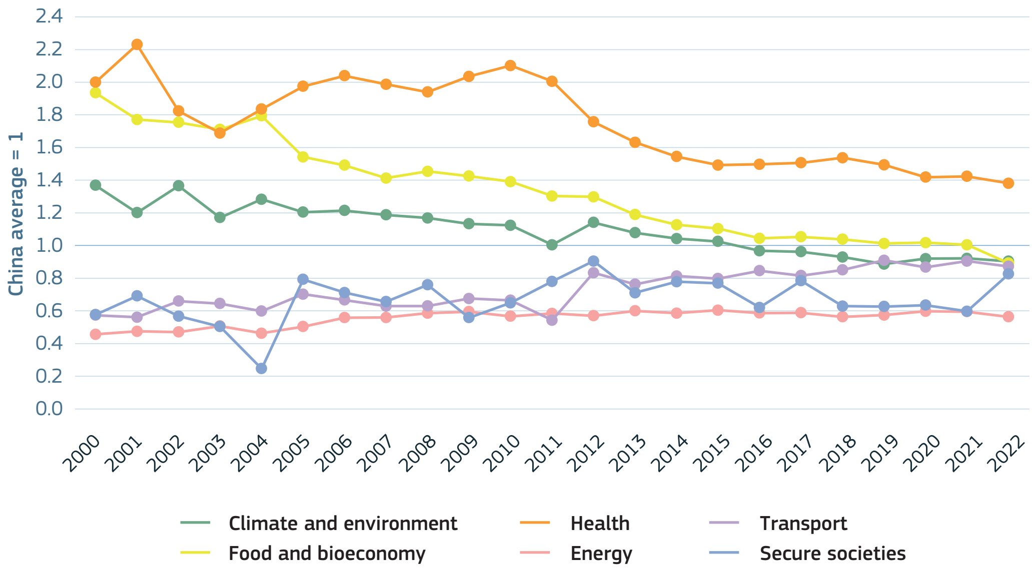
Figure 3.1-31 EU Specialisation Index compared to the US, 2000-2022



Science, research and innovation performance of the EU 2024

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

Figure 3.1-32 EU Specialisation Index compared to China, 2000-2022



Science, research and innovation performance of the EU 2024

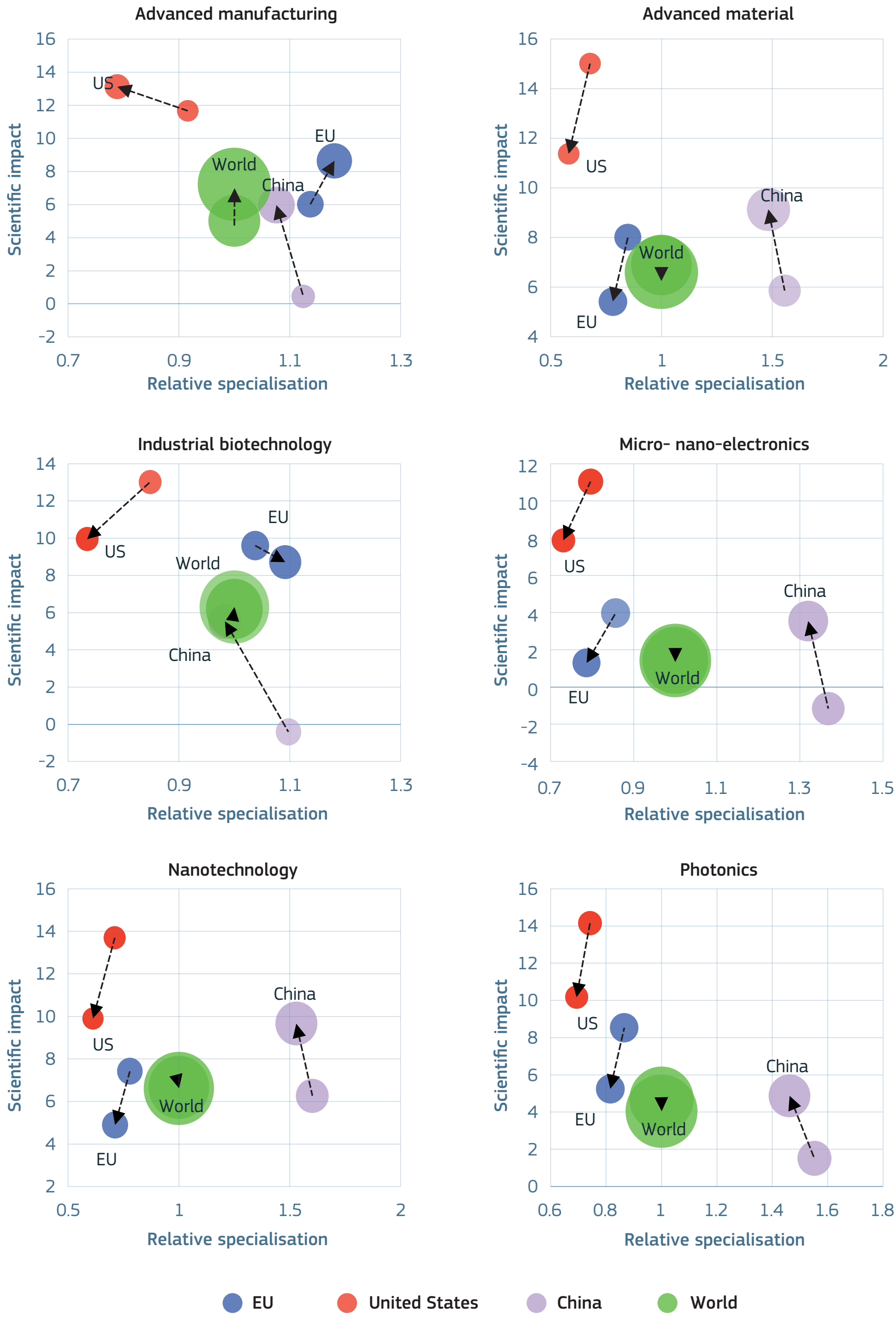
Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on Science-Metrix data using the Scopus database.

Key enabling technologies (KETs)[22] are critical for boosting industrial innovation, and the EU is a global player in these technologies. Specifically, the EU has improved its position over the years in advanced manufacturing, showing a higher level of specialisation than its global competitors, as well as producing more impactful publications. Additionally, the EU maintains an advantage in industrial biotechnology, with publications that are more impactful than the global average and a higher level of specialisation. China has shown a relatively high level of specialisation in most of the KETs, along with a clear upward trend in the quality of its publications, which is consistent with what is observed in STEM fields. Meanwhile, the US tends to be less specialised in KETs but produces more impactful publications, despite a decline between the 2013-2017 and 2018-2022 periods (Figure 3.1-33).

More specifically, in the field of AI, which comes under the new KET definition, China is leading. According to Stanford University's Artificial Intelligence Report 2023, China accounted for almost 40% of all publications on AI in 2021, surpassing EU and the UK (15%) and the US (10%). In addition, papers from China accounted for 29% of all AI citations in 2021, again exceeding those from Europe and the UK (21.5%) and the US (15%).

22 The definition of KETs used here is a group of six technologies, identified in the KET Communication COM (2012) 3413: micro and nanoelectronics, nanotechnology, industrial biotechnology, advanced materials, photonics, and advanced manufacturing technologies.

Figure 3.1-33 Dynamic positions in scientific impact and specialisation in the Key Enabling Technologies, 2013-2017 and 2018-2022



Science, research and innovation performance of the EU 2024

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

Note: Relative specialisation is measured by the Specialisation Index (SI), which indicates the research intensity of a country or region in a specific research area, relative to the global intensity in the same area. The global-level SI is 1; a higher index indicates greater specialisation than the global level. Scientific impact is assessed using the Citation Distribution Index (CDI); a higher CDI signifies greater scientific impact, as measured by citations.

The SDGs remain a fundamental aspect of European policy. The European Commission continues to monitor progress towards the achievement of specific targets through a set of indicators developed by Eurostat for this purpose. The key features of the EU SDG indicator set remain consistent, structured on the basis of the 17 SDGs[23]. Additionally, the EU SDG indicator set is aligned with, but not identical to, the UN list of global indicators[24], reflecting regional nuances and the unique priorities of the EU (European Commission, 2024).

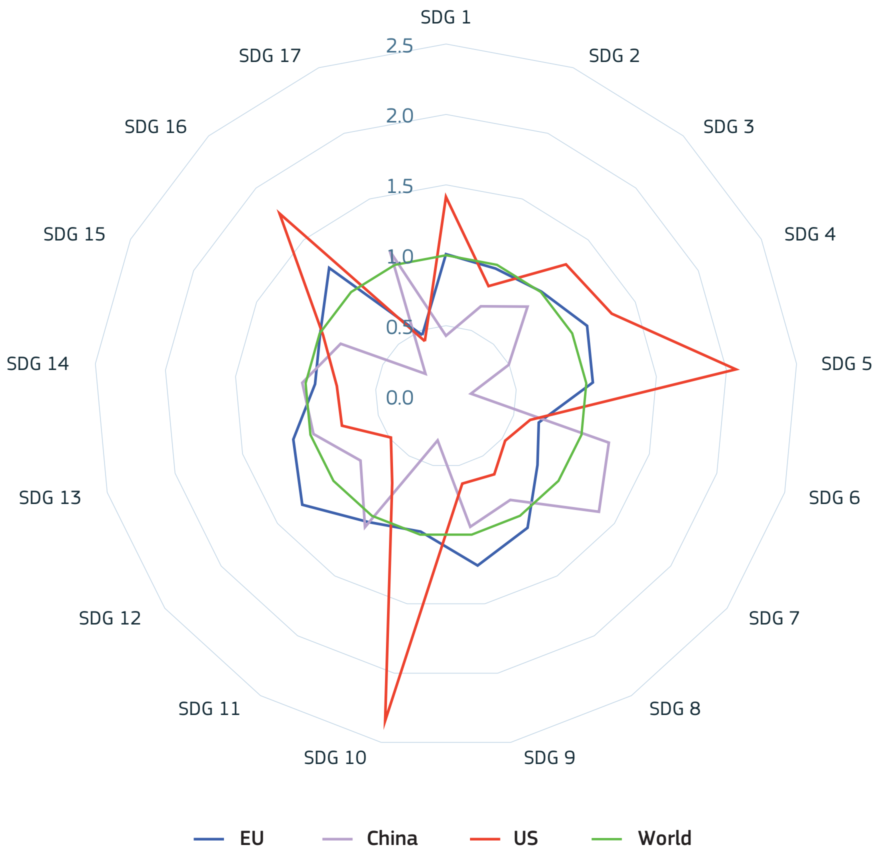
Progress towards the SDGs over the past 5 years is also partially reflected in the EU's specialisations in terms of scientific output compared with other key global players. The EU leads in SDGs 8 (decent work and economic growth), 9 (industry, innovation and infrastructure), 12 (responsible consumption and production) and 13 (climate action). China is the leader in SDGs 6 (clean water and sanitation), 7 (affordable and clean energy), 11 (sustainable cities and communities), 14 (life below water) and 17 (partnerships for the goals). The US shows the highest level of specialisation in SDGs 1 (no poverty), 3 (good health and well-being), 4 (quality education), 5 (gender equality), 10 (reduced inequalities) and 16 (peace, justice and strong institutions) (Figure 3.1-34).

Attempts to measure, at global level, the coherence between progress towards the SDGs and research priorities (measured by specialisation in scientific output) reveal that alignment is not always evident or consistent (Confraria et al., 2024). For example, for SDGs 3 (good health and well-being), 7 (affordable and clean energy) and 10 (reduced inequalities), there seems to be a positive alignment between SDG challenges and research priorities. Nevertheless, this alignment appears to be linked to historical research specialisation patterns and potential international research funding trends to a greater extent than to current challenges. In the case of SDG 12 (responsible consumption and production), countries with the most unsustainable consumption/production patterns, primarily high-income countries, are not typically specialising or becoming specialised in research into related themes.

23 Each with six indicators and incorporating multi-purpose indicators for efficient monitoring.

24 The EU SDG indicator set, reviewed annually, ensures continuous policy relevance and improved statistical quality. For instance, in the 2024 version, 68 out of 102 indicators in the set are considered to be aligned with the UN list, highlighting the nuanced alignment with global goals to accommodate regional specificities.

Figure 3.1-34 Specialisation Index for each SDG(1), 2022



Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit based on Science-Metrix data 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 inequalities; 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; SDG 17 – partnerships for the goals.

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CHAPTER 3.2

UNIVERSITIES, RESEARCHERS AND OPEN SCIENCE

Key questions

- What are the best universities in the world?
- What are the dynamics regarding flows of researchers around the globe?
- What are benefits of and challenges in industry-academia collaborations, and how can they be addressed?
- What are the challenges and opportunities associated with open science?

Highlights

- The EU approach features a broad range of moderately performing institutions, which contrasts with the Anglo-Saxon academic system's focus on a concentration of elite institutions.
- Immigration, particularly skilled immigration, plays a crucial role in enhancing research and innovation (R&I), with immigrants disproportionately represented among inventors and entrepreneurs.
- Factors contributing to the EU's brain drain include language barriers, rigid academic hierarchies, low salaries and strict immigration laws, in contrast to more welcoming policies in the US, Canada and Australia.
- Universities and their industrial partners have different missions; they also have complementary skillsets. Universities excel in problem-solving and exploration, while industry partners are skilled at developing and refining discoveries.
- Open access democratises knowledge access and increases research visibility but faces challenges like shifting of publication costs to authors, potential quality compromises and creation of financial disparities within the research community.

Policy insights

- Liberal immigration policies can serve as catalysts for innovation by attracting highly skilled immigrants who often make significant contributions to research, patenting and scientific achievements. These talents enrich the host country's intellectual capital without adding to educational costs.
- The EU brain drain is diminishing thanks to internationalisation policies such as the Bologna and Lisbon processes.
- Public-private collaborations in research are increasing worldwide.
- The EU leads other countries in open access rates, with significant growth in numbers of open access publications in most Member States.

This chapter explores the integral role of universities in spurring innovation and shaping global intellectual landscapes through detailed analysis of higher education systems worldwide, flows of researchers, the role of industry-academia collaborations and open science.

The chapter highlights differing educational philosophies between the EU and Anglo-Saxon countries (US, UK). The EU prioritises broad access to universities of moderate quality, whereas the Anglo-Saxon approach favours a smaller number of exceptional institutions. Migration policies that aim to retain and attract talent are crucial for R&I performance. Public and private institutions serve distinct yet complementary roles in R&I, underscoring the importance of collaboration between these sectors. Additionally, open science offers a host of benefits and poses several challenges, which the EU is actively addressing.

1. Higher education systems around the world

Universities can significantly boost innovation in different ways. Firstly, by their establishment and growth, they augment the pool of individuals with qualifications in science, technology, engineering and mathematics (STEM). STEM professionals are in a position to drive innovation forward. Secondly, academic research cultivates new ideas that can be transformed into commercial innovations. This transformation often occurs through channels such as entrepreneurial ventures by scientists, collaborations between universities and corporations, or informal networks (Teichgraeber and Van Reenen, 2022). In their comprehensive study, Valero and Van Reenen (2019) examined data spanning 50 years across more than 100 countries. Their findings reveal that the establishment of a university positively impacts local per-capita output and increases patenting activity in subsequent years.

The US and the UK have the best universities in the world. Table 3.1-1 shows the world's top universities according to three of the most established world university rankings. The QS World University Rankings feature almost 1 500 institutions across 104 countries, evaluating them based on academic and employer reputation, research citations, international research networks, employment outcomes and sustainability.[1] The Times Higher Education (THE) World University Rankings include 1 799 universities across 104 countries, using various performance indicators to assess teaching, research, industry knowledge-transfer and international outlook.[2] The Academic Ranking of World Universities (ARWU), also known as the Shanghai Ranking, includes 1 000 universities, ranking them based on several academic or research performance indicators, including Nobel Prizes and Fields Medals won by alumni and staff, highly cited researchers, papers published in the Nature and Science journals and papers indexed in major citation indices.[3] For all rankings, information is collected through surveys of academic faculties and employers, and administrative, bibliometric and patent data.

1 See more on the methodology of the QS ranking here.

2 See more on the methodology of the THE ranking here.

3 See more on the methodology of the Shanghai Ranking here.

Table 3.2-1 Top 20 world universities

QS ranking	University	Ctry	THE ranking	University	Ctry	Shanghai Ranking	University	Ctry
1	Massachusetts Institute of Technology	US	1	University of Oxford	UK	1	Harvard University	US
2	University of Cambridge	UK	2	Stanford University	US	2	Stanford University	US
3	University of Oxford	UK	3	Massachusetts Institute of Technology	US	3	Massachusetts Institute of Technology	US
4	Harvard University	US	4	Harvard University	US	4	University of Cambridge	UK
5	Stanford University	US	5	University of Cambridge	UK	5	University of California, Berkeley	US
6	Imperial College London	UK	6	Princeton University	US	6	Princeton University	US
7	ETH Zurich	CH	7	California Institute of Technology	US	7	University of Oxford	UK
8	National University of Singapore	SG	8	Imperial College London	UK	8	Columbia University	US
9	University College London	UK	9	University of California, Berkeley	US	9	California Institute of Technology	US
10	University of California, Berkeley	US	10	Yale University	US	10	The University of Chicago	US
11	The University of Chicago	US	11	ETH Zurich	CH	11	Yale University	US
12	University of Pennsylvania	US	12	Tsinghua University	CN	12	Cornell University	US
13	Cornell University	US	13	The University of Chicago	US	13	University of California, Los Angeles	US
14	The University of Melbourne	AU	14	Peking University	CN	14	University of Pennsylvania	US
15	California Institute of Technology	US	15	Johns Hopkins University	US	15	Paris-Saclay University	FR
16	Yale University	US	16	University of Pennsylvania	US	16	Johns Hopkins University	US

17	Peking University	CN	17	Columbia University	US	17	University College London	UK
18	Princeton University	US	18	University of California, Los Angeles	US	18	University of Washington	US
19	The University of New South Wales (UNSW Sydney)	AU	19	National University of Singapore	SG	19	University of California, San Diego	US
20	The University of Sydney	AU	20	Cornell University	US	20	ETH Zurich	CH

Science, research and innovation performance of the EU 2024

Note: QS ranking refers to the QS World University Rankings 2024. THE ranking refers to The Times Higher Education World University Rankings 2024. Shanghai Ranking refers to the ARWU 2023.

The University of Oxford and the University of Cambridge in the UK, along with the Massachusetts Institute of Technology, Harvard University and Stanford University in the US, consistently rank among the top institutions in all three major global university rankings. Slightly further down, Chinese universities, particularly Peking University and Tsinghua University, have also made their mark in the top 20. Representing Australia and Singapore are the University of Melbourne, UNSW Sydney, the University of Sydney and the National University of Singapore. Europe's presence in the top 20 of all three rankings is led primarily by ETH Zurich, in Switzerland.

Although they are not at the very top, EU universities have a strong presence in the medium-to-high sections of the world rankings. Table 3.1-1 restricts the sample to EU universities, showing the positions in the world rankings of the top 20 universities in the EU. French and German universities top the EU rankings, with the Netherlands, Belgium, Sweden and Denmark consistently represented in the top 20. Noticeably, southern European universities are much further down in the rankings.

Table 3.2-2 Top 20 EU universities

QS ranking	University	Ctry	THE ranking	University	Ctry	Shanghai Ranking	University	Ctry
24	Université PSL	FR	31	Technical University of Munich	DE	15	Paris-Saclay University	FR
37	Technical University of Munich	DE	39	Ludwig-Maximilians-Universität München	DE	32	University of Copenhagen	DK
38	Institut Polytechnique de Paris	FR	40	Université PSL	FR	37	Karolinska Institutet	SE
47	Delft University of Technology	NL	45	KU Leuven	BE	41	Université PSL	FR
53	University of Amsterdam	NL	47	Universität Heidelberg	DE	46	Sorbonne University	FR

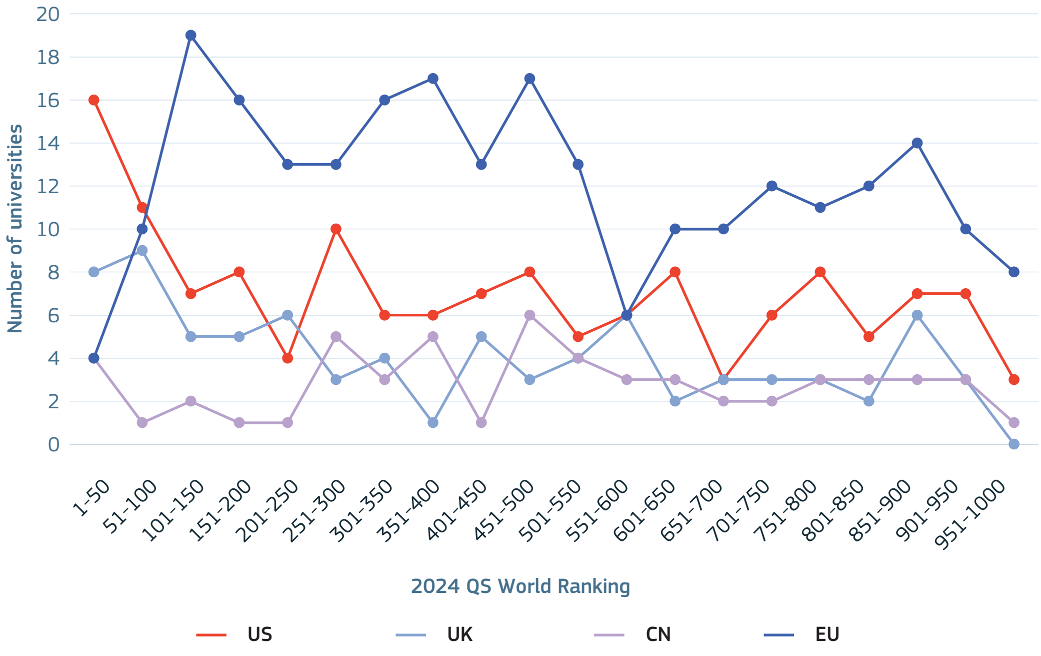
55	Ludwig-Maximilians-Universität München	DE	48	Delft University of Technology	NL	52	Utrecht University	NL
59	Sorbonne University	FR	50	Karolinska Institutet	SE	55	Universität Heidelberg	DE
61	KU Leuven	BE	58	Paris-Saclay University	FR	59	Technical University of Munich	DE
71	Paris-Saclay University	FR	61	University of Amsterdam	NL	61	Ludwig-Maximilians-Universität München	DE
73	KTH Royal Institute of Technology	SE	66	Wageningen University & Research	NL	67	University of Bonn	DE
81	Trinity College Dublin, The University of Dublin	IE	71	Institut Polytechnique de Paris	FR	69	Université Paris Cité	FR
85	Lund University	SE	75	Sorbonne University	FR	76	University of Groningen	NL
87	Universität Heidelberg	DE	77	Leiden University	NL	78	Aarhus University	DK
98	Freie Universität Berlin	DE	79	University of Groningen	NL	82	Uppsala University	SE
105	Uppsala University	SE	89	Humboldt University of Berlin	DE	84	Ghent University	BE
106	RWTH Aachen University	DE	90	RWTH Aachen University	DE	86	KU Leuven	BE
107	University of Copenhagen	DK	91	University of Bonn	DE	88	Erasmus University Rotterdam	NL
108	Utrecht University	NL	94	Charité Universitätsme-dizin Berlin	DE	99	Stockholm University	SE
109	Aalto University	FI	96	University of Tübingen	DE	110	Leiden University	NL
115	University of Helsinki	FI	97	KTH Royal Institute of Technology	SE	116	Radboud University Nijmegen	NL

Science, research and innovation performance of the EU 2024

Note: QS ranking refers to the QS World University Rankings 2024. THE ranking refers to The Times Higher Education World University Rankings 2024. Shanghai Ranking refers to the ARWU 2023.

The Anglo-Saxon academic system features a concentration of high-performing institutions, while the EU exhibits a more uniform distribution, prioritising a large number of moderate-quality institutions rather than a few exceptional universities. Figure 3.1-1 shows that while the US and the UK are home to many of the world's most prestigious institutions, the EU possesses a higher number of both mid-tier and lower-tier universities. China's distribution is particularly interesting, displaying a concerted effort by a select group of institutions to ascend the rankings, while a majority remain at the lower end of the spectrum. Figure 3.1-2 conveys the same message by adjusting for the total number of universities in each country. The UK and the US outperform the EU in terms of universities per capita in the top 50 and ranked from 51 to 100, while the EU outperforms the US in terms of universities per capita ranked from 101 to 1 000.

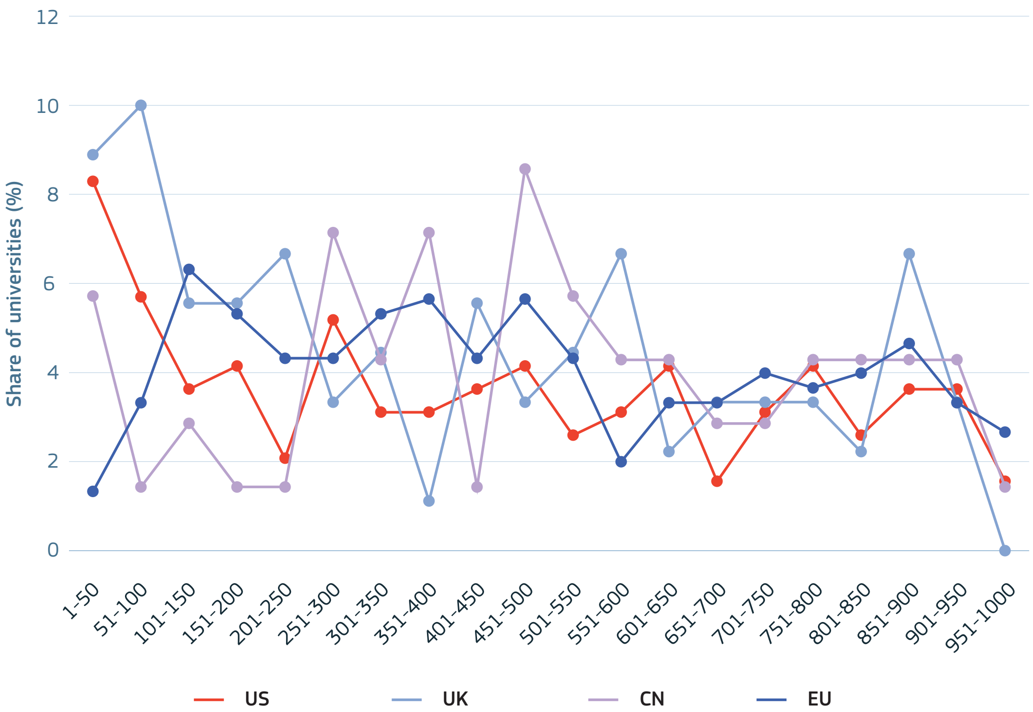
Figure 3.2-1 **Distribution of university quality (in absolute terms) around the world**



Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on the QS World University Rankings 2024.

Figure 3.2-2 Distribution of university quality (in relative terms) around the world



Science, research and innovation performance of the EU 2024
Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on the QS World University Rankings 2024. Note: Shares are computed as the ratio of the number of universities within each ranking window for each country to the total number of universities in each country (from rank 1 to rank 1 000).

University rankings, while informative, are inherently imperfect due to the complex and multifaceted nature of university performance. This performance spans numerous dimensions, many of which are challenging to quantify. Consequently, these diverse factors are condensed into a single numerical ranking, necessitating some level of arbitrariness in the weighting and prioritisation of different criteria (Fauzi et al., 2020; Elsevier, 2023).

Box 3.1: U-Multirank - a different way of ranking universities

In response to the increasing prominence of global university rankings, there has been significant criticism of the reliance on a single composite indicator to rank universities. This criticism has spurred the development of alternative approaches.

One notable alternative is U-Multirank, which adopts a user-driven approach to the international ranking of higher education institutions. Unlike traditional methods that offer a uniform ranking, U-Multirank acknowledges that the definition of excellence varies depending on individual student needs and aspirations. Consequently, U-Multirank provides a platform that allows users to customise their rankings based on what matters most to them. Through a brief survey that explores key priorities such as academic field, teaching quality, research output and international scope, users can obtain a list of universities that align with their specific preferences and requirements. This approach emphasises that there is no one-size-fits-all method for finding the best university; each person has to find the one that is right for them.

Despite the imperfect measurements provided by such rankings, some countries have started to use them to shape their migration policies. As an example, the UK has introduced a new simplified visa programme, the High Potential Individual visa, to attract talented graduates from top global universities. Recent graduates from universities ranked in the top 50 in at least two of the three major global ranking systems referred to above are eligible for this programme. These individuals can apply to live and work in the UK for up to 3 years, even without a job offer. This initiative is part of the UK's move to a points-based immigration system, where eligibility is determined by skills, occupation and educational background.

2. The dynamics of global research talent

Immigration, though not typically seen as an R&I policy, plays a critical role in these domains. Immigrants are disproportionately represented among inventors and entrepreneurs. In the US, for instance, while immigrants make up 14% of the workforce, they account for 52% of STEM doctorates, a quarter of all patents and a third of all US Nobel Prizes. Extensive research, including surveys by Kerr and Kerr (2021), confirms that immigration, particularly of highly skilled individuals, significantly boosts innovation. Studies like Hunt and Gauthier-Loiselle (2010) demonstrate that a 1% increase in the proportion of immigrant university graduates can lead to a 9-18% rise in patenting per person. Other studies, such as Kerr and Lincoln (2010), and Bernstein et al. (2018), have identified positive impacts on innovation from policy changes related to H-1B visas. Similarly, Moser, Voena and Waldinger (2014) demonstrated how the Nazi expulsion of Jewish scientists from Germany in the 1930s inadvertently spurred innovation in American chemistry when these scientists relocated to the US.

Immigration, especially skilled immigration, increases innovation. The advantages of a liberal immigration policy are particularly striking given that the educational costs of these immigrants are often borne by their countries of origin, not by the host country's taxpayers. Moreover, this influx of human capital can have a swift impact, distinguishing liberal immigration policy from other human capital supply-side policies like educational improvements (Teichgraeber and Van Reenen, 2022).

The pursuit of enhanced competitiveness in higher education has led the EU to implement internationalisation policies, notably through the Bologna and Lisbon processes. These initiatives have successfully promoted mobility within Europe and attracted international talent. However, this progress is not without its challenges, as Europe faces the issue of brain drain – the emigration of skilled academics to other countries – leading to a loss of human capital.

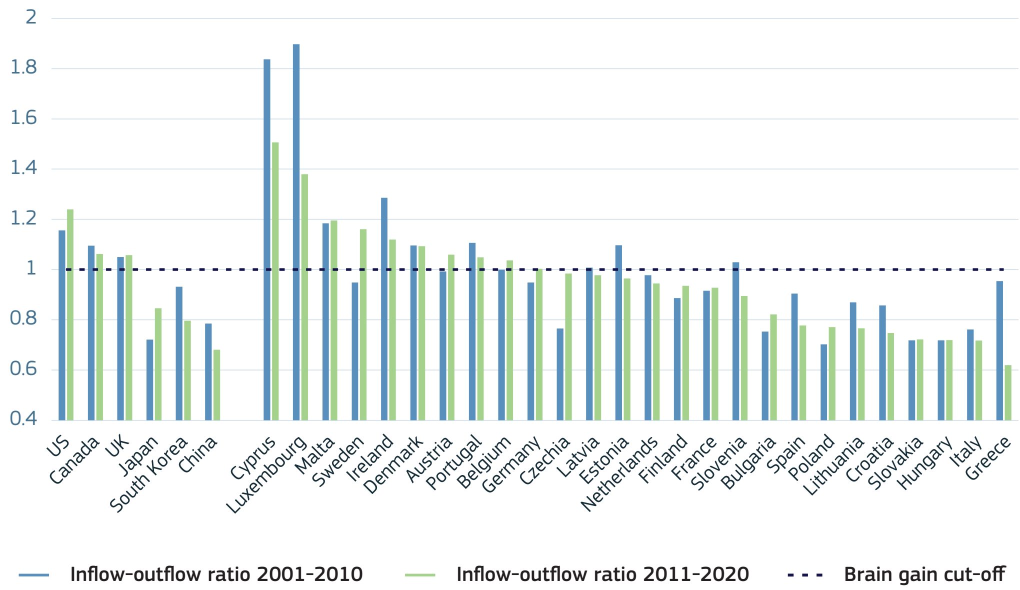
One significant recent development affecting European academic mobility is the UK's decision to leave the EU. The UK has been a pivotal player in the European Research Area (ERA), and its departure poses a challenge to ERA's attractiveness to international researchers. While brain drain is sometimes counterbalanced by brain circulation, the ongoing exodus of academics from Europe remains a concern.

Several factors undermine the EU's appeal and contribute to brain drain. These include language barriers, rigid academic hierarchies, staffing and governance issues and discrepancies between national higher education systems and the international demands of a borderless university. The recognition of achievements by non-EU students and staff often presents challenges. And even the highest academic salaries in Europe still fall short of those in the US or Japan. The majority of EU researchers rely on grants due to a lack of permanent positions, while recruitment processes in some southern European institutions lack fairness. Strict immigration laws in many European countries further discourage academic migration, unlike the more welcoming policies tailored for highly skilled individuals in the US, Canada and Australia (Khan, 2021; European Commission, 2021).

The EU's strengths are perceived to lie in areas not directly related to research, such as social and job security, pension plans and the quality of education and training. However, the EU still lags in aspects crucial to scientific productivity, like career progression, research funding and availability of suitable positions. To combat these issues, the EU has implemented initiatives like the Marie Skłodowska-Curie Actions, which are aimed at retaining European talent, attracting foreign researchers and encouraging Europeans abroad to return (Dėlkutė et al., 2022).

From 2010 to 2020, most EU countries reduced their brain drain. Figure 3.2-3 shows countries' brain drain in relative terms.[4] A value below 1 means that more researchers left the country than entered it. A value above 1 means that the country had more researchers entering than leaving. From 2001 to 2010, some Member States, including Belgium, Finland, France, Germany, the Netherlands and Sweden, experienced significant brain drain. From 2011 to 2020, the situation in Belgium, Germany and Sweden improved. In contrast, southern European countries continue to face challenges related to brain drain. In absolute terms[5], the US has witnessed the most substantial brain gain globally, whereas China has experienced the biggest brain drain.

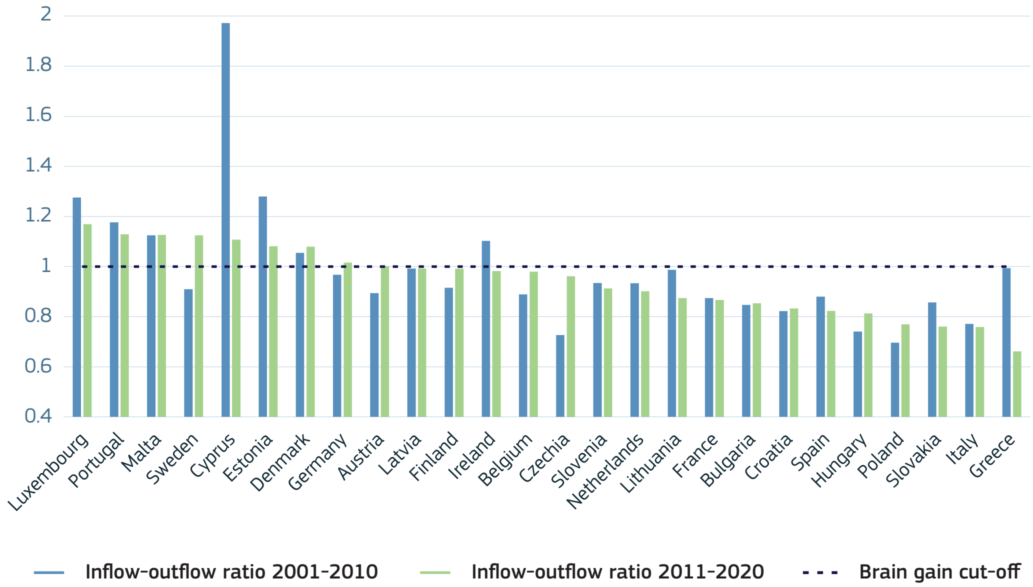
Figure 3.2-3 Brain drain trends around the world



Science, research and innovation performance of the EU 2024
Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on ScienceMetrix data using the Scopus database.

4 Relative brain drain is measured as (researcher inflow)/(researcher outflow).
5 Absolute brain drain is measured as researcher inflow- researcher outflow.

Figure 3.2-4 EU brain drain trends excluding flows within ERA

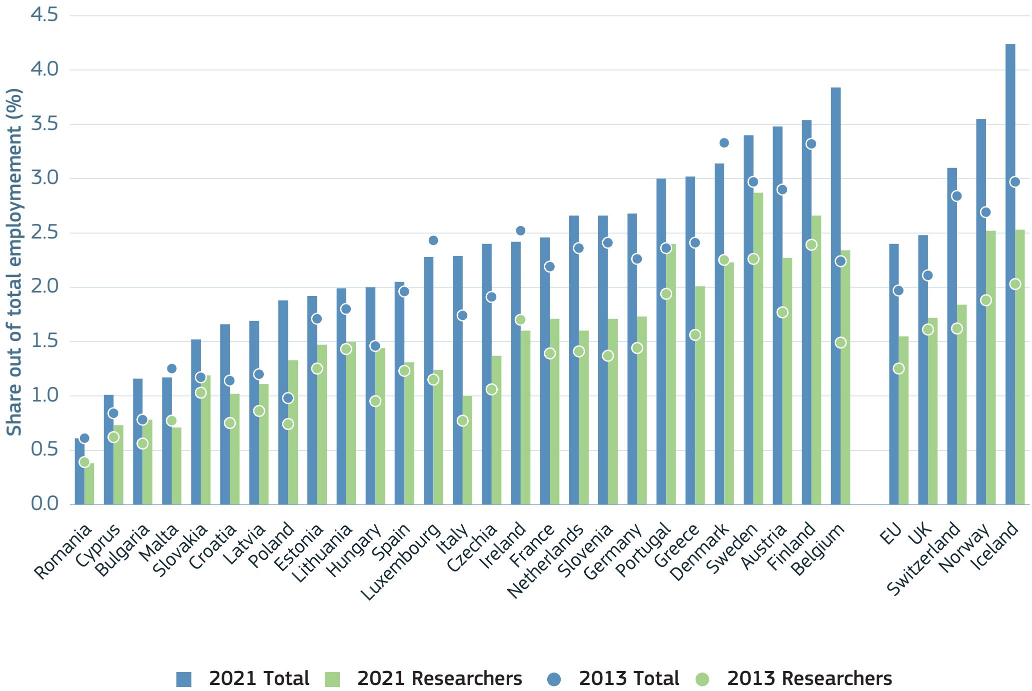


Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on ScienceMetrix data using the Scopus database. Note: To exclude flows within ERA, only inflow from and outflow to non-ERA countries are considered.

From 2013 to 2021, most EU countries increased their numbers of research and development (R&D) personnel and researchers. Austria, Belgium, Denmark, Finland and Sweden are the countries with the highest numbers of R&D personnel and researchers as a share of total employment. In 2021, researchers and R&D staff accounted for 2.4% of total employment in the EU, while researchers alone accounted for 1.97%. (Figure 3.2-5).

Figure 3.2-5 R&D personnel and researcher numbers as a share of total employment



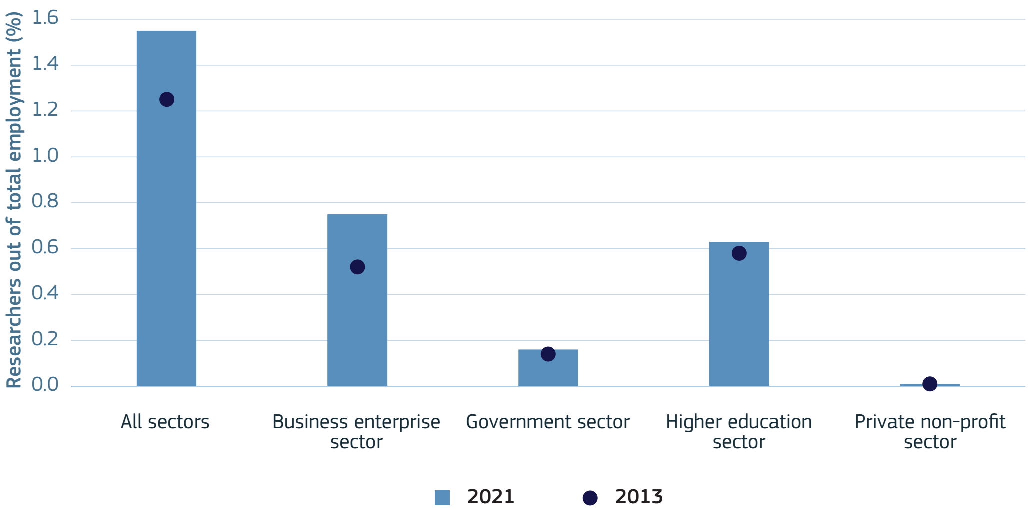
Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on Eurostat data (online data code: rd_p_perslf). Note: Data for Denmark refer to 2020, data for the UK refer to 2018 and data for Switzerland refer to 2015.

3. Industry-academia collaboration

The business sector has the highest number of researchers in the EU, followed by academia and the government sector. This is a result of a recent boom in the number of researchers hired by private companies. Between 2013 and 2021, the share of researchers in total EU employment rose from 1.25% to 1.55%. However, this increase was mostly driven by the business sector, in which the share of researchers in total employment climbed from 0.52% to 0.75%, while in academia the share remained steady at around 0.6% of total employment (Figure 3.3-6).

Figure 3.2-6 Researchers by sector (EU)

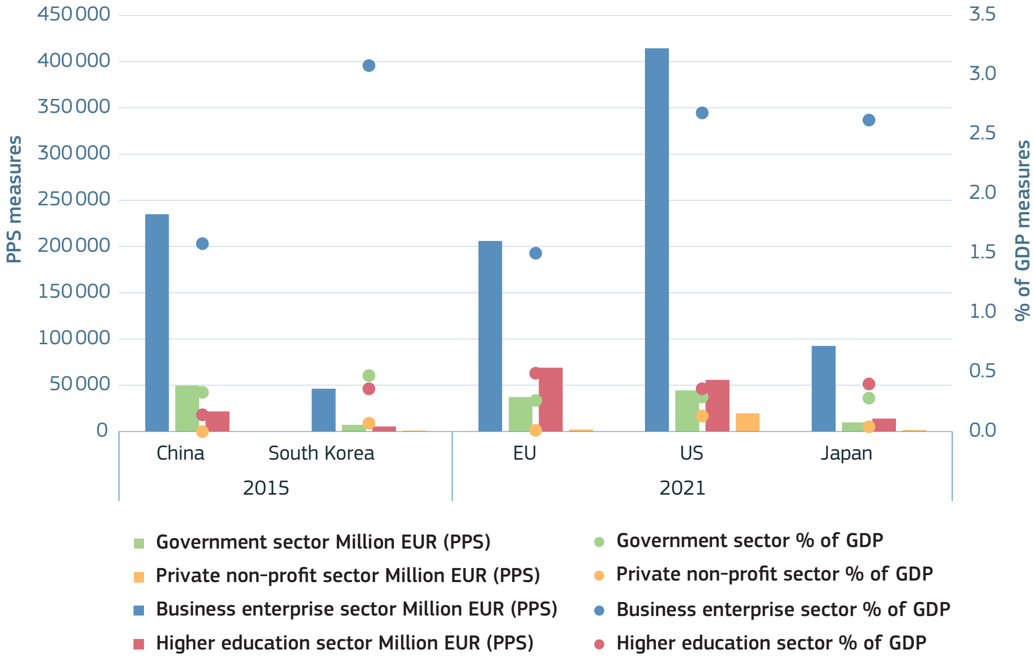


Science, research and innovation performance of the EU 2024

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

In the EU, the business sector invests the highest amount in R&D, followed by academia and the government sector. In all of the EU's main international competitors, the business sector is the main player when it comes to investment in R&D. In the US, South Korea and Japan, the second-largest investor is academia, while in China it is the government. In the EU, the private sector spends around 1.5 % of GDP on R&D, academia spends 0.5 %, government spends 0.3 %, and the private non-profit sector spends 0.01 % (figure 3.3-7).

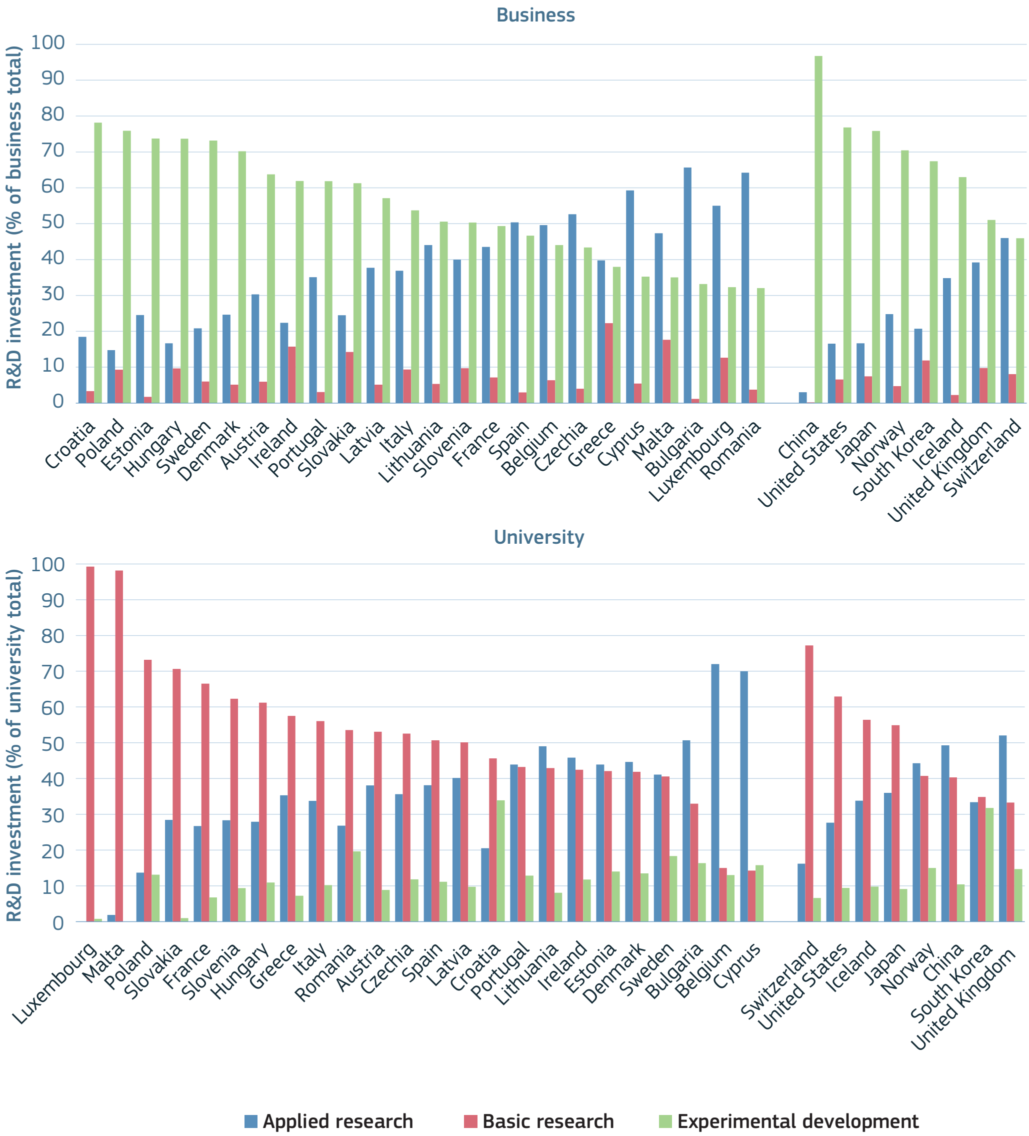
Figure 3.2-7 R&D investment by sector around the world



Science, research and innovation performance of the EU 2024
Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on Eurostat data (online data code: rd_e_gerdact).

Universities and their industrial partners have different missions; they also have complementary skillsets. Each brings something to the table when it comes to making innovative discoveries. University researchers are good at finding difficult problems and have the freedom to pursue different solutions; companies are good at taking discoveries and developing them. Figure 3.3-8 illustrates complementarities between business and university R&D. Specifically, it highlights how business R&D is primarily focused on applied R&D, while university R&D is predominantly focused on basic research.

Figure 3.2-8 Complementarities between university and businesses research



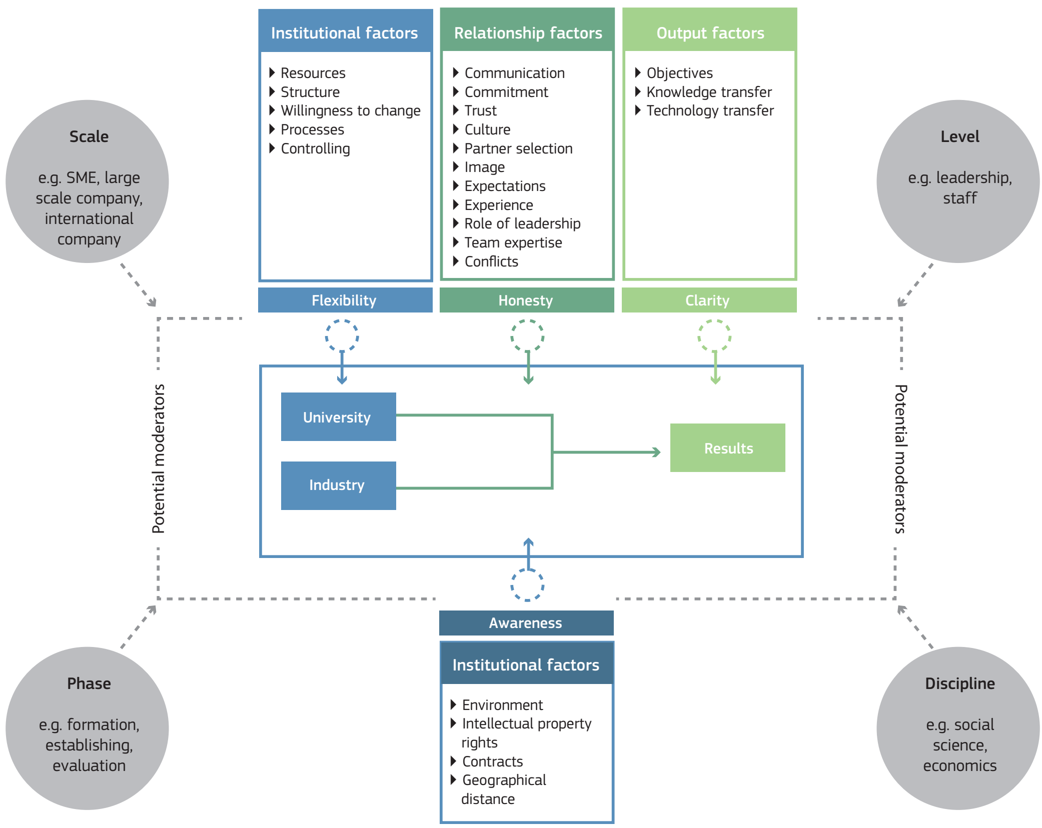
Science, research and innovation performance of the EU 2024

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

Industry-academia collaborations bridge the gap between theoretical research and practical application, ensuring that academic discoveries are translated into real-world solutions. Such collaborations facilitate the flow of knowledge and skills, allowing both sectors to benefit from each other's expertise. For academia, these partnerships provide valuable insights into industry needs and trends, enriching academic research and curricula with insights based on practical relevance. For industry, they offer access to cutting-edge research, innovative technologies and a pool of skilled graduates, fostering innovation and competitiveness. Additionally, industry-academia collaborations often lead to the development of specialised training programmes, internships and job opportunities for students, enhancing their employability. Furthermore, they play a crucial role in driving economic growth and addressing societal challenges by combining the research strength of universities with the market-oriented approach of businesses.

Although industry-academia collaboration is immensely beneficial, fundamental differences in operational culture and objectives often present challenges. Academic institutions, with their focus on long-term research and knowledge dissemination, operate within a structured, often bureaucratic system, which contrasts with the dynamic, results-driven nature of industry. These divergences can lead to misaligned expectations, particularly in terms of project timelines and desired outcomes. For instance, industry's push for rapid, practical results may conflict with academia's detailed, thorough research approach. Additionally, universities wish to publish findings, whereas companies seek to withhold them from competitors. Communication barriers further complicate these partnerships, as each sector typically employs distinct terminologies and styles of communication (Rybnicek and Königsgruber, 2019).

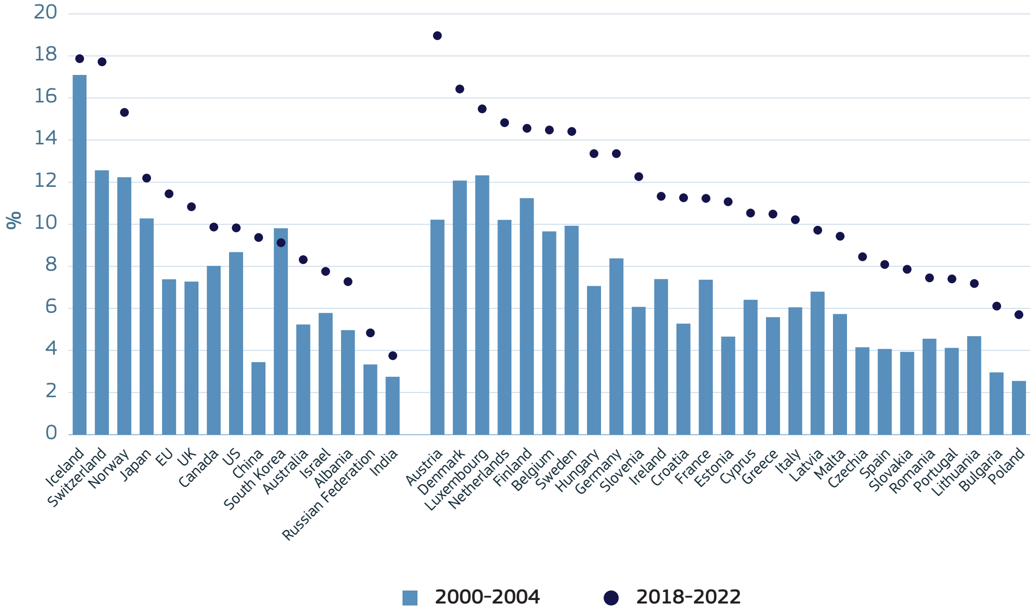
Figure 3.2-9 What makes industry-academia collaboration succeed?



Source: Rybnicek and Königsgruber, (2019).

The prevalence of public-private collaborations in research is increasing around the world. Figure 3.3-10 depicts trends in public-private co-publications from 2000 to 2022. Most countries have experienced an increase in the number of publications involving the participation of both a public and a private entity. Furthermore the EU has recently overtaken the US and the UK in this area.

Figure 3.2-10 Share of public-private co-publications



Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on ScienceMetrix data using the Scopus database.

4. Open science: challenges and opportunities

Open science is a scientific approach based on open, cooperative work and systematic sharing of knowledge and tools as early and widely as possible in the process. It has the potential to increase the quality and efficiency of research and accelerate the advancement of knowledge and innovation by sharing results, making them more reusable and improving their reproducibility. It entails the involvement of all relevant knowledge actors.

Open science practices include early and open sharing of research, for example through preregistration, registered reports, pre-prints or crowd-sourcing; research output management; measures to ensure reproducibility of research outputs; provision of open access to research outputs, such as publications, data, software, models, algorithms and workflows; participation in open peer review; and involvement of all relevant knowledge actors, including citizens, civil society and end users in the cocreation of R&I agendas and content, such as through citizen science activities.

An important element of open science is open access to peer-reviewed academic research. Open access fundamentally seeks to transform the traditional model of scholarly publishing, which often restricts the dissemination of research findings to those who can afford journal subscriptions or individual article fees.

Provision of free access for all readers is one of the foremost advantages of open access. It eliminates the need for costly subscriptions, allowing anyone to access academic articles freely. This democratisation of knowledge is in line with the increase in mandates to ensure public access to publicly funded research, reflecting a growing global consensus on the importance of unrestricted access to scientific knowledge.

Another advantage lies in the potential for increased readership and citations for authors. Open access broadens the reach of research papers, enhancing their visibility and impact in an age where the volume of published work is continually increasing. This increased visibility can translate into a higher number of citations, thereby amplifying the academic impact of the research.

Open access is also particularly beneficial for globally inclusive research. It is a boon for readers in developing countries, who often encounter barriers to accessing subscription-based journals. The flexibility of the model, including the possibility of waiving publication fees for authors from low-income countries, facilitates the creation of a more inclusive and diverse global research community.

However, open access does present challenges. A significant challenge is the shifting of publication costs to authors or their institutions. Traditionally, readers or their institutions have borne publication costs through subscriptions, but in open access, the financial burden is often shifted onto the authors or their funding bodies, who may have to pay publication fees, known as article processing charges (APCs). This shift can be a substantial challenge, especially for researchers with limited funding or from smaller institutions (Sanderson, 2023).

There are also concerns about potential compromises on quality control. The pay-per-article system might incentivise journals to prioritise quantity over quality in order to sustain revenue, as evidenced by instances where even reputable journals have accepted less rigorous articles. This issue raises critical questions about the integrity and reliability of the peer-review process in open access publishing (Greussing, 2020).

A further potential challenge is the risk of financial exclusion. Open access publishing may create disparities within the research community, segregating those who can afford it from those who cannot, particularly in developing countries. This disparity poses a significant challenge to the ethos of equal opportunity in scientific research and publication (Massarani, 2021). Indeed, the high rejection rates of prestigious journals often lead to elevated APCs for open access publications in such journals. This increase in cost is a direct consequence of maintaining the exclusivity and high standards associated with top-tier journals. However, in the academic world, publishing in these renowned journals remains crucial for professional success. Publication in such journals is not only a mark of scholarly excellence; it also contributes significantly to an academic's reputation, career advancement and potential to obtain future funding. This can make life easy for so-called predatory journals, which often promise low publishing fees and rapid publication but fail to provide proper quality control, which undermines the integrity of the peer-review process.

In response to these challenges, the scientific community, including journals and institutions, is exploring alternative models and transformative agreements. These include agreements where consortia of institutions pay lump sums covering both open access publication and traditional subscription content, and 'subscribe to open' models, where traditional subscribers agree to continue paying their subscription fees, but the funds collected are used to make the journal's content freely available to all (Else, 2021). These innovative approaches are not without problems, such as free-riding incentives. However, they reflect ongoing efforts to balance the benefits of open access with financial and quality control challenges and thus showcase the dynamic and evolving nature of the open science movement in the EU and beyond.

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CHAPTER 3.3

RESEARCH PRODUCTIVITY AND THE ROLE OF AI IN SCIENCE

Key questions

- Has scientific productivity been slowing down in recent decades?
- What is the role played by AI technologies in different scientific domains?
- What does the recent evidence on AI in science mean for R&I policy?

Highlights

- Research productivity has been slowing down in recent decades. The decline has been observed across different sectors and economies. Additionally, scientific discoveries and ideas are becoming less disruptive.

- The diffusion of AI in science is increasing at a significant pace worldwide, with China in the lead, followed by the US and the EU. If current growth rates continue in the future, the window of opportunity for the EU to catch up with China is expected to shrink further.

- AI tools are penetrating all scientific domains, making scientists and researchers more efficient across a wide spectrum of fields. The most typical uses of AI in science include supervised learning, anomaly detection, reinforcement learning and generative AI models.

Policy insights

- AI has the potential to accelerate research productivity, thereby helping to push forward scientific and technological advances.

- Nevertheless, the diffusion of AI in science poses important challenges (e.g. impact on jobs, ethics, transparency and privacy) calling for multifaceted policy actions aimed at balancing the risks and the potential of AI, thereby promoting a shift from technology-driven advancements to a human-centric approach that emphasises human creativity and potential.

- R&I policy has an important role to play in boosting the uptake of AI technologies through financing instruments and the development of the right enablers to promote multi-disciplinarity and strengthen collaborations across different scientific fields.

- Additionally, R&I policy can play a pivotal role in redirecting AI research and development towards a more productive path and turn AI tools into powerful channels for human creativity, supporting the creation of new tasks and complementing existing activities.

Scientific discoveries play a pivotal role in addressing and mitigating global challenges. From advances in renewable energy and climate science to breakthroughs in healthcare and disease prevention, science remains key to tackling pressing issues (including climate change, health crises, environmental degradation and the energy transition) and driving economic growth and societal progress.

In this regard, understanding the role of Artificial Intelligence (AI) in advancing scientific discoveries is of key relevance. AI is revolutionising the way in which research is conducted and represents an extremely powerful and versatile research tool able to impact knowledge creation in many different ways (Bianchini et al., 2022). The integration of AI tools into scientific work has the potential to shift the current scientific paradigm (Kuhn, 1962), offering new ways to process and interpret vast amounts of data, identify patterns and even formulate hypotheses. Furthermore, as AI becomes more capable of generating novel hypotheses and even conducting experiments, it might redefine what constitutes scientific progress, posing new challenges for policymakers in terms of reconciling the transformative impact of AI on the structure and progression of scientific knowledge with more human-centred approaches to knowledge creation.

1. The slowdown of research productivity

The productivity of scientific research has been decreasing over time. Although measuring research productivity is not an easy task (as empirical evidence can be significantly sensitive to the type of metrics used), there exists a wide consensus that the number of researchers needed to attain a given level of productivity growth or innovation has been increasing over time (Aghion et al., 2021).

The secular decline in scientific productivity is observed across different economic sectors. As an example, the 'Moore's law'[1] appears to have been slowing down, as the number of researchers necessary today to double the number of transistors in a chip is 18 times higher than in the 1970s (Bloom et al., 2020; Aghion et al., 2021). A similar decline in R&D productivity and technological progress has been observed in the agricultural and pharmaceutical sectors (Bloom et al., 2020).

A similar trend is observed across economies characterised by very different features. In Germany, the average annual increase in R&D expenditure registered over the period 1992-2017 (about 3.3%) was accompanied by an average decline in research productivity of 5.2% per year (Boeing and Hünermund, 2020). A faster decline is reported in China, where an average annual increase of 21.9% in the numbers of researchers in publicly listed firms was reported over the period 2001-2009, while the drop in research productivity amounted to 23.8% per year (Boeing and Hünermund, 2020).[2]

1 Moore's law is an empirical observation and prediction made by Gordon Moore in 1965, stating that the number of transistors on a microchip (integrated circuit) roughly doubles every 2 years, leading to an exponential increase in computing power and a decrease in the cost of electronics.

2 The decline in Chinese research productivity drops to 7.3% per year when the analysis is restricted to the most recent decade, due to the large-scale R&D activities implemented by the Chinese government.

A similar pattern is observed in Japan, where R&D efficiency in the manufacturing and information services sectors declined between 1995 and 2015 (Miyagawa and Ishikawa, 2019). For more evidence on the EU's performance using alternative indicators, see Box 3.1-1 in Chapter 3.1.

Furthermore, new scientific and technological ideas are becoming less disruptive. Consolidating discoveries tend to improve existing streams of knowledge, while disruptive ideas tend to propel science and technology along new trajectories. Scientific progress typically needs both types of scientific and innovative endeavour. Nevertheless, the degree of disruptiveness of both scientific papers and patents has been decreasing significantly over time, for reasons unrelated to changes in publication, citation or authorship practices (Park et al., 2021). Additionally, the willingness of scientists to adapt to evolutions in scientific knowledge appears to decrease with age. Ageing scientists tend to promote and defend old work, at the expense of more recent scientific contributions by younger researchers (Cui et al., 2022).

The observed secular stagnation may be the result of constraints on the supply side of innovation (Aghion et al., 2021). According to the 'low-hanging-fruit theory', great innovations have already occurred, and it is easier to prioritise readily accessible solutions than to dive into complex, resource-intensive projects (Gordon and Mokyr, 2016).[3]

Changes in scientists' incentives can also contribute to scientific stagnation. The evaluation of scientific contributions and scientists' performance is now largely based on numbers of citations. Potentially groundbreaking ideas, which tend to gather fewer citations, are penalised by a system that mostly favours incremental science, which advances established ideas. The shift towards reward systems based on the degree of popularity of a given scientific contribution has thus contributed to reducing scientists' incentives and willingness to engage in more innovative and riskier projects (Bhattacharya and Packalen, 2020).

Alternative hypotheses link the decline in disruptive ideas to the scope of the scientific field and to the increasing burden of knowledge. As the number of research publications increases, scholars' attention risks being directed towards already widely cited contributions, thereby hampering the visibility of less-established papers, regardless of their scientific merit. This focus on scientific quantity can have significant detrimental effects on fundamental progress, especially in broad scientific fields (Chu and Evans, 2021). Additionally, as science progresses, it develops along and articulates new knowledge trajectories that often branch into new disciplines. The increasing interdisciplinarity of knowledge activities creates additional burdens for scientists and researchers, who need to devote more time to training at the expense of scientific research (OECD, 2023).

Furthermore, the increasing size of research teams negatively affects the making of new discoveries. As science diversifies and becomes more interdisciplinary, larger scientific teams are needed to absorb new knowledge. Nevertheless, larger teams appear to be less likely to make fundamental discoveries than smaller teams (Wu et al., 2019).

3 Nevertheless, such a theory seems to conflict with the empirical evidence (Park et al., 2021).

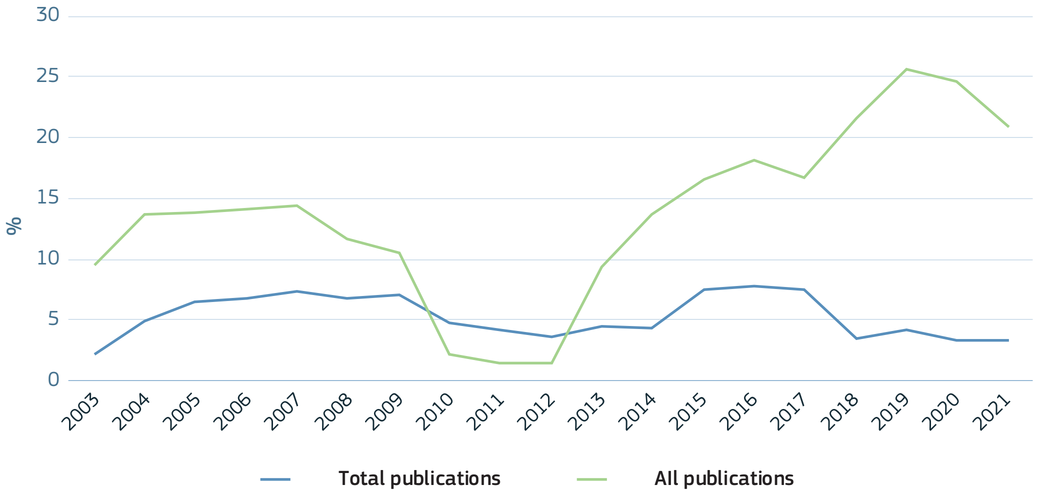
2. An increasing diffusion of AI in science and its potential to accelerate scientific and technological progress

AI is rapidly becoming an essential instrument in the scientific process as it has the potential to accelerate progress in science and technology. AI enhances human cognitive capacities and is able to solve complex problems and generate research outcomes that would be beyond the reach of more conventional tools. Although its overall impact on scientific productivity is still uncertain, AI has the potential to shorten the typical timeframe needed for scientific discoveries to be taken up, and it is thus set to play a key role in making scientific and innovation activities more efficient (Arranz et al., 2023).

Researchers across a broad range of scientific domains are increasingly relying on AI tools to carry out their scientific activities. While AI has been part of the scientific toolkit since the 1960s, its use was primarily confined to disciplines with strong computer science foundations, such as physics or mathematics. The development of large language models (LLMs) has triggered a remarkable surge in the adoption of AI technologies, which have the potential to significantly transform the scientific research landscape (Arranz et al., 2023).

The applications of AI in science and research have grown at a significant rate in recent years, and faster than overall global scientific publications. Between 2004 and 2021, the annual growth rate of global scientific activity was around 5 %, while the number of AI-related publications grew at around or above 15 % per year (Figure 3.3-1), with the exception of the period 2010-2012, during which scientific production in the field of AI stagnated, presumably due to a shift in research priorities and funding linked to the onset of the financial crisis.

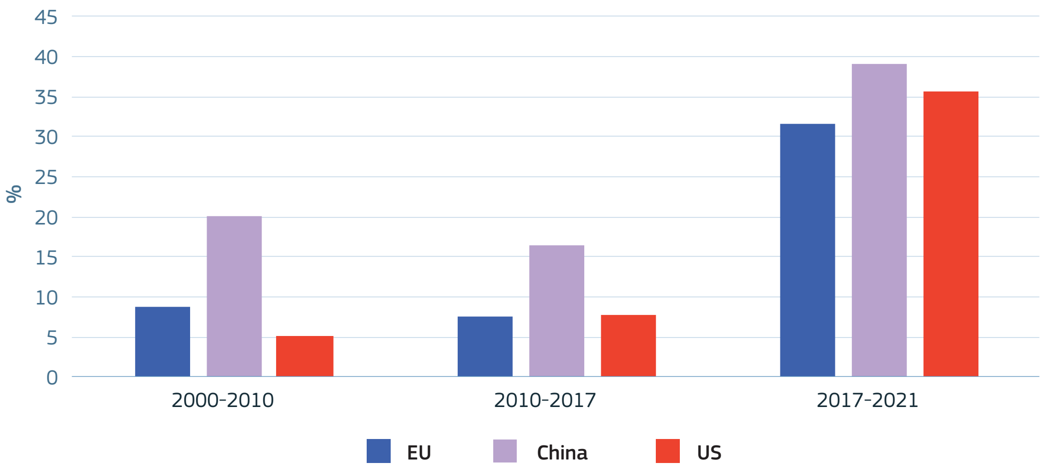
Figure 3.3-1 **Growth in scientific activity (3-year rolling average)**



Source: Arranz et al. (2023).
Note: Annual growth calculated as a 3-year rolling average.

China is the global leader in terms of publications related to AI applications in science, followed by the EU and the US. The EU and the US have reported similar levels of AI-related publications over the last few decades, with the EU holding a modest lead up to 2017. Striking has been the performance of China, which was able to catch up with its competitors quickly and has outperformed them since 2017 (Arranz et al., 2023). A remarkable increase in the number of publications dedicated to AI applications in science was observed between 2017 and 2021, with China reporting an average yearly growth rate of 39 %, followed by the US (36 %) and the EU (32 %) (Figure 3.3-2).

Figure 3.3-2 Average yearly growth of AI-related publications in the EU, the US and China, by period



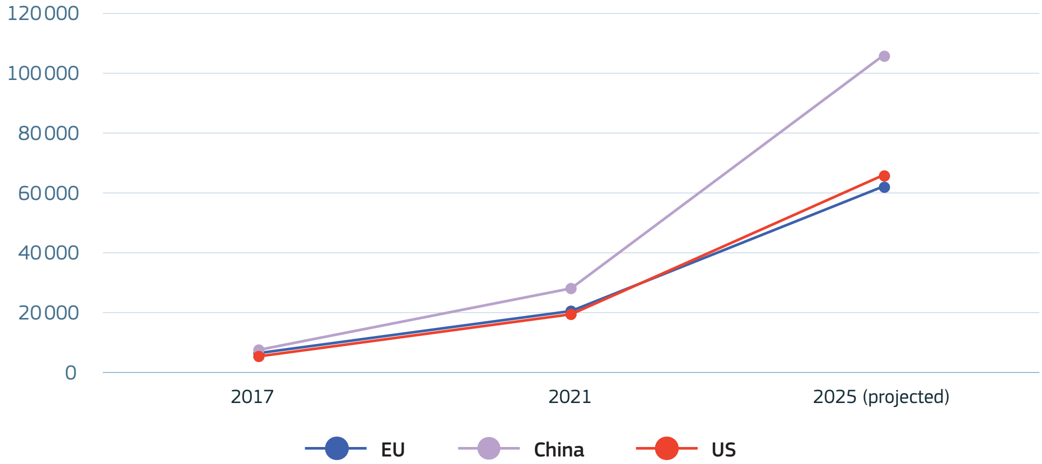
Science, research and innovation performance of the EU 2024

Source: Arranz et al. (2023).

Although the Chinese advantage narrows when the quality of publications is taken into account, the gap between China and the EU is expected to increase in the future (Figure 3.3-3). If current growth rates continue in the next 4 years, China will pull further ahead of the EU, thereby further shrinking the window of opportunity for the EU to catch up (Arranz et al., 2023).

The performance of the EU is quite heterogeneous across different Member States, both in terms of quantity and quality. Germany, Italy, Spain and France are in the lead in terms of scientific publications related to the application of AI to science. Sweden and the Netherlands follow, both in terms of absolute number of publications and growth rate. In most Member States, between 20 % and 30 % of AI-related publications have received no citations. A higher incidence (more than 40 %) is observed in eastern European countries, such as Romania and Czechia. When looking at publications of higher quality (the top 10 % of publications in terms of citations received), Germany leads, followed by Italy, France, Spain and the Netherlands (Arranz et al., 2023).

Figure 3.3-3 Projected number of publications on AI applications in science in the EU, the US and China



Science, research and innovation performance of the EU 2024

Source: Arranz et al. (2023).
Note: The projections for 2025 are calculated by applying the yearly growth rate from 2017-2021 for each country/region.

Furthermore, AI tools are penetrating all scientific domains, making scientists and researchers more efficient across a wide spectrum of fields (Box 3.1-1). As an example, tools like the GitHub Copilot can enable researchers and analysts to write software 55 % faster.[4] In 2022, AI models were used to aid hydrogen fusion, improve the efficiency of matrix manipulation and generate new antibodies (Maslej et al., 2023). Additionally, AI systems are very efficient at data interpolation, allowing researchers and scientists to process significantly higher amounts of data and automate complex calculations, which can ultimately improve the quality of knowledge within different disciplines.

Therefore, AI has the capability to accelerate research productivity, thereby helping to push forward scientific and technological advances. AI systems have the potential to help scientists to better model complex systems, allowing scientific research to shift towards a bottom-up, data-driven approach to understanding complicated processes and identifying patterns, rules and solutions. The most typical uses of AI in science include supervised learning, anomaly detection, reinforcement learning and generative AI models (OECD, 2023). Furthermore, AI can support the analysis of existing data and scientific literature to detect potential knowledge gaps and new scientific avenues to be explored. This could help with identifying potential research collaborations that could further stimulate interdisciplinary works, thereby producing economically and socially valuable effects.[5]

4 https://www.economist.com/science-and-technology/2023/09/13/how-scientists-are-using-artificial-intelligence.
5 https://www.economist.com/leaders/2023/09/14/how-artificial-intelligence-can-revolutionise-science.

Box 3.3-1: Applications of AI in the sciences[6]

AI has a vast array of potential applications that span a continuum between the two extremes of search and discovery. At the search end of the spectrum, AI can support access to knowledge and information, especially during periods characterised by an explosion of data and information; at the discovery end of the spectrum, often as the end result of a research project, AI can be employed to identify data patterns in an open-ended manner, leading to new discoveries and insights (Xu et al., 2021; Bianchini et al., 2022).

The most common use of AI in science is to address complex prediction problems, i.e. mapping inputs to predicted outputs. The problems can be of any kind, as can the type of methodological approach adopted. For instance, convolutional neural networks (CNNs) can be used to process magnetic resonance imaging (MRI) and to predict the possible presence of cancer. Examples of the many computer vision tasks include semantic segmentation, where the goal is to categorise pixels according to the high-level group to which they belong, and pose estimation, where the goal is to predict and track the location of a person or object. Other techniques, such as recurrent neural networks (RNNs), are common in scientific applications involving the prediction of sequential structures, such as in genomics and proteomics, but also in finance.

A second common application of AI is to perform transformations of input data, including dimensionality reduction, clustering, data augmentation and image super-resolution, to name but a few. Dimensionality reduction and clustering are simple but effective methods for revealing hidden properties in data and are often the first step in exploring and visualising data, before any other prediction tasks are undertaken. Image super-resolution and data compression are other common applications that can facilitate data analysis and enable the researcher to save and optimise space.

A third application is the optimal parameterisation of complex systems. Here, techniques such as reinforcement learning can be used to search for the optimal set of parameters that maximise or minimise a specific objective function or produce a desired outcome. A recent example is the configuration of tokamaks (for nuclear fusion) with deep reinforcement learning, which has enabled scientists to model and maintain a high-temperature plasma within the tokamak vessel, a problem that had hitherto proved impossible to solve (Delgrave et al., 2022).

6 Note that the examples considered constitute a non-exhaustive list of potential applications of AI in science.

Another valuable application of AI is automating (or partially automating) the literature review process, which can be facilitated by powerful search engines based on LLMs. Platforms like Elicit and Perplexity work through a chatbot-style interface, enabling researchers to interact dynamically with the machine. The researcher can initiate a conversation to search for information about past research in a certain area and receive a summary of key information about that field. The newest tools can even remember the conversational context, improving the quality of the exchange between user and machine. Most of these AI-powered platforms offer other functionalities, such as assisting researchers in brainstorming research questions and directions – i.e. rephrasing their research questions and suggesting potential research directions based on the current state of the art – and providing suggestions on how to improve prose writing and editing.

Still within the context of academic literature reviews, **another interesting application is literature-based discovery**, where AI can uncover implicit, hidden associations from existing studies, resulting in interesting, surprising, non-trivial hypotheses that are worth studying. Machine reading comprehension systems are particularly useful in this context, as they can identify gaps in the literature and propose variations on existing experiments.

Finally, AI, and specifically simple robotics, can be used to automate tedious, routine laboratory tasks such as media and buffer preparation or pipetting. These tasks require a high degree of accuracy but have relatively low value added.

3. Targeted policy actions to balance benefits and risks of AI in science

Despite its high potential, the diffusion of AI in science also poses important challenges. The recent acceleration in both the skills and popularity of AI systems has been accompanied by increasing fears regarding human ability to keep this fast-developing technology under control. Concerns in this regard are mostly linked to the black-box nature of complex AI models, which makes the understanding and correct interpretation of their predictions and decisions a difficult task (OECD, 2023).

Furthermore, the risk of misuse and the potential creation of biases in the scientific process also needs to be taken into account. One example is the biases that AI could create in its simulations, especially if the algorithm is trained on types of human data from which it can learn social biases (including sexism and discrimination against minorities) (OECD, 2023). Additionally, the risk of misuse is also high, especially in potentially hazardous fields such as chemistry and materials science (Shankar and Zare, 2022).

Furthermore, the increasing overreliance on AI for data analysis and hypothesis generation risks reducing the role played by human intuition, creativity and critical thinking. As AI tools become more sophisticated, the complexity of their underlying algorithm increases. This can lead to a lack of interpretability of AI-driven results, which risks hindering the ability to critically assess and validate AI findings, posing important questions about the future quality of scientific research that relies heavily on these technologies. Furthermore, AI algorithms can be highly sensitive to the specific data they are trained on, raising concerns about the reproducibility of AI-driven scientific results – a cornerstone of scientific integrity.

AI technologies are accompanied by broader existential dilemmas that policymakers are called to address. All major technological advances have led to disruptions in the labour market. AI is no exception, and the current trajectory appears to be set towards increased automation, which is not always aimed at exploiting complementarities between AI technologies and humans (Acemoglu, 2021).

Data-driven AI also raises privacy and ethical concerns. AI and humans will increasingly work together in a form of hybrid intelligence, which calls for a re-evaluation of how we approach and manage innovation. In this regard, the EU is taking measures to regulate AI. At the end of 2023, the European Parliament approved the AI Act (originally proposed by the European commission in 2021), the first regulatory framework for AI, aimed at providing rules to ensure that AI systems are used in a safe, transparent, ethical and unbiased manner.

Box 3.3-2: Opportunities and challenges linked to AI in science

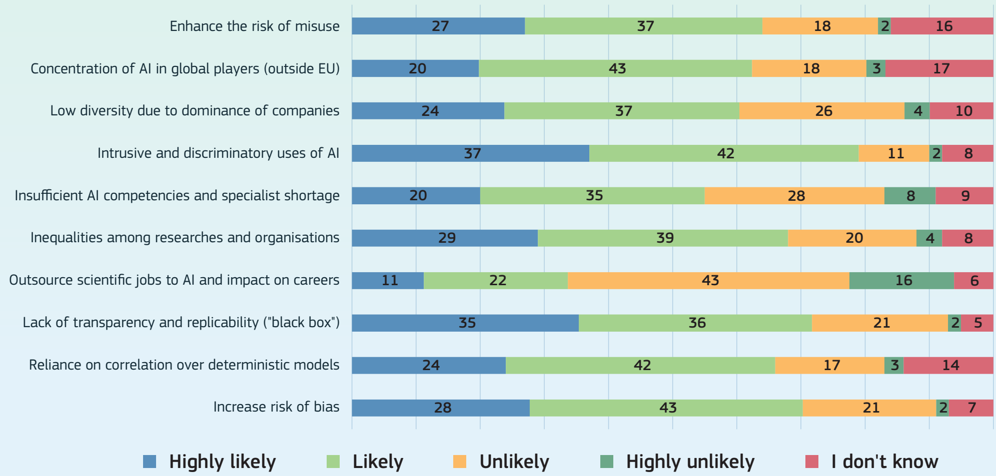
The European Research Council (ERC) is the premier European funding organisation for excellent frontier research. Since its establishment in 2007, the ERC has played a pivotal role within the EU's funding programmes for research and innovation. The ERC funds a rich and diverse portfolio of projects spanning all fields of science and scholarship, without any predefined academic or policy priorities. These projects can have an impact well beyond science and provide frontier knowledge and innovation to help solve societal challenges and contribute insights to shape and inform key EU policy objectives (ERC, 2023).

In pursuing their research endeavours, ERC-funded researchers are increasingly relying on AI tools. The results from a foresight survey conducted among ERC grantees (focusing on their present use of AI and their views on future developments up to 2030) suggest extensive and diverse use of AI in ERC grantees' scientific work, including non-domain-specific uses of AI-based tools, such as text writing and editing, language translation, coding and programming, generation of images for presentations, and literature retrieval (ERC, 2023).

Furthermore, the role of AI in supporting the scientific process is expected to continue to increase in the period to 2030. AI is expected to enhance analysis and visualisation of complex datasets, assist in coding and experiment design, and help with cross-linking of data, thereby contributing to the discovery of related results from different fields and enhancing interdisciplinary works. However, opinions vary on the role of AI in scientific discovery, with some envisioning AI as a collaborative tool or 'research assistant', while others foresee it generating new hypotheses or even conducting research autonomously (ERC, 2023).

Concerns remain about the reliability and transparency of AI and the necessity for human validation, pointing towards the development of a collaborative, rather than autonomous, role for AI in scientific processes. In more detail, 79% of respondents reported concerns about the risk of AI being intrusive or discriminatory, while 71% appeared worried by the lack of transparency and replicability of AI systems and potential biases in data or models due to flawed inputs (Figure 3.3-4). Concerns about unequal access to AI resources among researchers and organisations were cited by 68%. There is less concern about AI replacing scientific jobs (59% of respondents found it unlikely), confirming the belief that the role of AI will be that of an assistant, rather than a replacement, in scientific endeavours (ERC, 2023).

Figure 3.3-4 **Challenges and risks by the use of AI in science up to 2030 (% of respondents)**



Source: ERC (2023).

Policy actions are needed on multiple fronts to balance the risks and the potential of AI, and so promote a shift from technology-driven advancements to a human-centred approach that emphasises human creativity and potential. In this regard, it is important to improve understanding of these technologies at every stakeholder level so as to allow researchers, companies and policymakers to fully exploit the potential of AI. On the one hand, this calls for a better understanding of the current state of knowledge in the field, so as to steer research efforts in directions more likely to generate higher economic and social benefits. On the other hand, the quality of available evidence needs to be improved in order to be able to monitor future trends and developments in this area (Arranz et al., 2023).

The need for better understanding requires actions to provide training and better educational opportunities within and outside research projects, and to equip people with the right skills to deal with AI tools. In this regard, skill development requires investment of resources at both public and private level, with private companies sharing the responsibility of providing their employees with learning experiences that could create new economic opportunities for workers at all levels of the labour market (Acemoglu, 2021).

Increasing the financial resources directed towards strengthening the EU's position in the application of AI in research and scientific activities remains of pivotal importance. Given its multiple applications across a range of fields, AI is one of the digital technologies with the greatest potential to boost EU productivity and competitiveness. Additionally, if AI tools and applications are expected to be the primary drivers of future scientific discoveries, lagging behind in the development and uptake of AI in the scientific domain can pose significant challenges to the EU's strategic autonomy, increasing the risk of developing dependencies in strategic scientific fields (Arranz et al., 2023).

R&I policy has an important role to play. Increased efforts are needed to catch up with the EU's main competitors (see Chapter 2.2) and boost the uptake of AI technologies. Reducing barriers to AI adoption and developing the right enablers, with policies that are better targeted at the scientific community, remain key to the creation of an ecosystem able to harness the potential of AI.

This entails upgrading existing funding instruments and creating conditions for researchers that favour greater interdisciplinarity. The versatility of AI in various fields makes it well suited for collaborative and multidisciplinary research endeavours. The interdisciplinary nature of AI is also of key relevance to the establishment of ethical and transparent guidelines and protocols for the use of AI language models, which would leverage collaborations among researchers and developers across different fields.

Nevertheless, data concentration remains a concern. AI innovation often tends to concentrate in specific regions and big tech companies, which also account for most of the money spent on AI research (Acemoglu, 2021). This poses important questions for the future direction of AI, which risks being shaped largely by profit-maximisation considerations. Public policy and support thus have a crucial role to play in preventing the increasing connections between academia and the big tech industry from giving big tech excessive influence in setting the AI research agenda.

Furthermore, the untapped potential of AI in boosting human productivity is still significant. In this regard, R&I policy can play a pivotal role in redirecting AI research and development towards a more productive path and turn AI tools into powerful channels for human creativity, supporting the creation of new tasks and complementing existing activities (Acemoglu, 2021).

Box 3.3-3: The need for a dedicated 'AI in Science' policy

Daniela Petkova

Just as science contributes to the development of excellent AI, it increasingly relies on AI to progress, innovate and overcome societal challenges. As AI is likely to be a main driver of discovery and innovation in the future, helping science to effectively integrate AI requires a dedicated policy effort.

A distinct science-oriented AI policy is crucial to contextualise, refine and focus existing measures, amplify their impact and ensure coherent use of resources. It is needed to address the specific AI risks and challenges in science, while harnessing the potential of AI for discovery, innovation and shaping the future of science.

The AI in Science policy needs to be developed in synergy with the EU's digital, AI, education and cohesion policies by mobilising the AI in science ecosystem, including researchers and public and private R&I players. A dedicated AI in Science policy[7] should.

Accelerate AI uptake by scientists in the EU. To achieve this, policy measures will focus on:

- reducing barriers to adoption and developing the right enablers for attracting talent and training researchers in AI-driven science;
- developing a portfolio of R&I investments, focusing on AI for solving scientific challenges and making the scientific process more effective and efficient;
- strengthening the computer-, data- and AI model-sharing ecosystem for the adoption and development of AI for scientific purposes, including by widening access to research and computing infrastructure, leveraging initiatives such as the European Open Science Cloud (EOSC) and other data spaces, and reducing dependence on non-EU actors;
- engaging with Member States to develop and design similar policies at national level, focusing on creating conditions for researchers that favour more AI-based research, interdisciplinarity and knowledge sharing.

7 https://research-and-innovation.ec.europa.eu/document/download/1e2a4c9c-d3f1-43e9-9488-c8152aabf25f_en

Monitor and steer the impact of AI in the scientific process. This includes:

- understanding the impact of AI on the work and life of scientists and preparing the scientific sector for new scientific methods;
- preserving scientific integrity by providing guidance to research community, like the recently published 'Living guidelines on the responsible use of generative AI in research;[8]
- addressing AI challenges to methodological rigour and verifiability of outputs, and the potential for misuse of the technology in fields such as biology or drug discovery;
- preserving public trust in AI-driven science through proactive communication actions.

The AI in Science policy design is informed by the recommendations of the Scientific Advisory Mechanism[9], as well as the opinions provided by stakeholders through discussions and consultations.

8 https://research-and-innovation.ec.europa.eu/document/download/2b6cf7e5-36ac-41cb-aab5-0d32050143dc_en?filename=ec_rtd_ai-guidelines.pdf
9 https://scientificadvice.eu/advice/artificial-intelligence-in-science/

CHAPTER 4

EU R&I ECOSYSTEMS

CHAPTER 4.1

THE EU R&I DIVIDE

Key questions

- What are the main characteristics and latest trends of the EU regional R&I ecosystems?
- How has the R&I divide evolved across EU Member States and regions?
- How concentrated are R&I activities, specifically those addressing societal challenges and increasing strategic autonomy?

Highlights

- Between 2000 and 2022, there was a clear innovation divide among European countries, with innovation leaders and strong innovators primarily located in northern and western Europe, and moderate and emerging innovators more common in southern and eastern Europe.
- Between 2014 and 2023, some European regions improved their R&I performance, while others were left further behind, creating a pattern of regional differences.
- There is evidence of regional gaps in R&I collaborations, spending, and employment over the last decade.
- Small and medium-sized enterprises (SMEs) in less advanced regions tend to have improved their R&I performance, while those in strong regions have declined in several R&I indicators.
- The industrial structure of European regions and asymmetric developments in productive specialisation across countries and regions have underpinned the emergence of spatial disparities in R&I.
- Smaller and diverse social innovation clusters focusing on local or regional areas have emerged in the EU.

Policy insights

- Overall, European funding has a strong potential to narrow the divide, as low R&I performers rely more on EU funding to support their R&I systems than top performers.

- However, the European Framework Programme for R&I funding is quite concentrated, raising the risk of widening the R&I gap.

- Actions under the Framework Programme (FP) and European Structural and Investment Funds (ESIF) to support territories' development, to enhance institutional capacity and to improve public administration, are therefore critical for promoting cohesion, counterbalancing potential closed-club effects and enhance the overall competitiveness of the EU.

- The Recovery and Resilience Facility (RRF) funding dedicated to R&I is also expected to play a role in reducing the R&I gap, as it represents a significant support in countries with weaker innovation performance.

Europe's economic landscape is marked by considerable territorial disparities (Rodríguez-Pose, 2002; Pike et al., 2017; Diemer et al., 2022), and Research and Innovation (R&I) activities are no exception (Crescenzi et al. 2017). Since the 2000s, regional convergence was observed in the European Union, but it has been challenged over recent years (European Commission, 2022a; European Commission, 2022b). This chapter brings insights on the latest trends and characteristics of the R&I spatial divide, investigating recent changes and long-term trends, linking these to the European industrial structure and the economic divide.

Since the Single European Act, the aim of the EU R&I policy has been to strengthen the scientific and technological basis of EU industry and to make it more competitive at international level (Article 179 of the Treaty of the Functioning of the European Union (TFEU)). The TFEU also provides that the EU shall aim at "reducing disparities between the levels of development of the various regions and the backwardness of the least favoured regions or islands" (Article 174). This chapter, in its second part, by examining the spatial allocation of European funding across the EU, offers an overview of the significance and role of European policies, encompassing R&I, Cohesion, and Recovery instruments, in EU territories based on their level of development and their R&I performance.

1. Territorial disparities in research and innovation

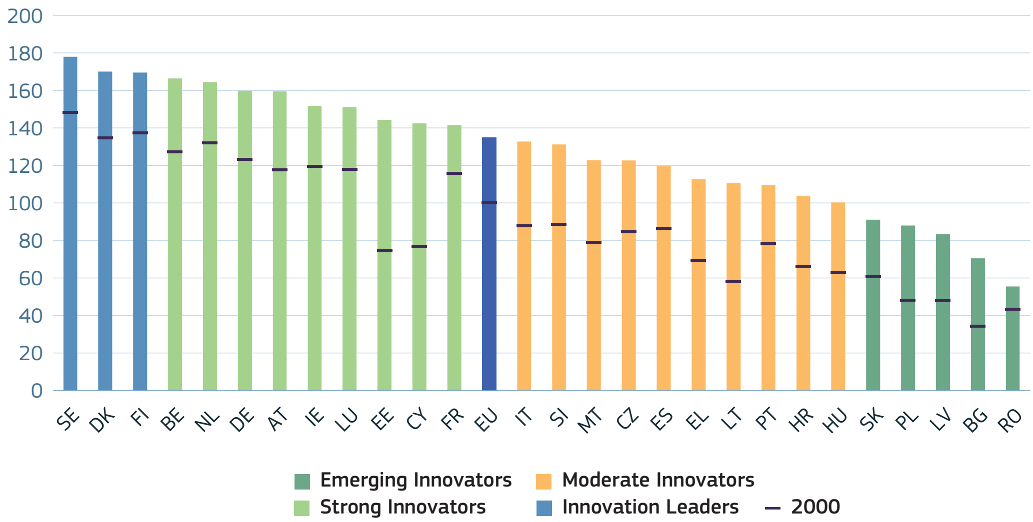
Europe's economic landscape is marked by disparities (Rodríguez-Pose, 2002; Pike et al., 2017; Diemer et al., 2022) **in R&I activities** (Crescenzi et al., 2017). Since the 2000s, the European Union has been observing regional convergence, but this convergence has been challenged over recent years (European Commission, 2022a; European Commission, 2022b).

All Member States have progressed in innovation performance over the last two decades despite persistent disparities. The long-term series of the European innovation scoreboard (EIS) measures the innovation performance of countries from 2000 to 2022, based on 32 indicators. The composite index is calculated using indicators grouped into four main dimensions – framework conditions, investments, innovation activities, and impacts – covering multiple aspects of R&I beyond investment in R&D.[1]

There is a clear innovation divide, with innovation leaders and strong innovators primarily located in northern and western Europe, and moderate and emerging innovators more common in southern and eastern Europe (Figure 4.1-1). In 2022, the Nordic countries – Sweden, Denmark and Finland – led the ranking, performing at levels above 125 % of the EU average for that year. Estonia and Cyprus stand out among the strong innovators, showing significant progress over two decades, despite not being part of the EU-14. Conversely, some EU-14 countries, like Italy and Spain, are performing below the EU-27 average. This geographical divide has remained persistent over the 20-year period, with a few notable exceptions, such as Cyprus.

1 More information on the measurement framework of the EIS: European Commission Directorate-General for Research and Innovation (DG Research and Innovation), EIS 2023, Publications Office of the European Union, 2023, https://data.europa.eu/doi/10.2777/119961.

Figure 4.1-1 Performance of EU Member States innovation systems in 2000 and 2022



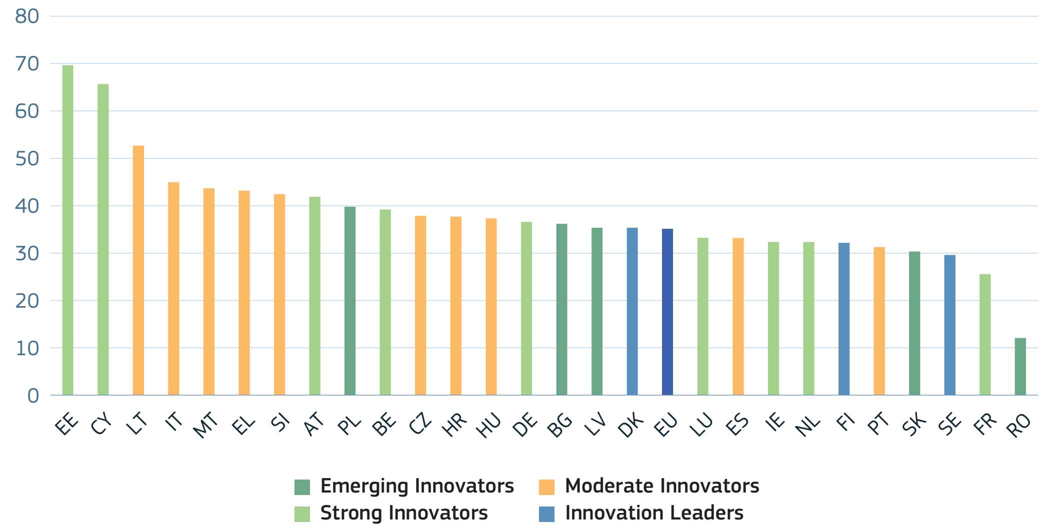
Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on the EIS long-term series.

Note: Performance groups are defined as follows: innovation leaders are Member States where performance is above 125% of the EU average. Strong innovators include Member States with a performance of between 100% and 125% of the EU average. Moderate innovators are those with performance of between 70% and 100%. Emerging innovators have a performance level below 70% of the EU average. The innovation performance groups are based on the year 2022. The scores are expressed relative to the EU average in 2000, with the EU average for 2000 set at 100.

Between 2000 and 2022, innovation performance increased in all EU Member States. Overall, the EU progressed by 35 percentage points during this period. In 17 Member States, progress rates exceeded that of the EU. Interestingly, these faster-paced countries belong to different performance groups. When examining the performance change over time, no clear pattern emerges, either among the Member States that have joined since 2004 or along the north-west/south-east divide (Figure 4.1-2).

Figure 4.1-2 Performance change between 2000 and 2022 in percentage points



Science, research and innovation performance of the EU 2024

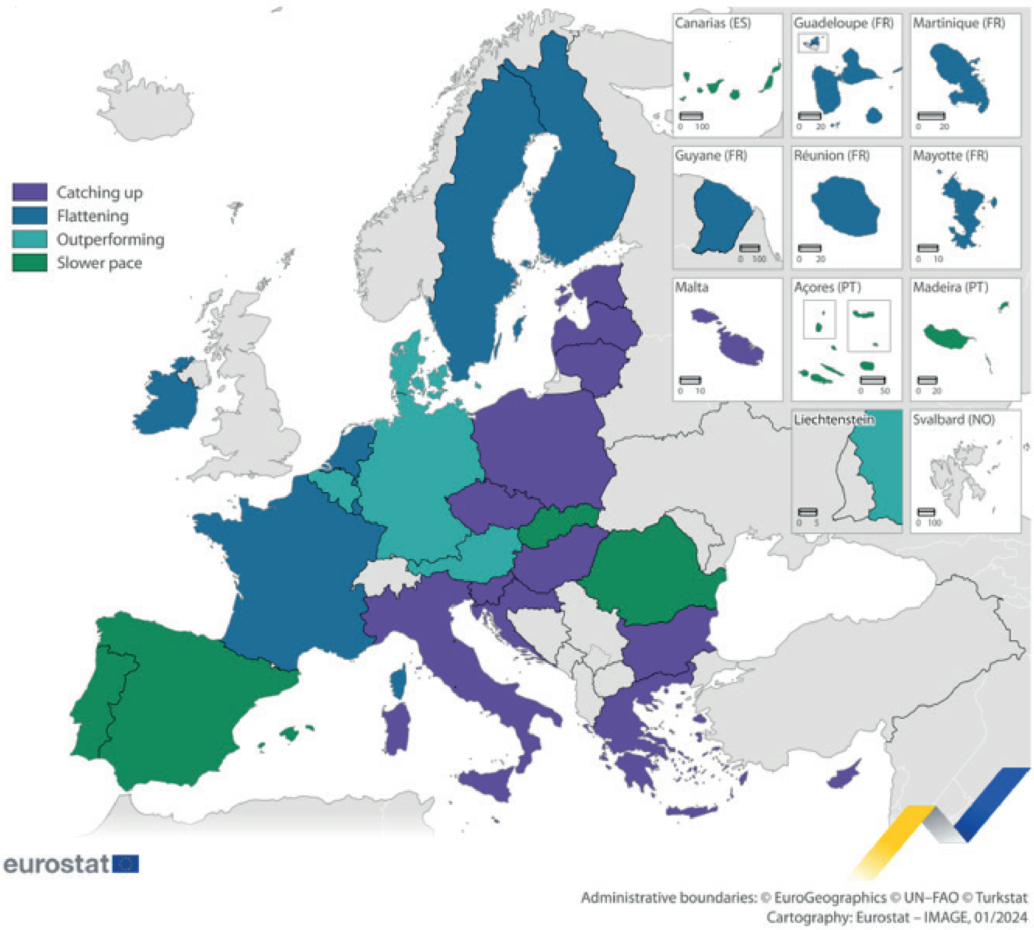
Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on the EIS long-term series.

Note: Performance change is measured as the percentage point difference between the 2000 and 2022 scores.

There is some evidence of overall convergence in innovation performance in terms of catching up. The concept of convergence is typically associated with economic growth models. One way to define the process of convergence is to measure whether countries with initially lower performance scores tend to progress faster than those with initially higher performance scores. This process is known as beta convergence (See for instance Barro, 2015).

In Europe, some countries are following a process of convergence in innovation performance (Figure 4.1-3). Thirteen countries in the southern, eastern and Baltic regions are catching up, with scores lower than the EU average in 2000 but higher progress rates than the EU average ('catching-up' category). Finland, Sweden, the Netherlands, Ireland, France and Luxembourg are experiencing a flattening trend, with lower progress rates than the EU average, starting from a higher position ('flattening' category). Germany, Austria, Belgium and Denmark are outperforming the EU average, having started from a higher than average position ('outperforming' category). Finally, Romania, Portugal, Spain and Slovakia have evolved at a slower pace than the EU average, starting from performance levels lower than the EU average in 2000 ('slower pace' category).

Figure 4.1-3 Patterns of convergence on the EIS, 2000-2022

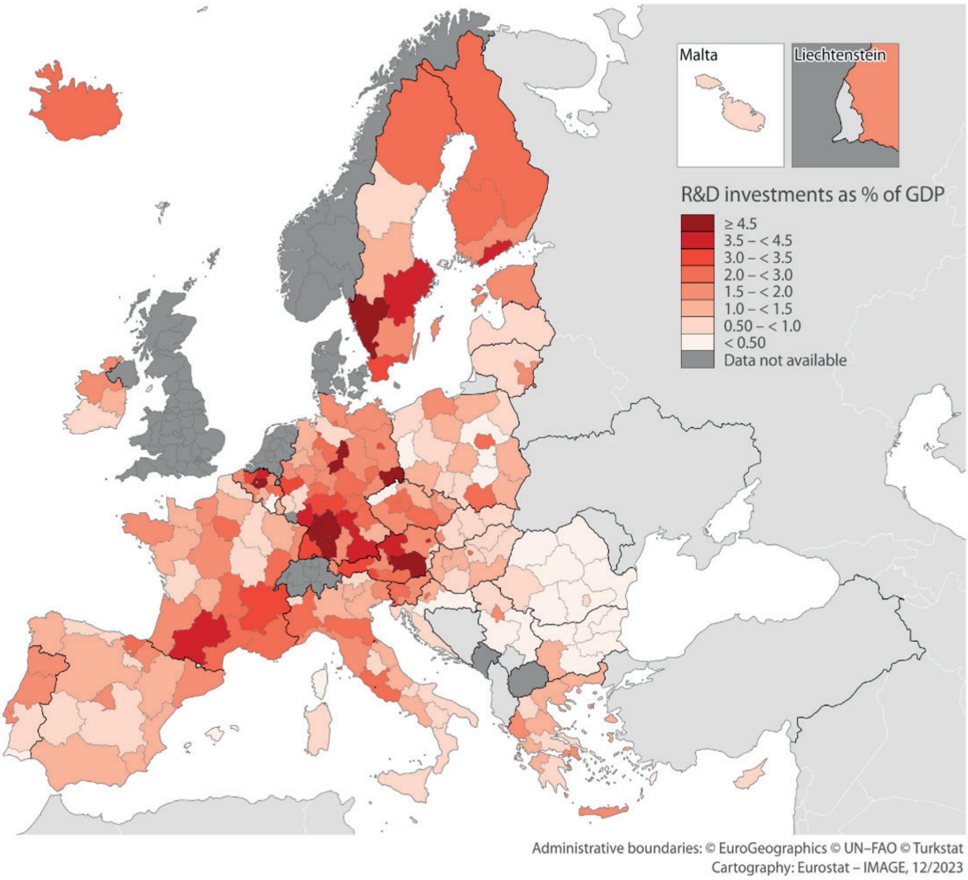


Science, research and innovation performance of the EU 2024

Source: : DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on EIS long-term series.

The regional innovation divide in the EU is pronounced, both in terms of R&I inputs, such as R&D investment, and outputs, such as patenting activity. There is a pronounced regional concentration of R&D investment in the EU (Figure 4.1-4). In particular, R&D intensity is high in western and northern Europe, although well-performing regions can be found in other parts of Europe, too. The regional pattern of technological production is also driven by the existing innovation divide.

Figure 4.1-4 R&D intensity (R&D investments as percentage of gross domestic product (GDP)) per NUTS 2 region in Europe, 2021



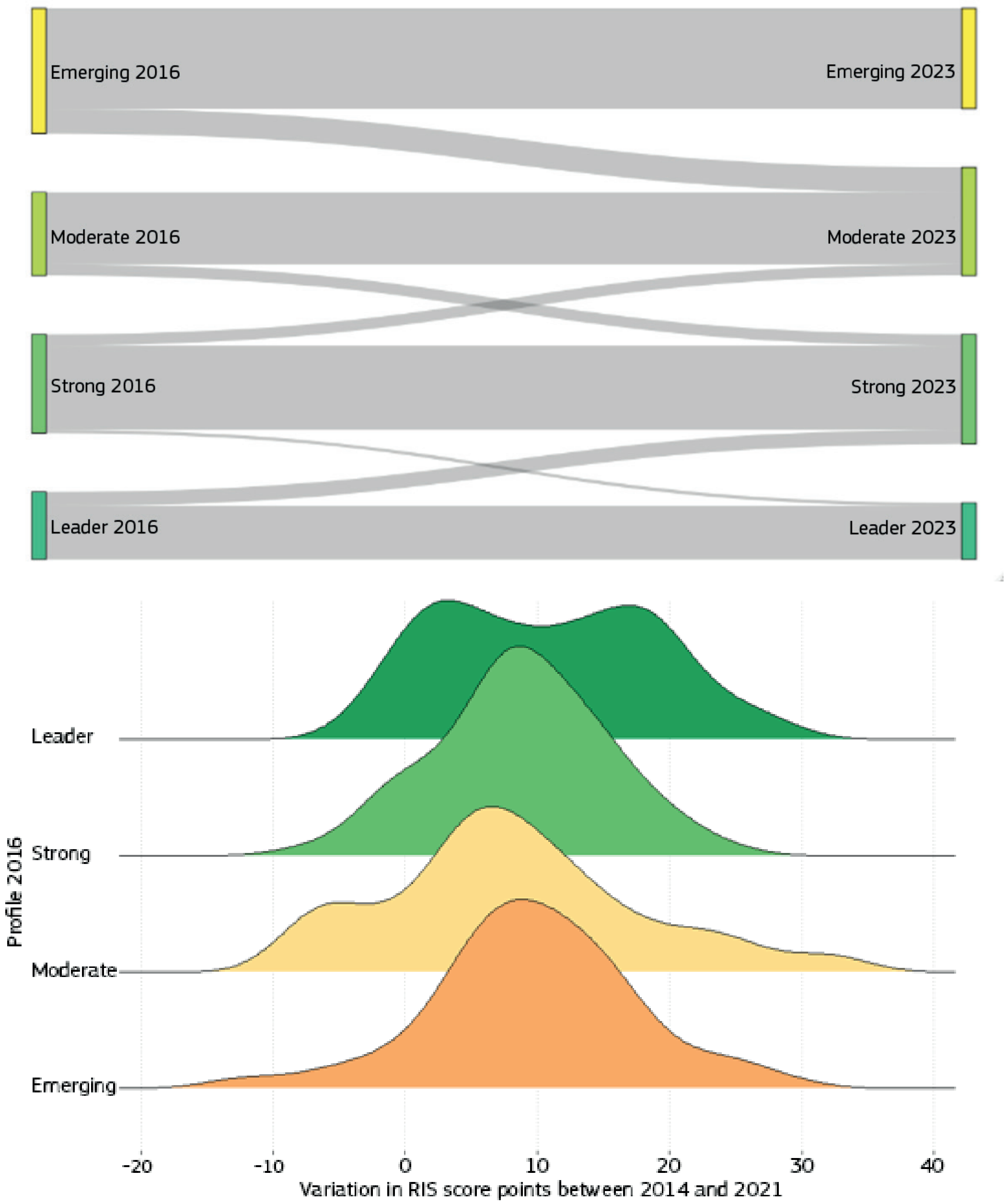
Science, research and innovation performance of the EU 2024
Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on Eurostat.

Between 2014 and 2021, some European regions made remarkable progress in their regional performance indexes, while the majority improved slowly, and others underwent a decline, leading to a particular pattern of regional divergence.[2] There is a significant divide between the regions labelled as innovation leaders and those labelled as moderate innovators (Figure 4.1-5). Within the two categories, one group of regions made significant advances in their regional performance indexes (increases of 15-35 points during 2014-2021 for some 2014 leaders and of 20-40 points for some who were moderate innovators in 2014), while another group experienced a decline, or even a severe decline in the case of moderate innovators (nine 2014 leaders with indexes of over 43 regressed to become strong innovators by 2021 and some moderate innovators saw declines of 10-15 points in their indexes).

As for the emerging and strong innovators in 2016, a more homogeneous evolution can be noted, with only a small fraction witnessing small negative changes over time (Figure 4.1-5). However, this progress was slower compared to the improvements achieved by the top-performing moderate and strong innovators, as well as the leaders, reducing the possibility of achieving regional convergence in the 2014-2023 period. Similar trends of regional divergence in R&I are corroborated by Iammarino and McCann, 2018, OECD, 2021, Crescenzi et al., 2021, and European Commission, 2023a.

2 The European Regional Innovation scores used are for 2016 and 2023, but there is a 2-year lag on the data.

Figure 4.1-5 **Distribution of EU NUTS 2 regions according to the change in their R&I performance indexes by regional innovation scoreboard (RIS) profile between 2014 and 2021**[3]



Science, research and innovation performance of the EU 2024

Source: : DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on the RIS 2023 data.

Note: Data and profiles in the RIS 2023 are based on data and indicators that usually have a two-year lag. Therefore, the RIS score for 2023 mainly captures data from 2021. More information can be found in the methodology report.

3 RIS profiles of 2016 and 2023 are based on 2014 and 2021 data for most indicators.

A closer look at the performance of the European Union regions across key R&I indicators between 2014 and 2020 reveals a mixed picture (Figure 4.1-6). In terms of R&I collaborations (international or public-private), R&I expenditures (business and public R&D investments) and employment (employed ICT specialists), there are signs of divergence; regions that were stronger performers in 2014 experienced relatively larger increases than those that were initially performing worse.

Achieving marginal gains in quantity and quality of R&I outputs becomes increasingly challenging for regions that are already among the top players, which explains the divide between the highest- and lowest-performing regions. This is certainly the case for some indicators of quality and quantity of research outputs, such as the top 10% of scientific publications in terms of citations received, patents and designs. The regions with the lowest performance levels in 2014 have shown the most significant improvement, while the top performers from 2014 have experienced a decline. Interestingly, variation in trademarks is positive for all groups of regions and with little variation from one performance group to another. This could be explained by the regional structure of the economy, as trademarks are used more often in industries such as textiles, education and training, or transportation[4], which are not the most R&D intensive.

SMEs located in emerging and moderately performing regions seem to have improved their R&I performance, while SMEs in strong and leading regions tend to have witnessed declines in terms of the R&I performance indicators examined in the community innovation survey. There are several factors that could explain such a divide. Since the financial crisis, SMEs have faced severe difficulties in accessing funding (European Central Bank, 2020), and this has led to different reactions. Firstly, exit rates have skyrocketed (OECD, 2009) and in areas that were the most affected, SMEs which survived might very well be the most innovative (Edwards et al., 2008; Ioanid et al., 2018). Secondly, SMEs located in higher-performing regions may face fiercer international and national competition, notably over skilled workers (Prasanna et al., 2019), which could affect their R&I capacity. Thirdly, some national and regional governments have developed support programmes for innovative SMEs and start-ups, and European funding has also been successful in supporting those located in less-developed regions and regions in transition (Romero-Martinez et al., 2010; Radicic et al., 2016; Henriques et al., 2022; Ferraro et al., 2023). Finally, the structure of the community innovation survey is such that coverage of groups of regions is sometimes only partial.

4 Dyvik, E., (2022), Percentage of trademark applications, by industry sector 2022. Statista.

Table 4.1-1 Variation in RIS indicators across EU regions between 2014 and 2021 or latest year available

RIS indicator	Group of regions based on their performance for each RIS indicator at the beginning of the period									
	Bottom 10 %	2nd decile	3rd decile	4th decile	5th decile	6th decile	7th decile	8th decile	9th decile	Top 10 %
Variation in number of public-private co-publications per million inhabitants (2015-2022)	19.637	41.517	55.843	73.140	83.219	88.607	121.174	138.052	158.888	196.416
Variation in number of international scientific co-publications per million inhabitants (2015-2022)	161.749	158.612	276.491	341.016	402.859	463.502	532.624	627.881	834.108	1098.979
Variation in R&D expenditure in the business sector as percentage of GDP (2013-2020)	0.074	0.187	0.189	0.134	0.193	0.164	0.041	0.178	0.017	0.257
Variation in R&D expenditure in the public sector as percentage of GDP (2013-2020)	0.029	0.023	0.047	0.042	0.062	-0.020	0.044	0.045	0.126	0.150
Variation in percentage of employed ICT specialists over total employment (2014-2021)	0.000	0.202	0.477	0.499	0.618	0.837	0.985	1.227	1.411	2.524
Variation in percentage of scientific publications among the top 10 % most cited (2013-2020)	3.992	1.230	1.586	1.282	0.448	-0.096	-0.175	-0.636	-1.712	-2.338
Variation in number of individual design applications per billion GDP (in Purchasing Power standards - PPS) (2015-2022)	0.456	0.365	0.743	0.465	-0.124	-0.974	-0.682	-0.100	-2.402	-6.286
Variation in number of patent applications per billion GDP (in Purchasing Power standards) (2014-2021)	0.063	-0.003	-0.086	-0.075	-0.163	-0.352	-0.504	-0.560	-0.947	-2.467
Variation in number of trademark applications per billion GDP (in Purchasing Power standards) (2014-2021)	1.276	1.780	1.151	1.534	1.092	1.626	1.341	1.492	0.855	1.938
Variation in innovation expenditures per person employed in innovative SMEs (2014-2020)	-0.007	0.037	0.059	0.023	0.029	0.043	0.046	0.041	0.070	0.090
Variation in non-R&D innovation expenditure as a percentage of total turnover (2014-2020)	0.027	0.039	0.043	-0.016	-0.024	-0.020	-0.056	-0.059	-0.117	-0.269
Variation in employed persons in innovative SMEs as a percentage of total employment (2016-2020)	0.077	0.133	0.085	0.089	0.093	0.131	0.044	-0.019	0.005	0.042
Variation in percentage of turnover of sales of new-to-market and new-to-firm innovations (2014-2020)	0.241	0.183	0.104	0.182	0.111	0.064	0.020	0.174	0.097	0.012
Variation in the percentage of SMEs introducing process innovations over total SMEs (2014-2020)	0.136	0.113	0.199	0.228	0.260	0.260	0.211	0.220	0.189	0.082
Variation in the percentage of SMEs introducing product innovations over total SMEs (2014-2020)	0.119	0.129	0.169	0.224	0.292	0.175	0.104	-0.001	-0.080	-0.041

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on the RIS 2023 data.

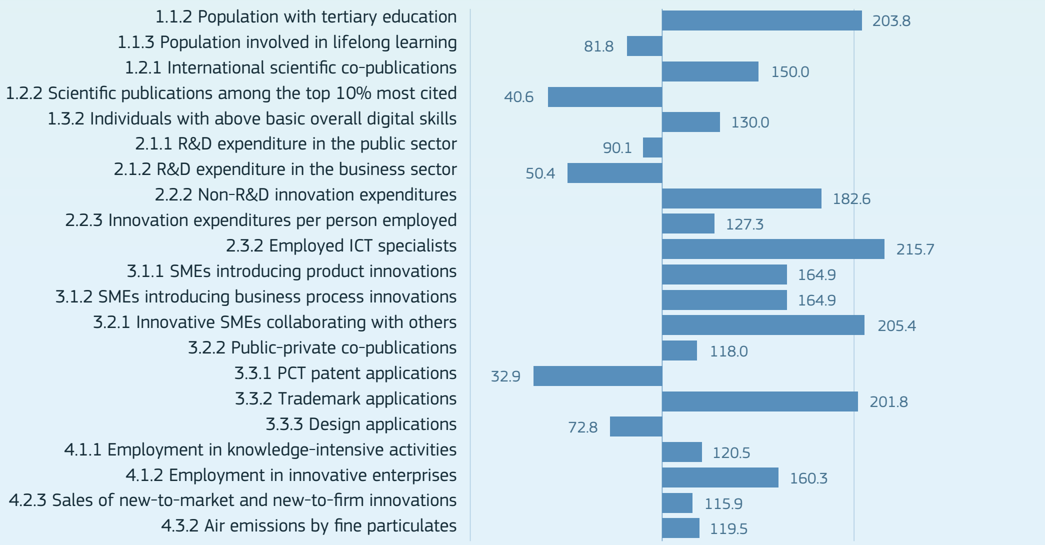
Note: See the methodology report of the RIS 2023 for details on each indicator.

Box 4.1-1: Regional case study using quantitative RIS 2023 data and a qualitative approach: the case of the Vilnius region

The RIS provides detailed information on each region's R&I assets. It makes it possible to perform case analysis to determine the key aspects of R&I systems and offer policy recommendations. Considering the Vilnius Capital Region, this box introduces an example of a combination of quantitative and qualitative analysis using RIS 2023 data.

On the RIS, the Capital Region is in the 'strong innovator' category. It ranks 96th out of 241 regions in the EU, and 1st in Lithuania. The region's innovation index rapidly increased from 70 % of the EU average in 2014 to 103 % in 2021, meaning that its performance is now slightly above the EU average (see Figure 4.1-6).

Figure 4.1-6 Capital Region RIS performance (2021 data relative to EU 2014)



Science, research and innovation performance of the EU 2024

Source: Regional case study from the Regional Innovation Scoreboard.

Using both quantitative data from the RIS and qualitative data in the form of interviews with policymakers and experts, the following key aspects driving innovation in the Capital Region have been identified.

- **A progressive regulatory policy** aimed at creating favourable conditions for high-tech and innovative companies, e.g., by significantly shortening the time needed to issue licenses, reducing the initial capital requirement or offering unique European license types.
- **A cluster effect of increasing innovation**. Since 2014, innovation has been increasing very rapidly; for example, the regional average for SMEs introducing business process innovations increased more than threefold (49 % to 165 %), and the share of innovative SMEs collaborating with other similar companies increased twofold (101 % to 205 %) compared with the EU average, establishing the Capital Region as a strong innovator in this field.
- **A well-developed infrastructure** for high-tech manufacturing companies (e.g., lasers, biotech) in the Capital Region, which it is oriented towards innovative business practices (e.g. fintech). There are multiple innovation clusters that facilitate cooperation between innovative companies from the same sector.[5] The situation regarding the research system and publications gradually improved during the 2014-2021 period, especially regarding international scientific co-publications and to a lesser degree the number of scientific publications in the top 10 % in terms of citations.
- **A high number of foreign direct investment** (FDI). Around three quarters of FDI in Lithuania is in the Capital Region.

On the other hand, there are sizeable barriers to innovation in the region.

- **Limited cooperation between the public and private sectors in the field of innovation or insufficient public financial support for innovation projects.** Although there has been a clear improvement for most of the expenditure indicators – for example, innovation expenditure per person employed increased from 96 % to 127 % – R&D expenditure in the public sector has decreased (from 139 % to 90 %).
- **The level of cooperation between educational institutions and businesses, which is relatively low** in Lithuania. In addition, research and education infrastructure in Lithuania is fragmented, which leads to weak knowledge- and technology-transfer processes from educational institutions to businesses.

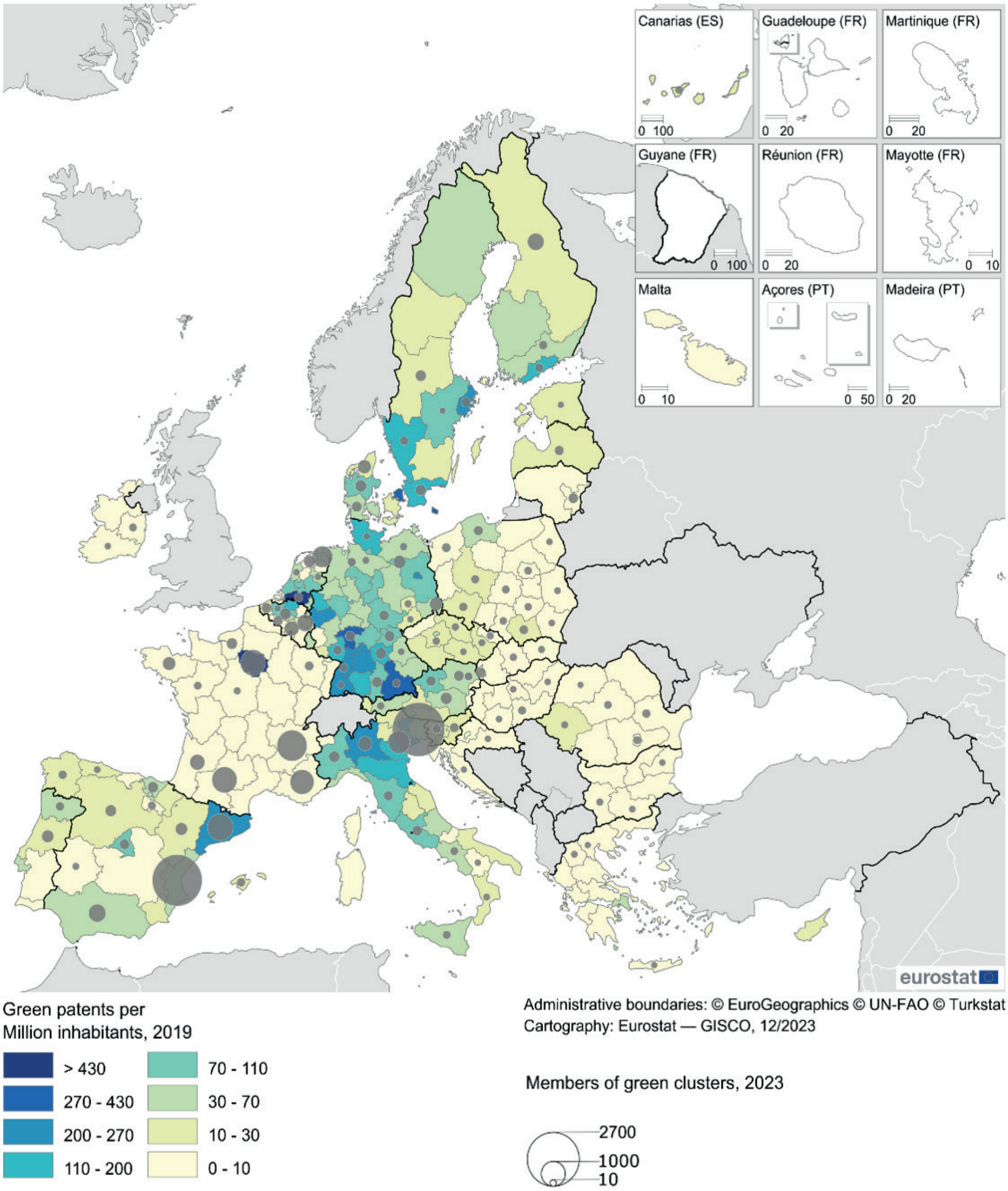
5 For example, Inovacijų Slėnys. More information is available at https://inovatoriuslenis.lt/

The industrial structure of European regions and asymmetric developments in productive specialisation across countries and regions are the most frequently quoted explanations for the existence of spatial disparities in R&I (Bracalente and Perugini, 2010; Mongelli et al., 2016; López-Villuendas and del Campo, 2023; Capello and Cerisola, 2023). Industrial clustering is a phenomenon which leads to SMEs, large firms and research organisations with sector-specific expertise basing themselves close to each other, creating pockets of specialisation across the EU to benefit from economies of scale (Krugman, 1991; Ottaviano and Puga, 1998; Fujita et al., 2001; Iammarino and McCann, 2006; Moretti, 2018). These industrial clusters have positive impacts on regional and industrial performance, including job creation and new business formation (Delgado et al., 2014), while playing a vital role in explaining the high concentration of technological innovation in various sectors across EU regions (Figure 4.1-7 for the green and digital sectors).

Over the last century, while industrial clustering has mainly been driven by production activities, location choices are now determined more by shared skill requirements, especially in service sectors (Diodato et al., 2018). This has resulted in stronger industrial clustering in cities in western Europe and an even spread across regions in central and eastern Europe, especially since the financial crisis (Odendahl et al., 2019). Finally, innovative clusters are becoming more specialised in related innovation activities, leading to a reinforcement of overall geographical concentration and a tendency toward regional divergence (O'Sullivan and Strange, 2018; Iammarino and McCann, 2018).

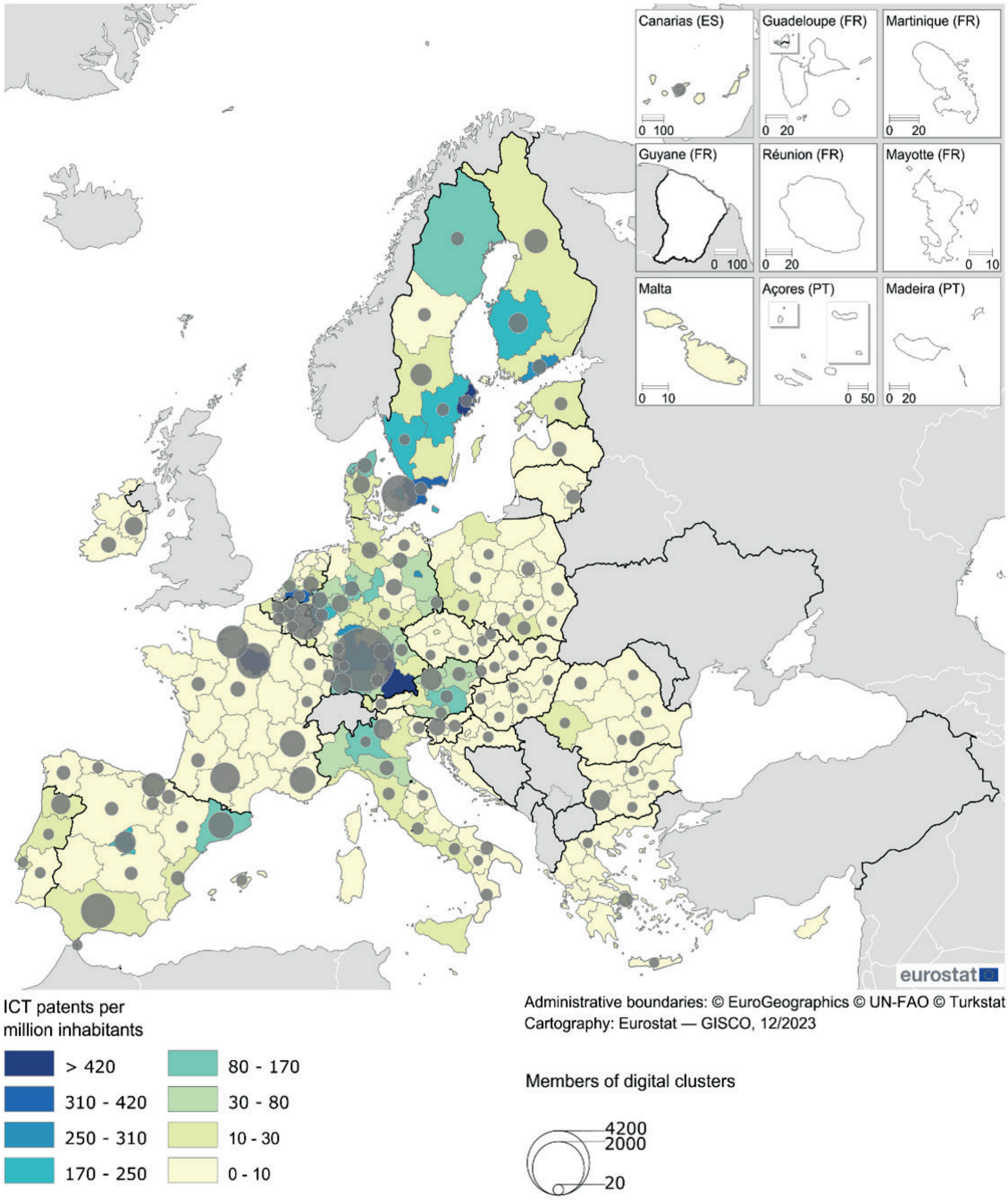
Figure 4.1-7 Members of green/digital industrial clusters registered with the European Cluster Collaboration Platform[6], 2021 and green/ICT patents per million inhabitants, 2018

Green patent clusters



6 The European Cluster Collaboration Platform hosts about 1 127 industrial clusters in Europe: [Homepage | European Cluster Collaboration Platform](#).

Digital patent clusters



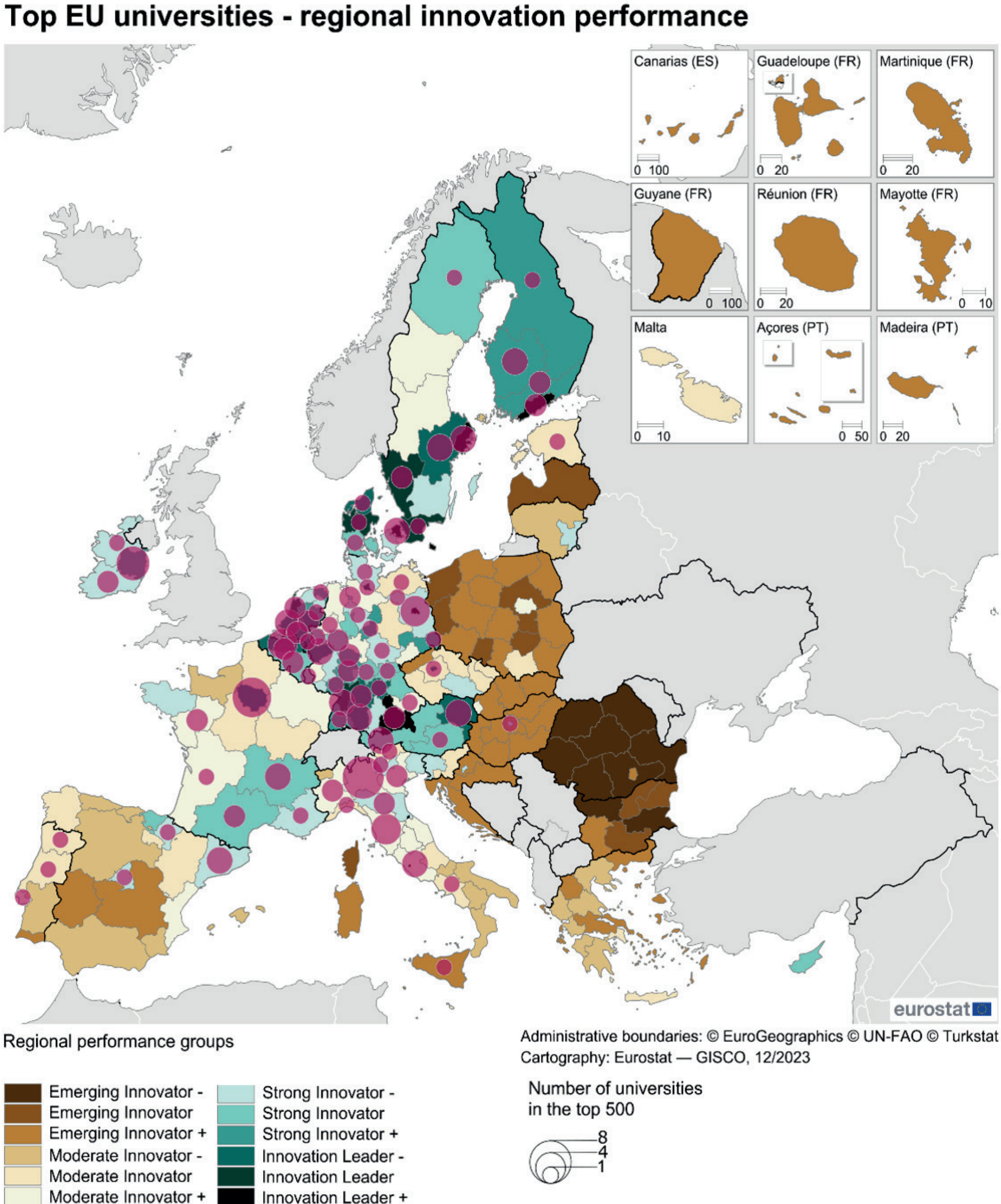
Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on Science Metrix using REGPAT data and on European Cluster Collaboration Platform data.

Note: Industrial clusters are registered under the European Cluster Collaboration Platform. Green industrial clusters are defined as 'working in green sectors and/or technologies' and digital clusters as 'working in digital sectors and/or technologies'. Green patents are defined as patents in the fields of climate action; the environment; resource efficiency and raw materials; secure, clean and efficient energy; and smart, green and integrated transport.

152 of the top 500 universities included in the Times higher education impact ranking 2021 are located in the EU and are highly concentrated in top-performing regions according to the RIS 2023 (Figure 4.1-8). Collaboration between public research institutions and the business sector is one of the most important channels for knowledge diffusion and valorisation and significantly increases the performance of regional R&I ecosystems.

Figure 4.1-8 Distribution of the top 500 universities using the Times higher education impact ranking 2021 and RIS 2023 scores



Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on RIS 2023 data and Times higher education impact ranking 2021.

Much place-based and social innovation in EU territories, including less populous areas, is difficult to measure with the usual research input and output indicators (Mihci, 2020). Social innovation refers to the process and the outcome of the process of development of new products, methods and services for and with society (Solis-Navarrete et al., 2021; Mulgan, 2006; Mulgan et al., 2007; Cajaiba-Santana, 2014).

At least 65 social innovation clusters[7] are scattered across the EU. Social economy enterprises, partnerships, cooperatives, and associations, sometimes organised in clusters, have proven to be innovative in dealing with socio-economic and environmental problems, while contributing to economic development and are often cited as key players for social innovation (European Commission, 2020). These social innovation clusters are often smaller in size than other industrial clusters, and also more diversified in terms of their types of members (see Table 4.1-2) and their sectors of intervention (health, waste management, energy, agriculture, housing, etc.). In addition, they have a geographical intervention scope that is predominantly local and regional, with no or few global or national activities. They also emerge in predominantly rural areas (see Table 4.1-2).

Table 4.1-2 Social, green and digital industrial clusters: a few characteristics

		Social innovation clusters	Clusters working in green sectors and/or technologies	Clusters working in digital sectors and/or technologies
Average number of members	Total	83	130	154
	SMEs	62	95	102
	Large companies	6	13	16
	Research organisations	5	11	13
	Associations/ cooperatives	9	0	0
Ratio of localisation in rural/urban regions (Eurostat typology)		1.2	1.0	0.7

Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on European Cluster Collaboration Platform data.

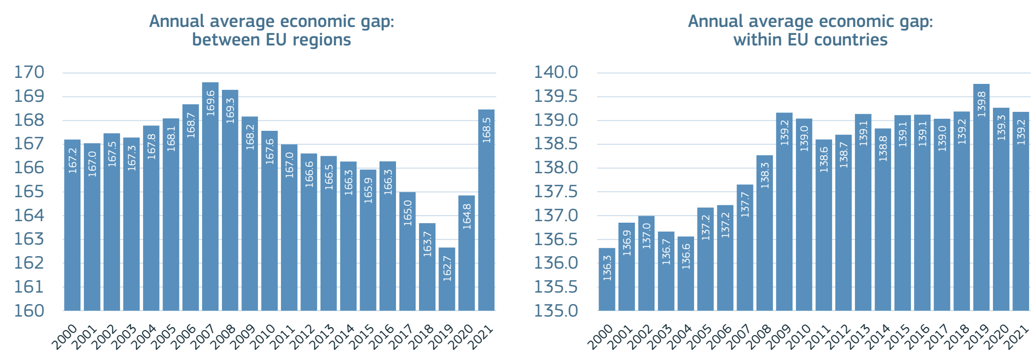
7 Identification of social innovation clusters has been the object of two studies financed by the European Commission.

2. Innovation divide and economic divide: what role for EU funding and policies?

Since the adoption of the Single European Act, the aim of EU R&I policy has been to strengthen the scientific and technological basis of EU industry and to make it more competitive at international level (Article 179 of the Treaty on the Functioning of the European Union (TFEU)). The TFEU also provides that the EU shall aim at 'reducing disparities between the levels of development of the various regions and the backwardness of the least favoured regions or islands' (Article 174).

The EU has experienced the emergence of subnational economic development clubs, consisting of regions with wide differences in dynamics of income, employment, industrial composition, education, productivity, innovation, urbanisation and demography (Diemer et al., 2022). Regional disparities in the EU, as measured by the gap or distance between a given region's GDP per capita and that of the region with the highest GDP per capita in the EU, decreased between 2000 and 2019. However, this convergence process, which was reversed in 2020 and 2021 by the effects of COVID-19, hides very diverse trends. Firstly, regions that have reduced their economic gap to the leading region are mainly located in northern and eastern Europe (Figure 4.1-9). By contrast, many Mediterranean regions have been diverging. Secondly, in-country regional differences in productivity levels are on the rise, which accords with existing studies (Mongelli et al., 2016; OECD, 2023; European Commission, 2023b); Marques-Santos et al., 2024). This is the result of several countries, in particular (but not only) in eastern Europe, experiencing further economic concentration in a few, mostly metropolitan, areas. These disparities can be observed when looking at the evolution of the GDP per capita gap in European regions (Figure 4.1-9) and in the regional competitiveness index (Figure 4.1-10).

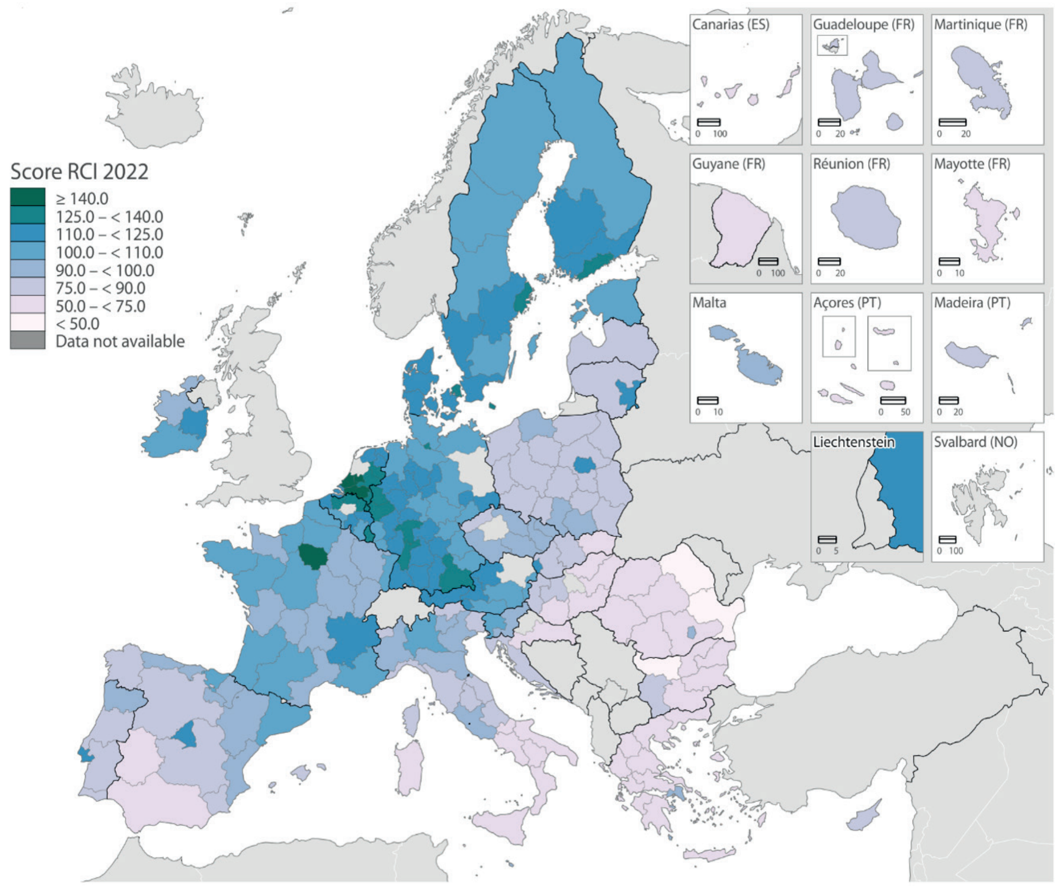
Figure 4.1-9 **Annual average economic gap: between (left) and within (right) indexes, 2000-2021**



Science, research and innovation performance of the EU 2024

Source: Joint Research Centre, Innovation Policies and Economic Impact Unit, based on Eurostat data.

Figure 4.1-10 Regional competitiveness index, 2022

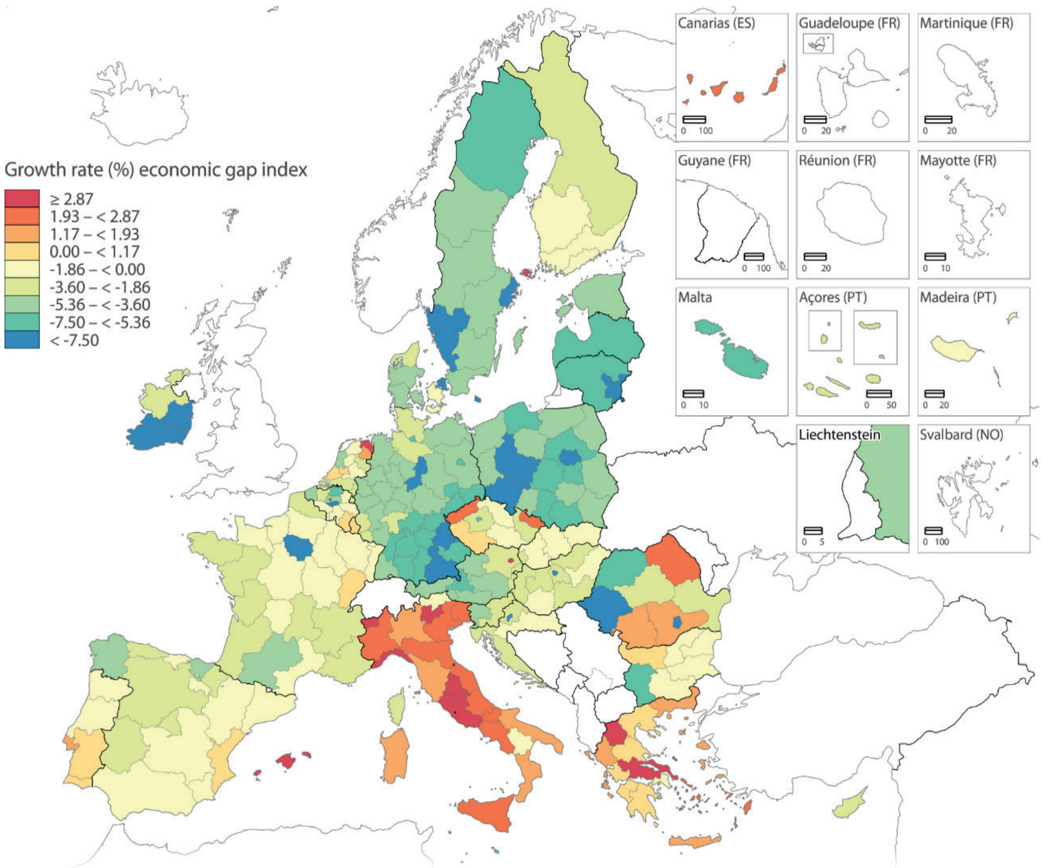


Science, research and innovation performance of the EU 2024

Source: DG Regional and Urban Policy.

Regions with weak innovation performance saw their economic gap vis-à-vis the richest region in their country widen significantly over the 20 years from 2000, whereas the best-performing areas experienced the opposite trend, though less markedly (Figure 4.1-11). At EU level, emerging innovator regions converged only modestly, whereas moderate innovator regions diverged, even before COVID-19 (Marques-Santos et al., 2024). These in-country disparities are also apparent when seen through the lens of RIS categories (Table 4.1-3). Interestingly, higher R&D expenditure seems to lead to increased regional convergence, both at EU and national level (Figure 4.1-12).

Figure 4.1-11 Changes in economic gap between European regions: growth rate (%) in 2019 compared with 2000



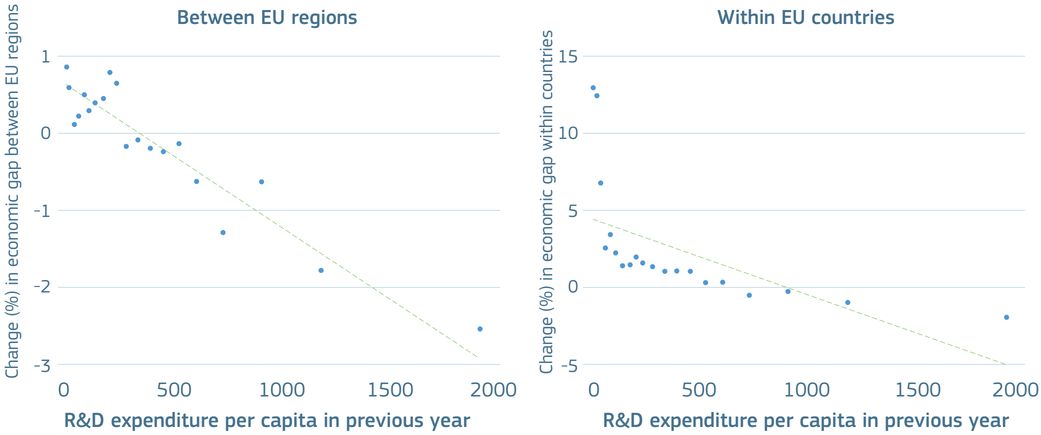
Science, research and innovation performance of the EU 2024
Source: Joint Research Centre, Innovation Policies and Economic Impact Unit, based on Eurostat data.
Note: 2019 has been chosen to avoid biases in the overall evolution of the productivity gap due to the COVID-19 effect in 2020-2021.

Table 4.1-3 Annual average economic gap (between EU regions and within EU countries) by RIS classification (RIS 2023)

Category	Between EU regions				Within EU countries			
	2000	2019	2020	2021	2000	2019	2020	2021
Emerging innovator	180.2	176.1	177.5	179.5	141.6	153.9	154.6	154.2
Moderate innovator	167.3	165.4	168.1	171.3	136.5	140.5	139.8	139.7
Innovation innovator	153.0	146.3	149.0	154.7	127.4	124.4	123.2	123.3

Science, research and innovation performance of the EU 2024
Source: Joint Research Centre, Innovation Policies and Economic Impact Unit, based on Eurostat and EIS data.

Figure 4.1-12 Relationship between change in economic gap between EU regions (left) and within countries (right) and R&D expenditure per capita in the previous year, 2000-2021



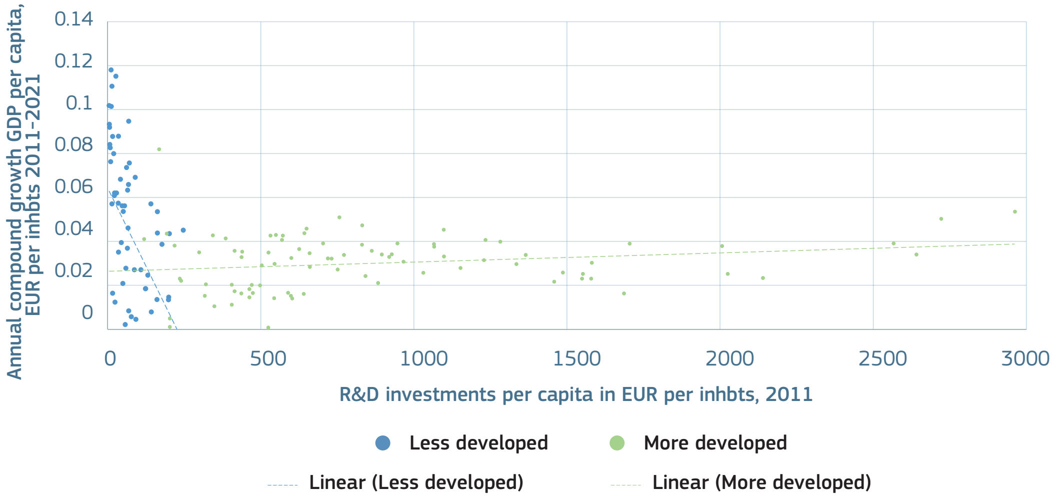
Science, research and innovation performance of the EU 2024

Source: Joint Research Centre, Innovation Policies and Economic Impact Unit, based on Eurostat data.
Note: The figure above is a binscatter constructed using panel data of 4 977 observations. Binned scatterplots provide an alternative way of visualising the relationship between two variables, based on a large number of observations, by computing the mean of the x-axis and y-axis variables within each bin and then creating a scatterplot of these data points.

Regions in the core of Europe with a higher initial level of investment in R&D have achieved a marginally greater degree of economic growth, while less-developed regions are less capable of generating innovation from R&D inputs (Rodríguez-Pose and Wilkie, 2019). In more-developed regions, the regression line between R&D expenditure and economic growth has a slightly positive slope (Figure 4.1-13). The clear negative regression line reinforces the idea that the effort to generate more innovation in many less-developed regions has not delivered on the final objective of unleashing greater economic activity and growth. This may curtail their capacity to grow in the medium to long term.

Hence, the basic tenet of the linear model of innovation – that R&D investment leads to greater innovation, and, in turn, to growth – is challenged in the EU, in particular across most of its less-developed regions. This has been explained in the literature by the fact that the capacity to generate innovation out of R&D inputs relies on the presence of strong institutions (Rodríguez-Pose and Di Cataldo, 2015).

Figure 4.1-13 From investment in R&D to economic growth in European regions according to their level of development, 2011-2021



Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on Eurostat data and the Science, Research and Innovation Performance of the EU Report, 2020.
Note: More- and less-developed regions are defined using the cohesion policy classification for the 2021-2027 programming period: more-developed regions have an average GDP/head (PPS) for 2015-2016-2017 of >= 90% of the EU average; less-developed regions have an average GDP/head (PPS) for 2015-2016-2017 of <= 75% of the EU average.

The EU FP for R&I and the ESIF[8] jointly contribute to achieving the TFEU objectives of strengthening the EU scientific and technological base, fostering R&I collaborations, and reducing spatial disparities (Art 174 and 179 TFEU). The vast majority of regions in north-western Europe, owing to their high performance in R&I, participate primarily in Horizon Europe. By contrast, eastern European regions and a non-negligible number of southern regions receive a larger share of structural funding for R&I to support their convergence (Čučkovic and Vučković, 2021; Izsak and Radošević, 2017; Figure 4.1-14) Therefore, structural funds, being to a significant extent earmarked for regions that are less developed and typically performing less well in R&I, compensate for the low capacity of these regions to tap into EU FP for R&I funding.

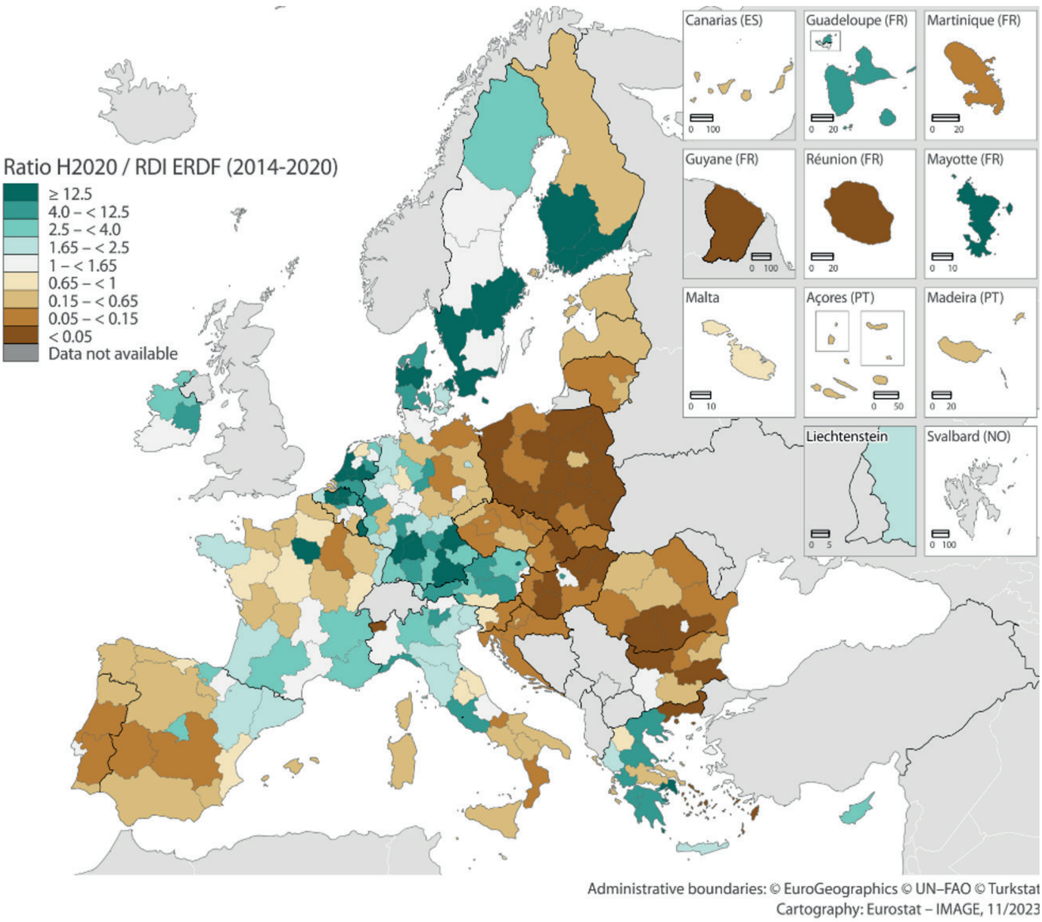
However, Europe is experiencing a 'closed-club effect' (Protogerou et al., 2010; Balland et al., 2019; Enger, 2018; Peiffer-Smadja et al., 2023), **which is linked with a high risk of widening the R&I divide**. Displaying a ratio of the use of Horizon 2020 to that of cohesion funds (only the R&I part of the European regional development fund (ERDF)), Horizon 2020 funding is much more concentrated than that of ESIF (Figure 4.1-14). The excellence criteria for funding awards under Horizon 2020 can further strengthen the competitive advantage of already-advanced regions, creating a cycle resulting in high concentration of public funding.

8 ESIF include the ERDF and the European social fund (ESF). In this analysis, we focus only on the funds dedicated to R&I activities under ESIF.

Complementary actions under the EU FP for R&I and ESIF, are therefore important to support cohesion, counterbalance the closed-club effect and promote the overall competitiveness of the EU. These may take the form of supporting territorial development, enhancing institutional capacity, and improving public administration and good governance at regional and local levels (Robinson and Acemoglu, 2012; Rodríguez-Pose and Di Cataldo, 2015 on the importance of institutional context for innovation and competitiveness).

The EU FP for R&I mainly supports R&I projects in sectors that allow research organisations and companies to collaborate to tackle societal challenges and compete with international players. However, it also dedicates resources to the development and improvement of research infrastructure, the governance of R&I systems and the integration of civil society into R&I.[9] This creates synergies with smart specialisation policies and ESIF which improve R&I assets and increase research capacities that are fundamental to meeting the TFEU objectives.

Figure 4.1-14 Distribution of the ratio of use of Horizon 2020 funds to cohesion policy funds (only the R&I part of ERDF funding) across EU NUTS 2 regions, 2014-2020



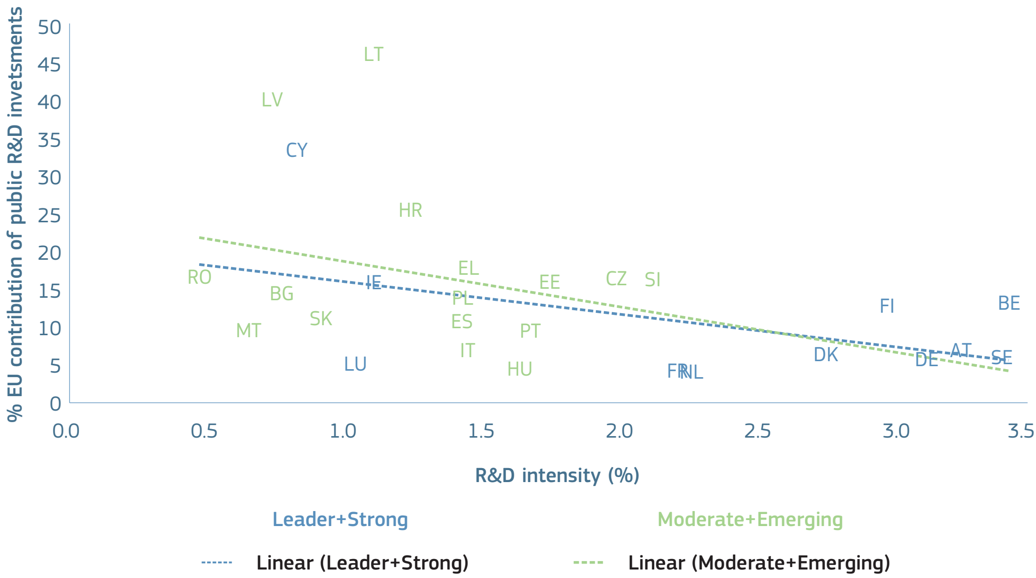
Science, research and innovation performance of the EU 2024

Source: Joint Research Centre, Innovation Policies and Economic Impact Unit, based on Territorial Economic Data viewer data and Marques Santos et al (2023).

9 For more detailed analysis, please refer to the evaluation of Horizon 2020.

Overall, European funding has strong potential to narrow the divide. There is a higher reliance of low R&I performers – those which dedicate fewer resources per capita to R&D – on EU funding, in particular ESIF, to support their R&I systems (Figure 4.1-15). In eastern Europe and some parts of the Mediterranean, even middle-income and more-developed regions depend on ESIF allocations to a greater extent than on EU FP for R&I resources (Molica and Marques-Santos, 2024). This observation is also valid across groups with different performance levels according to the European Innovation Scoreboard 2023.

Figure 4.1-15 Contribution of EU funding to public R&D investment by EU Member State R&D intensity and EIS profile (2023), 2021 or latest year available

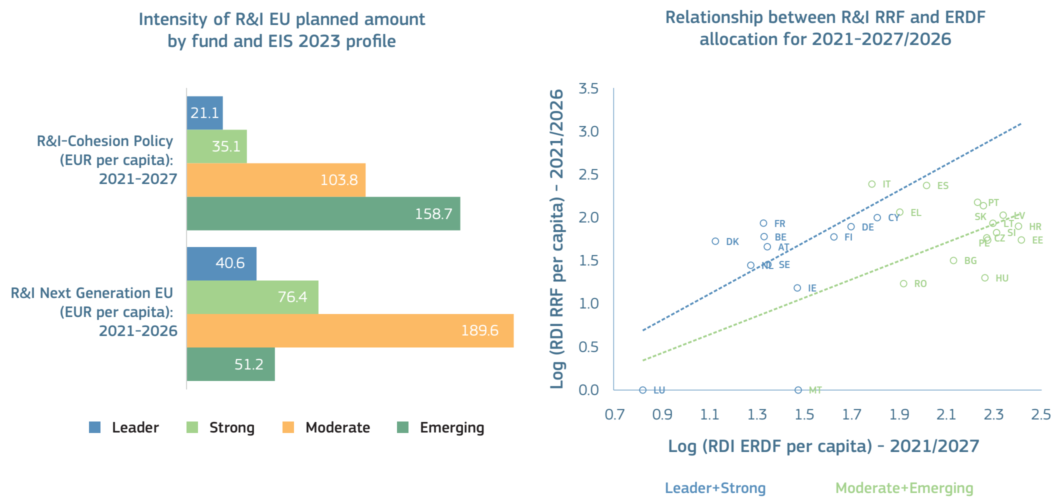


Science, research and innovation performance of the EU 2024
Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on Eurostat and EIS data.
Note: R&D investment data for Germany and the Netherlands are 2019 data. R&D public investment corresponds to government, higher education and rest of the world public investments. The total EU contribution might be underestimated due to reporting methods in some Member States.

The RRF is also expected to play a role in reducing the innovation gap. A number of countries with weaker innovation performance enjoy high per capita levels of both RRF and ERDF funding for R&I (Italy, Greece, Portugal, Latvia, Croatia, Estonia, Czechia and Poland; Figure 4.1-16). However, the per capita intensity of the R&I resources supplied under the RRF is also relatively significant in a few strong innovator countries (Belgium, France, Germany and Denmark), whereas it appears modest in some of the less-developed (and least innovative) countries (Romania, Hungary and Bulgaria) (Molica and Marques-Santos, 2024).

Overall, differences between per capita levels across EU countries are more pronounced for R&I ERDF funds than for the equivalent resources under the RRF, pointing to a weaker redistributive nature of the latter. This can be partially explained by the different allocation methodologies of the two instruments. The RRF allocation method takes more account of the size of the country alongside the impact of COVID-19 on national GDP. Planning decisions are also a factor.

Figure 4.1-16 Intensity and relationship of planned EU R&I funding amounts under cohesion policy funding (ERDF part) and RRF for the period 2021-2027 (2026), by EIS profile (2023)



Science, research and innovation performance of the EU 2024

Source: Joint Research Centre, Innovation Policies and Economic Impact Unit, based on Cohesion Open Data Platform, FENIX, Eurostat and EIS data.

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CHAPTER 4.2

R&I CONNECTIVITY

Key questions

- What is the state of play of R&I collaborations within the EU?
- What can R&I policy do to improve connectivity within the European R&I ecosystem?

Highlights

- Please replace by: The overall number of R&I collaborations has drastically increased in the EU.
- The European regional co-patenting network is fragmented along national lines and characterised by a strong cross-border effect.
- Complex technologies, such as digital ones, are those showing the highest shares of inter-country collaborations.

Policy insights

- EU R&I policies play a major role in increasing connectivity of the European R&I ecosystems.
- The EU Framework Programme for R&I has created an important collaboration network. This network makes it possible to steer R&I collaborations across the EU and overcome cross-border effects.
- Please repharse: Pillar 2 of the Framework Programme and initiatives such as Interreg, i.e., the European programme for territorial cooperation and promotion of cross-border exchanges between regions, fulfil the role of steering R&I collaborations across the EU.

The increasing geographical concentration of research and innovation (R&I) activities coexists with the increasing internationalisation of research collaborations, in a sort of "local-global duality" (Hidas et al., 2013): knowledge production activities have become increasingly interconnected in the last decades, due to globalisation. Collaborative R&I allows researchers and other innovative actors to engage in mutual learning endeavours, increasing the quality of the research output to have a stronger impact on the innovation system and, in turn, on the economy as a whole (Chesbrough, 2003; von Hippel, 2005; Hoekman et al., 2009; Wanzenbock et al., 2014).

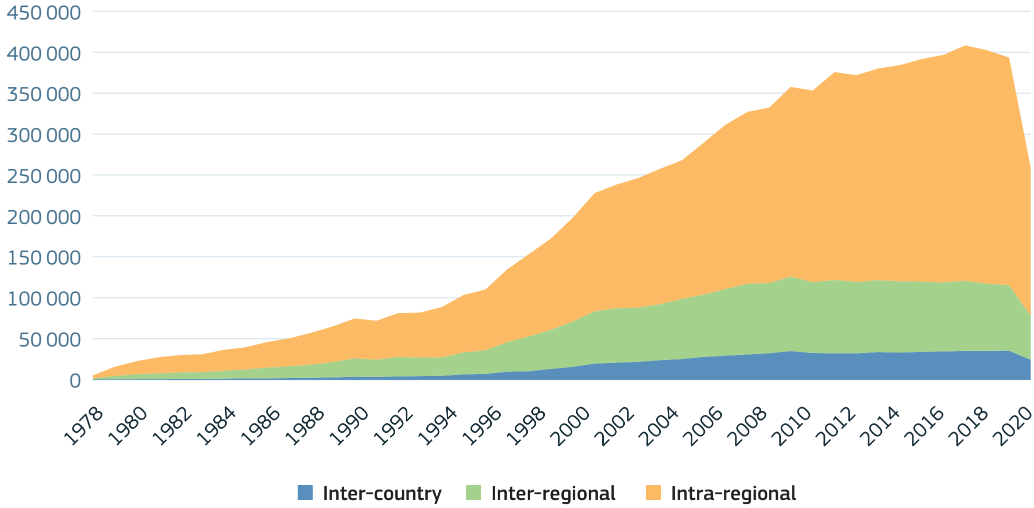
As a result, the number of scientific and innovation collaborations has increased. Nevertheless, this increase is also characterised by specific geographical and sectoral patterns in the EU. Furthermore, the EU has consistently supported collaborative projects in R&I, notably through the European Framework Programme for R&I (European Commission, 2022), and other initiatives, such as the Interreg programme. This chapter proposes, in this second part, an overview of the role and importance of European R&I policies and initiatives to improve the connectivity of EU R&I ecosystems.

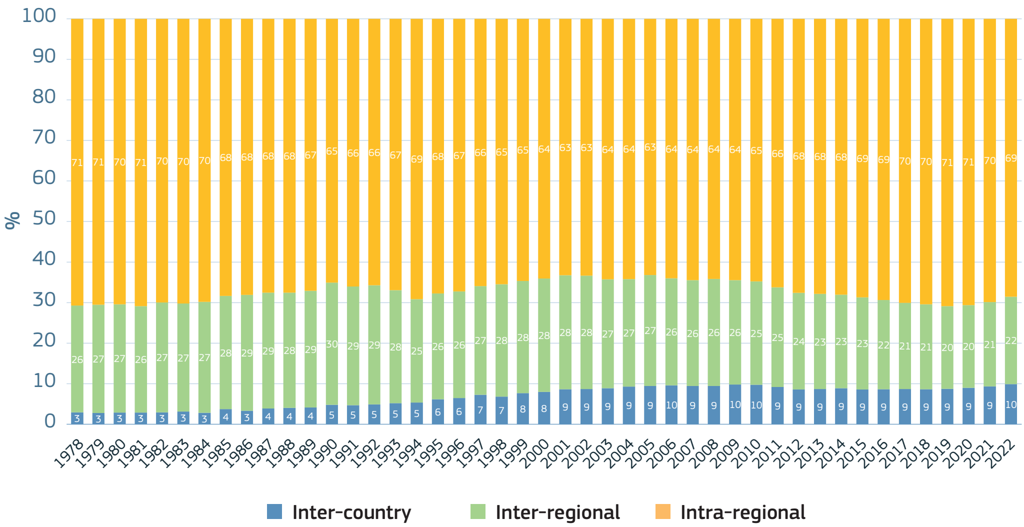
1. The state of play of R&I collaborations within the European Union

There is an increasing geographical concentration of R&I activities and an increasing internationalisation of research collaborations. Both phenomena coexist in a sort of 'local-global duality' (Hidas et al., 2013) where the globalisation process has caused knowledge production activities to have become increasingly interconnected in recent decades. Collaborations in R&I allows researchers and other innovative actors to engage in mutual learning endeavours. This increases the quality of the research output and leads to a stronger impact on the innovation system and, in turn, on the economy as a whole (Chesbrough, 2003; von Hippel, 2005; Hoekman et al., 2009; Wanzenbock et al., 2014).

The overall number of EU R&I collaborations has increased significantly. Co-patenting, while not the sole indicator of collaboration in the domain of R&I, can be considered a concrete result of successful collaboration between two or more innovators. Co-patenting in Europe has increased considerably since 1980, from 1000 to over 100 000 by 2020 (Figure 4.2-1). This trend is also observed globally (Breschi and Malerba, 2005; Agostini and Caviggioli, 2015; Belderbos et al., 2022) and can be explained by: (1) a growing significance of R&D collaborations, notably because of the many interdependencies among various high-tech industry process and product components (Agostini and Caviggioli, 2015); (2) the diminishing reluctance among firms to co-own patents (Hagedoorn, 2003) and the recognition of co-patenting as a useful strategy for companies (Belderbos et al., 2014); (3) dedicated public support for cooperation in R&I, involving both firms and higher education institutions.

Figure 4.2-1 Evolution of numbers of intra-regional, inter-regional and inter-country co-patents and the yearly percentage of each type of co-patent from 1980 to 2020 (all EU, UK, NO, IS and CH NUTS 2 regions)





Science, research and innovation performance of the EU 2024

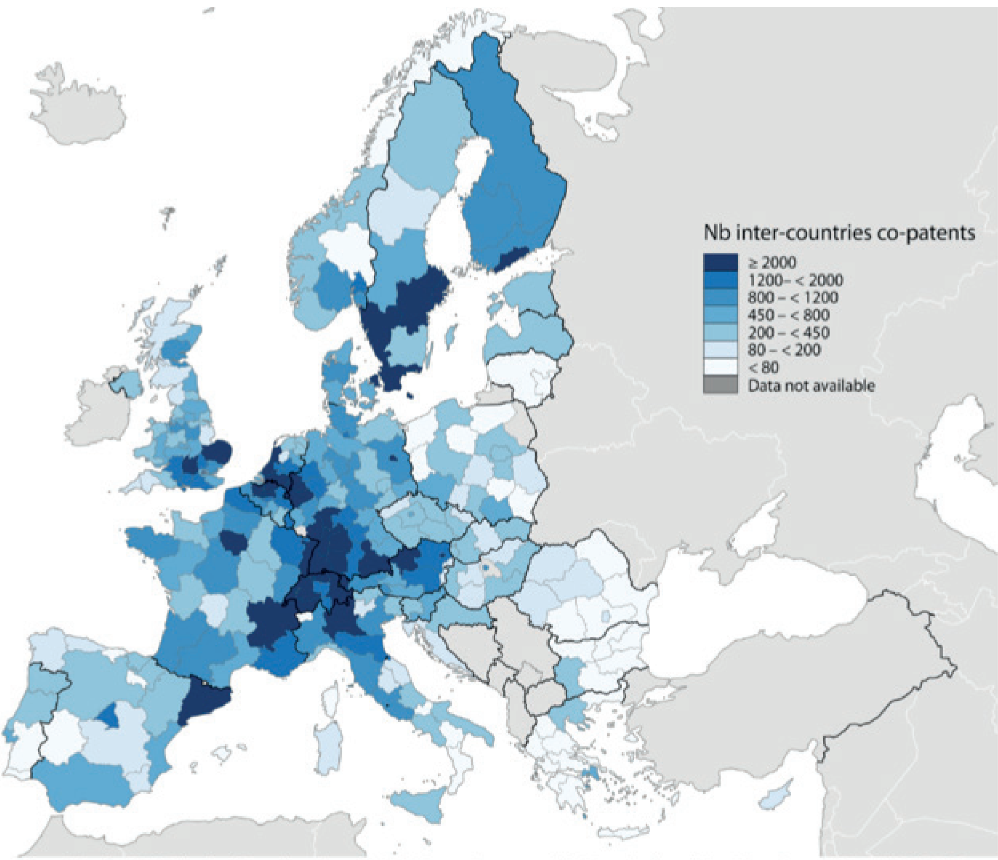
Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on REGPAT dataset.

Notes: Labels correspond to the three types of co-patents (inter-country, inter-regional, intra-regional). Inter-country co-patents involve at least two organisations located in different European countries; inter-regional co-patents involve at least two organisations located in different European regions but in the same country (intra-country); intra-regional co-patents involve only organisations located in the same region.

In Europe, a large majority of collaborations resulting in co-patents occur between organisations located in the same region (63-71% of all co-patents filed each year are the result of intra-regional collaboration). This can be explained by the role of spatial proximity, which creates a web of social, face-to-face interactions and networks that enable the rapid and effective diffusion of ideas and knowledge spillovers (Chakravarty et al., 2021) thereby boosting the overall productivity of local actors in the innovation system (Fleming et al., 2007).

Only 3-10% of co-patents filed each year involve organisations located in two different European countries. Inter-country co-patents mostly involve entities located in cross-border regions (next to one another but in a different EU Member State), notably along the Rhine valley, connecting German, Belgian, French and Swiss regions. R&I connectivity is also strong between entities located in capital cities, which have an excellent track record of patenting activity (Figure 4.2-2). Maintaining such extra-regional and inter-country collaborations may further stimulate and sustain the creation of knowledge capabilities and innovation (e.g., Cano-Kollmann et al., 2016).

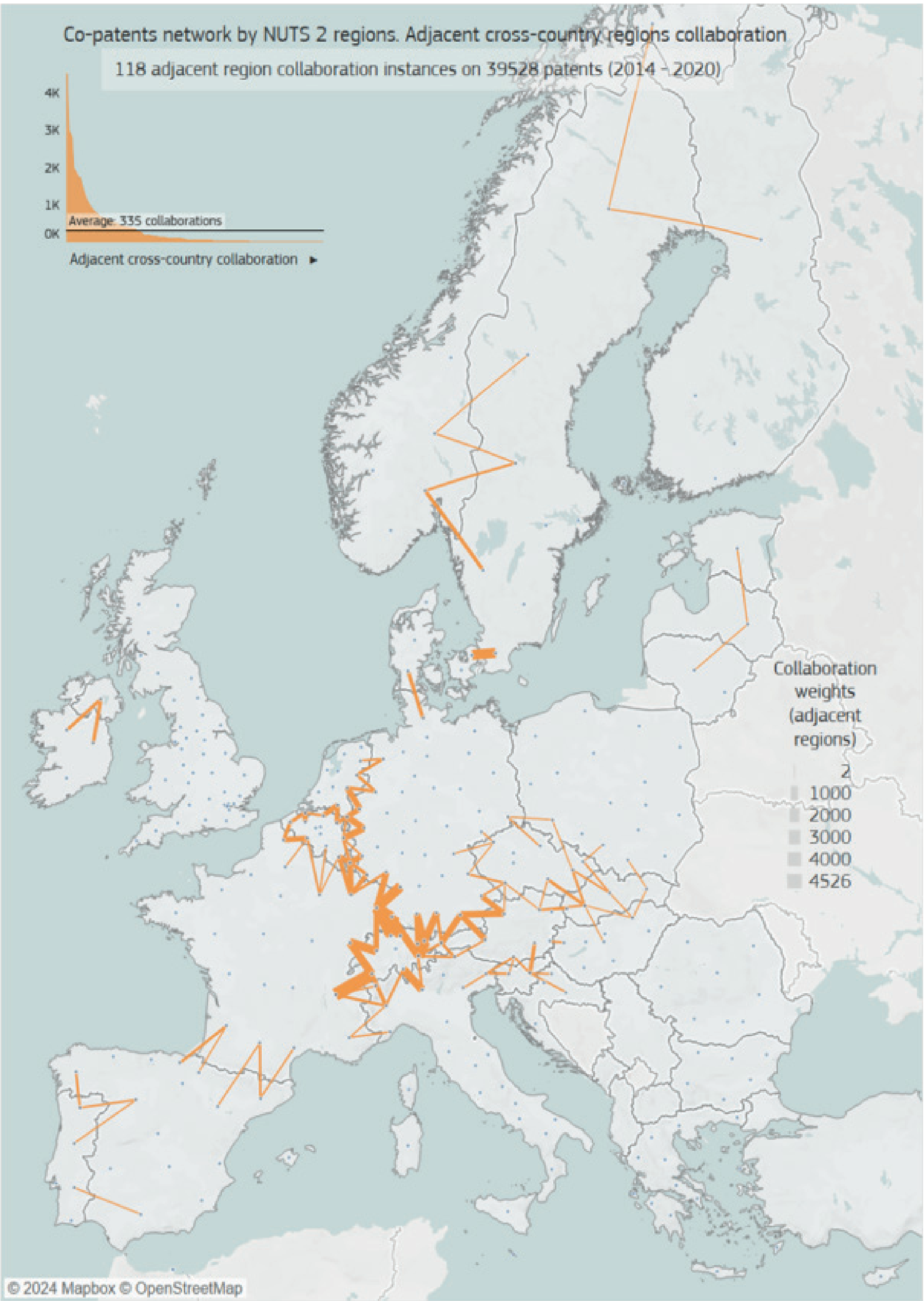
Figure 4.2-2 Number of inter-country co-patents by NUTS 2 regions, 1979-2020 and co-patents network by NUTS 2 regions - adjacent cross-country regions collaborations



Data may be missing for NUTS2 that have been discontinued from 2013 onwards.
Source: DG Research and Innovation– Common R&I Strategy and Foresight Service Chief Economist Unit based on REGPAT data.

Administrative boundaries: © EuroGeographics © UN–FAO © Turkstat
Cartography: Eurostat – IMAGE, 08/2023

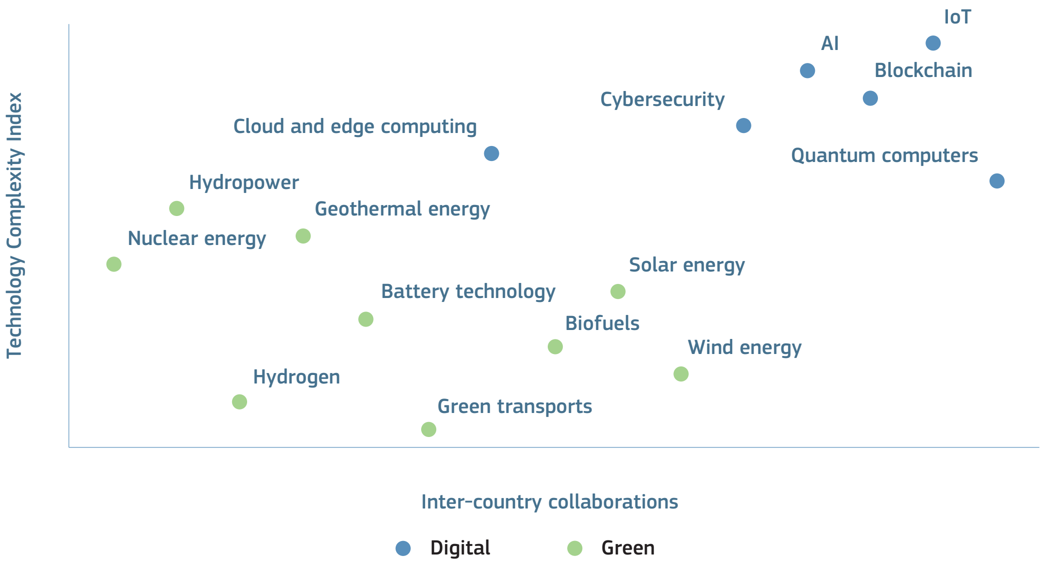
Science, research and innovation performance of the EU 2024
Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on REGPAT data.



Source: Joint Research Centre, Innovation Policies and Economic Impact Unit.

European R&I collaboration capacity is critical for innovation in complex technologies. Complex technologies are defined based on their rarity on the international scene: the fewer countries there are to file patents in a specific technology class, the more complex this technology class is.[1] There is an exponential positive correlation between the ranking by complexity index of a specific technology category and its share of European inter-country collaborations (Figure 4.2-3). Digital technologies, such as artificial intelligence (AI), Internet of things (IoT), blockchain and cybersecurity, are those with the highest shares of inter-country collaborations, suggesting that collaboration is more crucial for these complex technologies (a result corroborated by Bachtrögler-Unger et al., 2023). As complex activities combine many capabilities, it is harder for others to copy and develop them. They may then provide a more sustainable source of competitiveness for Europe (Maskell and Malmberg, 1999; Fleming and Sorenson, 2001; Balland and Rigby, 2017; Rigby et al., 2022). These results underline the importance of improving interlinkages between European R&I ecosystems to develop complex technologies and achieve greater competitiveness.

Figure 4.2-3 European inter-country collaborations by technology ranked according to complexity index, 2014-2020



Science, research and innovation performance of the EU 2024

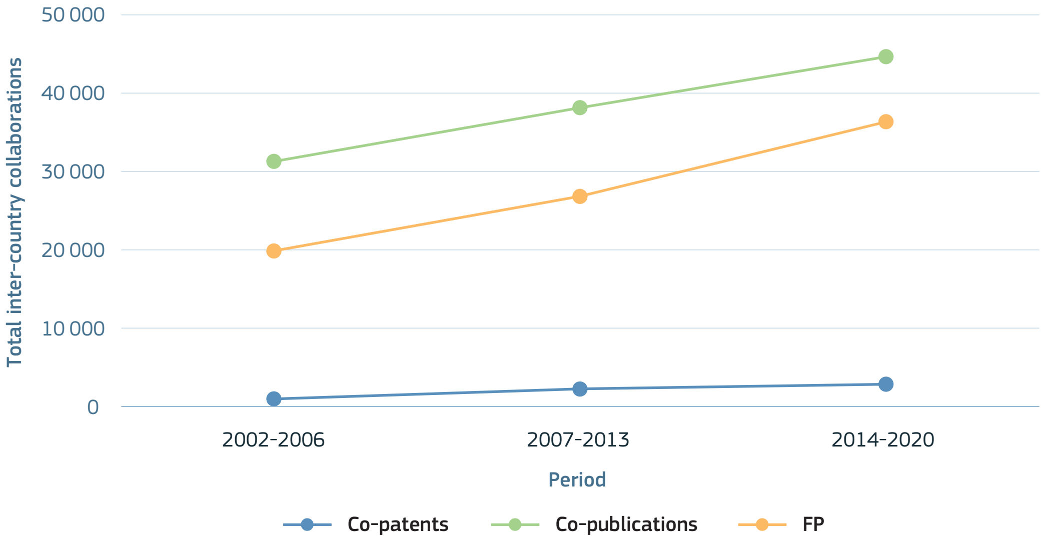
Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on REGPAT data (EPO).

1 For more information, see box 2.2-1 in chapter 2.2.

2. The role of EU policies in connecting European R&I ecosystems

European R&I policies play a major role in increasing the connectivity of European R&I ecosystems and in supporting international collaborations (European Commission, 2022; Figure 4.2-4). The EU FP for R&I went from supporting about 20 000 international collaborations through its 2002-2006 edition (FP6) to more than 35 000 through its 2014-2020 edition (Horizon 2020). With three quarters of its funding going to instruments supporting collaborative R&I[2], Horizon 2020 even supported more than 2 million collaborations between individual organisations worldwide. Finally, 74% of respondents to a stakeholder consultation carried out for the evaluation of Horizon 2020 agreed that participating in the programme improved cooperation with partners from other countries (within the EU and beyond) (European Commission, 2017).

Figure 4.2-4 European collaborations under the EU FP for R&I compared to total European inter-country collaborations resulting in co-patents and co-publications, 2002-2020



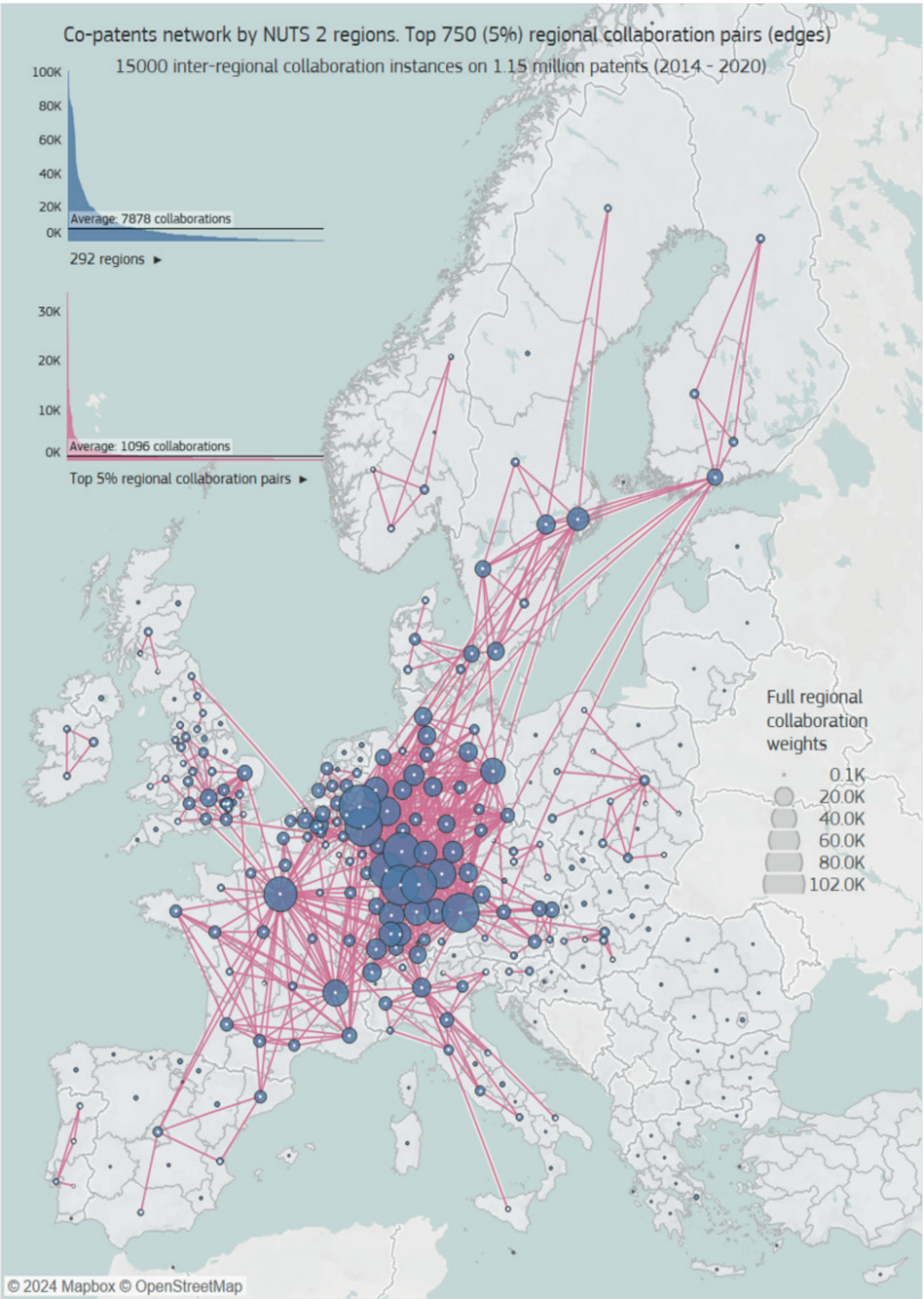
Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on REGPAT and Corda data.

2 E.g. R&I actions, innovation actions, Marie Skłodowska-Curie actions, innovative training networks (ITN), and coordination and support actions.

Co-patenting activity in Europe is quite highly concentrated amongst regions with excellent track records of patenting activity. There is a large concentration around a few regions, with German and capital regions being key nodes of the network (Figure 4.2-5a). Similarly, the network of regions collaborating on scientific publications shows concentration, albeit to a lesser extent than for co-patenting, with key nodes situated in eastern and southern Europe (Figure 4.2-5b). The large concentration around capital regions is in line with academic literature findings on the presence of agglomeration economies in capital regions, i.e., the advantages that firms enjoy when they are located near one another. The spatial proximity allows firms to benefit from various external economies of scale such as labour market pooling, infrastructure sharing and network effects, which can result in increased productivity and innovation (e.g., Duranton & Puga, 2004; Jacobs et al., 2014).

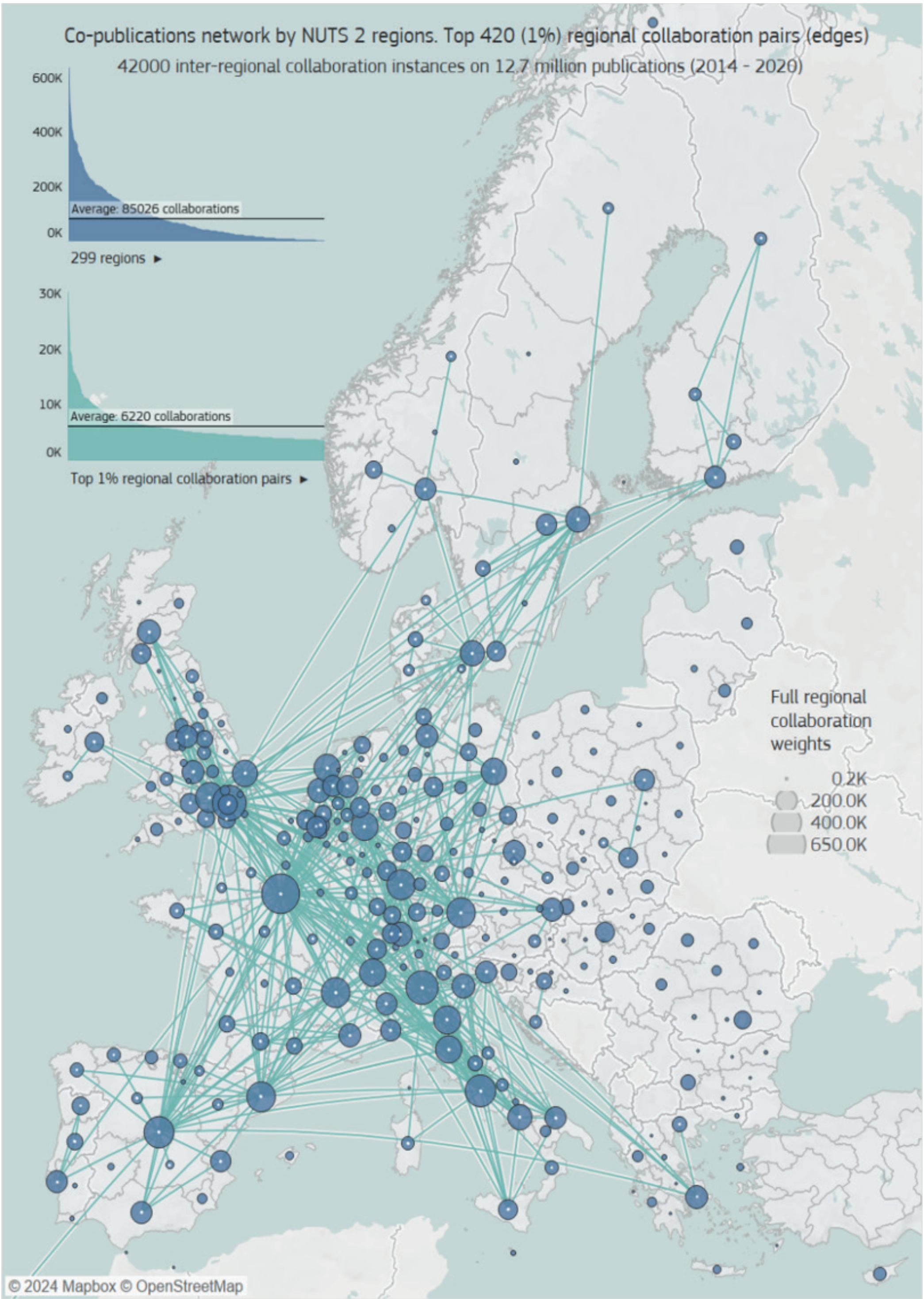
The EU FP for R&I created an important R&I collaboration network during 2014-2020 (Figure 4.2-5c). Compared to the European regional co-patenting network (Figure 4.2-5a), which is fragmented along national lines and characterised by a strong cross-border effect, the EU FP for R&I network makes it possible to steer collaborations across the EU and to overcome the cross-border effect. Interreg, the European programme for territorial cooperation aimed at fostering cross-border exchange between regions, also plays a role in steering collaboration across the EU (Figure 4.2-5d, Table 4.2-1) as well as synergies between programmes.

Figure 4.2-5a Connection maps linking NUTS 2 regions in Europe based on organisations which co-patent together



Source: Joint Research Centre, Innovation Policies and Economic Impact Unit and DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on REGPAT.

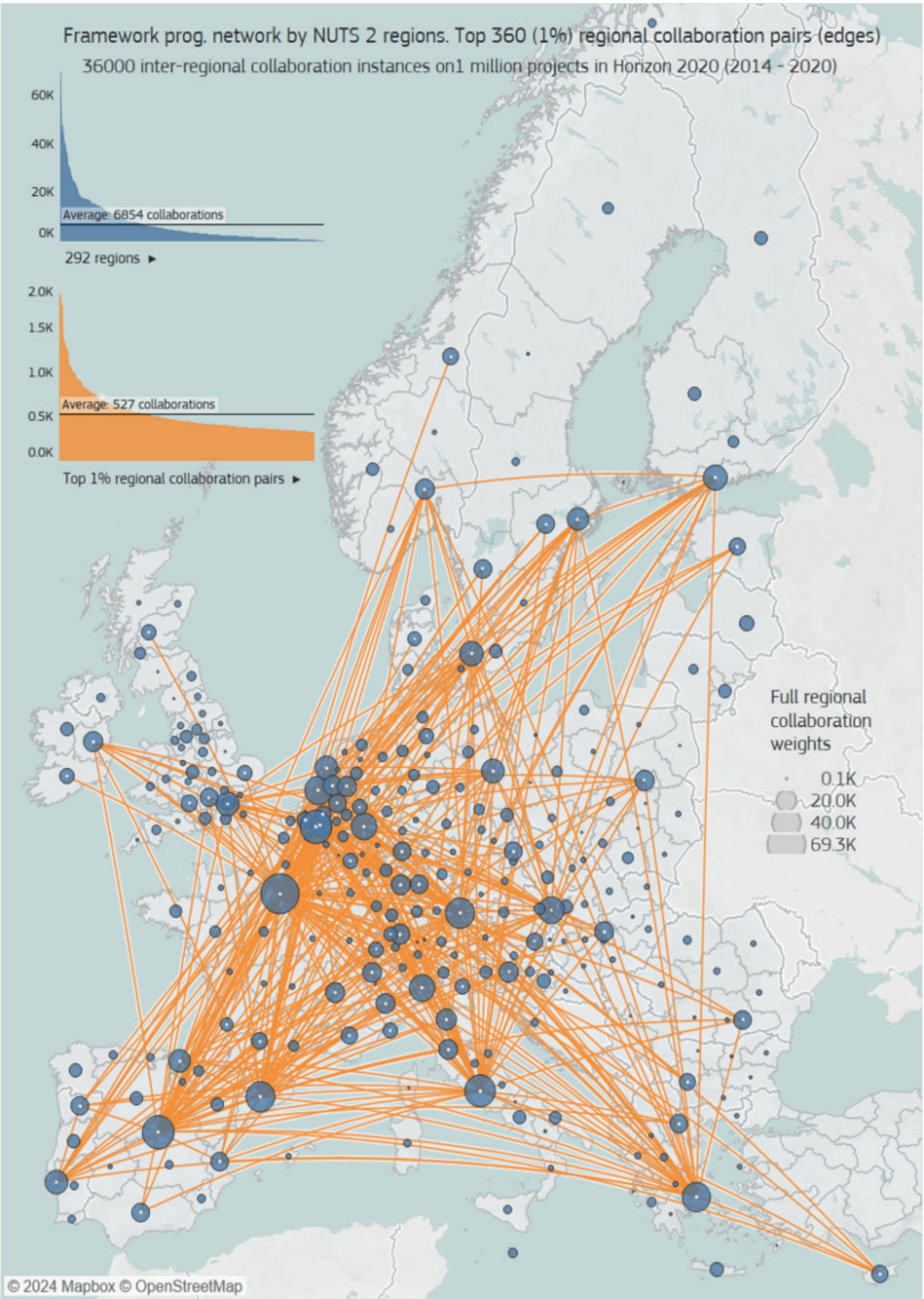
Figure 4.2-5b Connection maps linking NUTS 2 regions in Europe based on organisations which co-publish together



Science, research and innovation performance of the EU 2024

Source: Joint Research Centre, Innovation Policies and Economic Impact Unit and DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, using Science Metrix data based on Scopus.

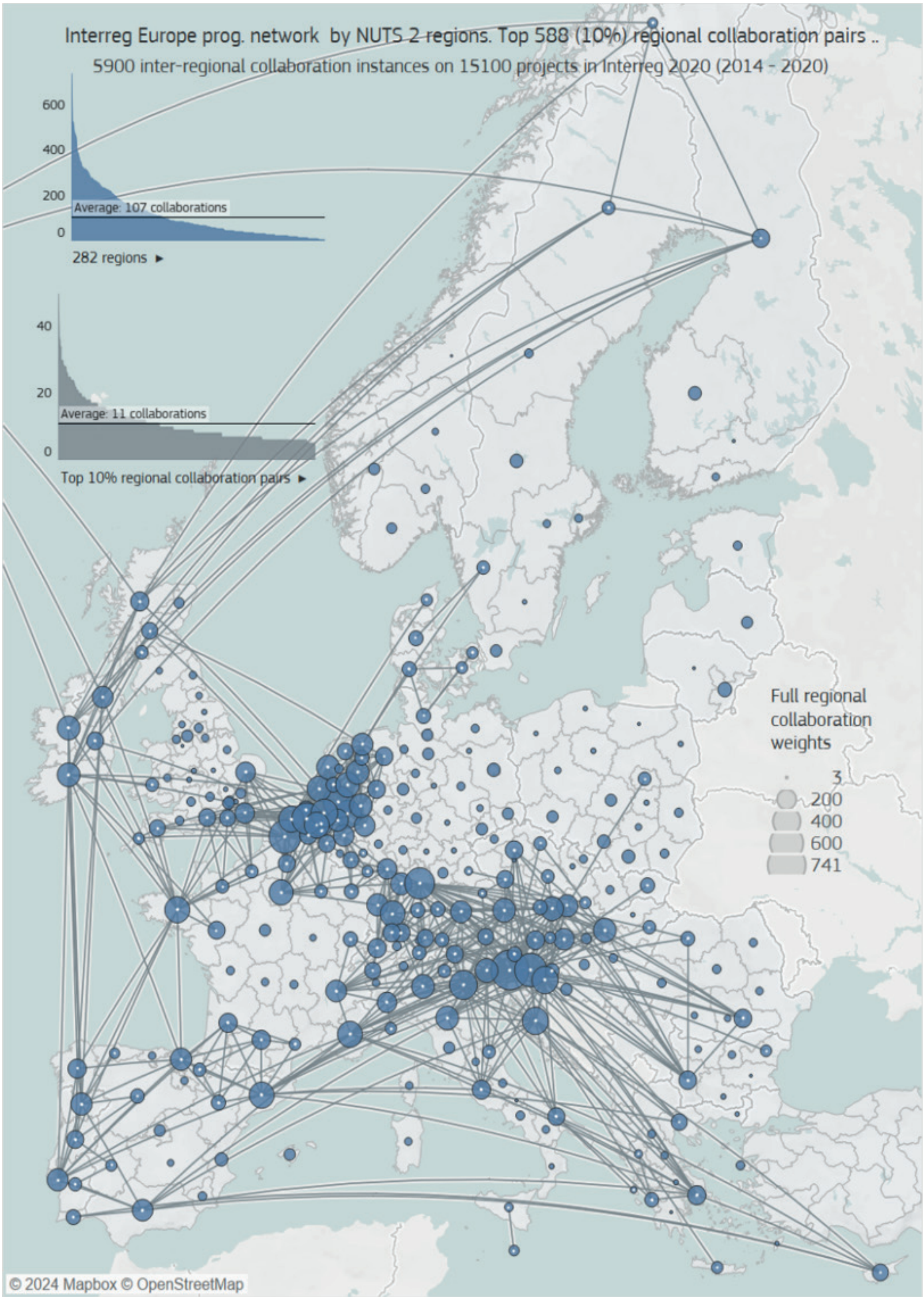
Figure 4.2-5c Connection maps linking NUTS 2 regions in Europe based on organisations that are involved in collaborations under the EU FP for R&I 2014-2020



Science, research and innovation performance of the EU 2024

Source: Joint Research Centre, Innovation Policies and Economic Impact Unit and DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on keep.eu and eCorda data.

Figure 4.2-5d Connection maps linking NUTS 2 regions in Europe based on organisations that are involved in collaborations under Interreg 2014-2020



Science, research and innovation performance of the EU 2024
Source: Joint Research Centre, Innovation Policies and Economic Impact Unit and DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on keep.eu and eCorda data.

Table 4.2-1 Collaborations through Interreg and the EU FP for R&I (Horizon 2020) resulting in joint publications and joint patents, 2014-2020

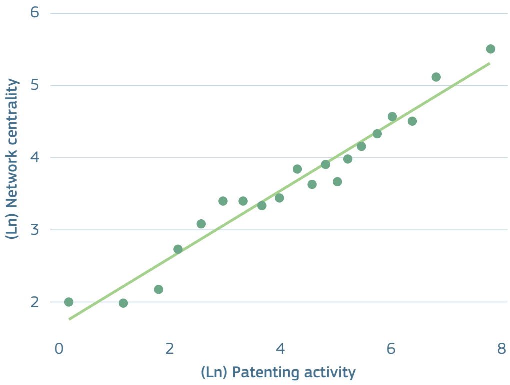
General characteristic	Inter-regional collaborations through Interreg	Inter-regional collaborations through Horizon 2020	Inter-regional collaborations resulting in a joint publication	Inter-regional collaborations resulting in a joint patent
Number of regions	283	297	299	297
Number of collaborations	5 883	35 985	41 596	15 101
Average (standard deviation) number of collaborations per region	41.576 (25.963)	242.32 (54.27)	278.234 (33.243)	101.690 (59.799)
Geodesic distance (length of shortest path) between any two regions	2.14	1.94	1.968	4.653
Diameter (longest distance in the network)	4	2	2	4
Density	0.147	0.75	0.819	0.344
Clustering (two of your partners are partners with each other)	0.401	0.852	0.892	0.599

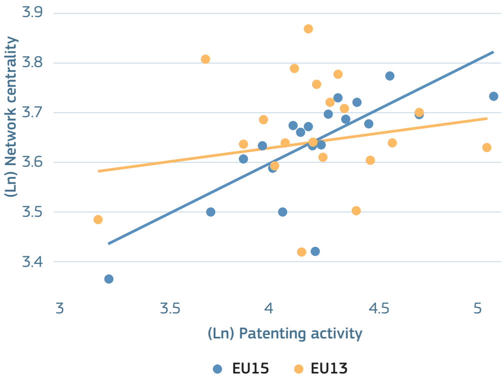
Science, research and innovation performance of the EU 2024

Source: Joint Research Centre, Innovation Policies and Economic Impact Unit and DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on REGPAT, keep.eu and eCorda data.

R&I collaboration networks created by the EU FP for R&I can accelerate the patenting activity of the regions involved (Lalanne and Meyer, 2024). For a European region, having a central position in the network of R&I collaborations under the EU FP for R&I positively impacts its patenting activity (Figure 4.2-6). This relationship between network centrality and patenting activity is much less strong for EU-13 regions (countries that have joined the EU since 2004) than for EU-14 regions (countries that joined before 2004).

Figure 4.2-6 **Relationship between centrality of a region in R&I collaboration networks created by the EU FP for R&I and patenting activity of the region, overall (left figure) and distinguishing between EU-13 and EU-15 regions (right figure)**

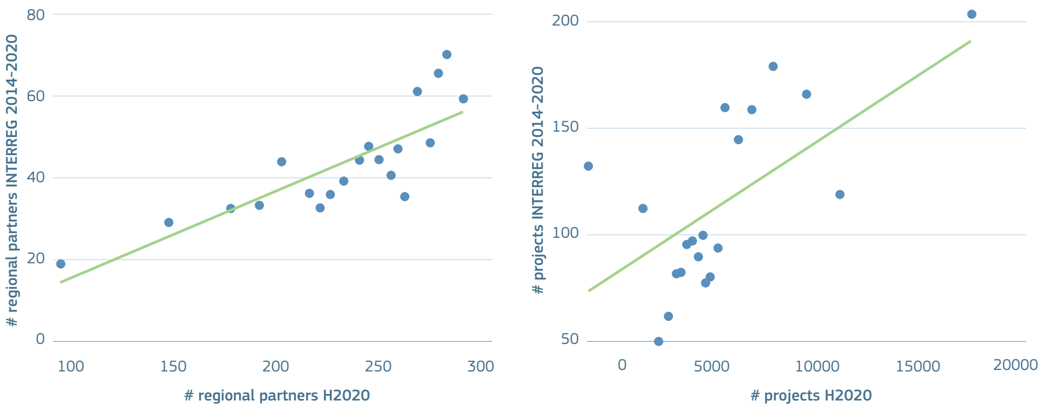




Source: Lalanne and Meyer (2024), Joint Research Centre, Regional Economic Monitoring Team (JRC B7-REMO).

Strong synergies between European R&I policy instruments can further reinforce cohesion between European R&I eco-systems. Participation of a region in Interreg programmes may have enhanced its participation in Horizon 2020, thereby increasing its relevance as an international partner (Figure 4.2-7). Nevertheless, differences exist between the two instruments, and these must be considered when exploring the topic of synergies. Interreg is comprised of a patchwork of programmes with varying levels of funding intensity, geographical coverage, and thematic scope (Lalanne and Meyer, 2024). These characteristics limit the scope for cooperation and access to funds across different territories, which was not the case for Horizon 2020. For instance, approximately 70% of Interreg funding is channelled to cross-border programmes, for which only border areas are eligible.

Figure 4.2-7 Correlation between numbers of regional project partners in Interreg 2014-2020 and Horizon 2020, with GDP serving as a control variable



Science, research and innovation performance of the EU 2024
Source: Lalanne and Meyer (2024), Joint Research Centre, Regional Economic Monitoring Team (JRC B7-REMO).
Note: The graphs are binned scatterplots with GDP controls of the number of regional project partners in Interreg 2014-2020 and Horizon 2020, i.e., they divide the data into equally sized bins with regard to the number of regional project partners in Horizon 2020 and compute the average number of regional project partners in Interreg 2014-2020 lying in each bin.

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CHAPTER 5

A THRIVING INNOVATIVE EUROPE

CHAPTER 5.1

R&I FOR GREEN PRODUCTIVITY GROWTH

Key questions

- What are the R&I drivers of labour productivity growth in the EU?
- What role does R&I play in decoupling economic growth from CO_2 emissions?
- Can AI defeat the productivity slowdown of Western economies?

Highlights

- Productivity growth is a key driver of economic prosperity, which, in turn, plays a significant role in reducing poverty and elevating the overall quality of life.
- In the EU, total factor productivity drives 48 % of labour productivity growth, followed by training and organisational capital (18 %), training (8%), R&D (4%), software (4 %) non-ICT tangible (13%) and ICT tangible 5 %.
- In the goods sector, tangible assets are key to productivity, while in the service sector, software, training, and organizational capital are more influential for labour productivity.
- Between 1990 and 2020, both the European Union (EU) and the United States (US) experienced GDP growth, alongside a decline in CO_2 emissions, even when accounting for offshore production.
- In 2020, even accounting for trade-adjusted CO_2 emissions, China's annual CO_2 output is approximately triple that of the EU, and twice that of the US.

Policy insights

- R&I is a key driver of European competitiveness and green growth.
- R&I plays a crucial role in accelerating economic growth decoupled from resource use by fostering the current decline in the cost of low-carbon technologies, as well as their deployment across the world.
- AI has the potential to address the productivity slowdown that has plagued Western economies in recent decades. However, for this success to be realised, it is crucial to implement policies that ensure AI augments rather than replaces human labour.

In the pursuit of economic growth and competitiveness, labour productivity stands as a pivotal metric, offering a lens through which we evaluate the efficacy of resource allocation within economies. Central to enhancing this productivity in the European Union (EU) are research and innovation (R&I) efforts, which have historically underpinned advancements in technology and society.

This chapter delves into the instrumental role of R&I in propelling labour productivity growth across the EU, with a particular focus on the concept of green growth (defined as economic growth decoupled from CO_2 emissions) and the productivity slowdown of which developed economies have been suffering in the past decades. The chapters also investigate the role of Artificial Intelligence in the mentioned dimensions.

1. R&I and labour productivity growth in the EU

Productivity is a vital economic indicator that reflects the efficiency with which inputs, like resources, are converted into outputs, such as products and services. Essentially, productivity measures our capability to generate more or equal output with the same or fewer resources. The higher our productivity levels are, the more we can do with less.

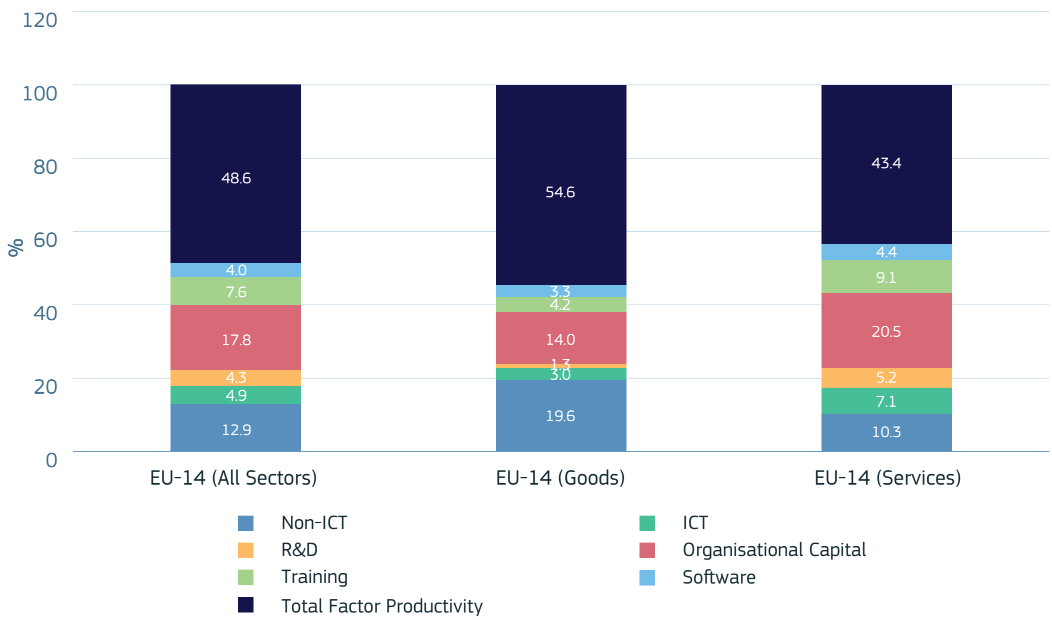
R&I are key engines to foster productivity growth. Indeed, since the Industrial Revolution, breakthroughs in technology, innovative organisational strategies, and the advancement of human capital have consistently fueled productivity improvements, which in turn have elevated living standards and economic growth (Dollar and Kraay, 2002).

Productivity growth is intrinsically linked to an economy's overall growth and competitiveness. On a broader societal level, productivity growth is instrumental in addressing critical issues like poverty. By enabling the production of more goods and services with fewer resources, productivity growth contributes to economic prosperity, which can lead to poverty reduction and improved quality of life (Kraay, 2004; Isaksson, 2004). Thus, the cycle of research, innovation and productivity growth is not only a catalyst for economic advancement, but also a crucial factor in fostering societal well-being and alleviating human suffering (Acemoglu and Guerrieri, 2008; Beugelsdijk et al., 2018).

In the EU, R&I significantly contribute to the growth of labour productivity. Specifically, between 1995 and 2019, intangible assets were responsible for nearly 80% of labour productivity increases. Breaking it down further, total factor productivity, often linked with innovation capacity, accounted for 48% of the labour productivity growth. Additionally, improvements in organisational capital contributed 18% to this growth, and training to 8%. R&D activities contributed 4%, while software investments alone added 4%. In contrast, non-ICT tangible assets, such as physical equipment and buildings, contributed 12% to labour productivity growth, and ICT (such as hardware) to 5% (see Figure 5.1-1).

The impact of various intangible and tangible assets on productivity growth varies significantly across different sectors of the economy. In the goods sector, non-ICT tangible assets, like machinery and buildings, play a crucial role in driving productivity. Conversely, in the service sector, intangible factors such as software, training, and organisational capital are more influential in enhancing labour productivity (see Figure 5.1-1). This diversity in the drivers of productivity growth across sectors can provide valuable insights for developing specific R&I strategies. Tailoring these strategies to the unique needs of each sector can effectively boost the overall competitiveness of the EU's economy.

Figure 5.1-1 Tangible and intangible drivers of EU-14 labour productivity growth by economic sector (1995-2019)



Science, research and innovation performance of the EU 2024

Source: Roth, Felix and Mitra, Alessio (2024).

Note: estimations performed using EU-KLEMS data and employing the cross-country sectoral growth accounting methodology as developed in the Horizon 2020 GLOBALINTO project by Roth Felix (2024). EU-14 refers here to Austria, Czechia, Denmark, Finland, France, Germany, Italy, Latvia, Lithuania, Netherlands, Slovakia, Slovenia, Spain, Sweden.

Box 5.1: The impact of EU R&I funding on firms' performance

The Horizon 2020 Framework Programme for Research and Innovation, a cornerstone initiative of the EU, was designed to foster and finance R&I endeavours in a wide array of scientific and technological fields. This flagship funding programme, operational from 2014 to 2020, not only supported entities within the EU member states, but also extended its reach globally.

In their 2024 study, Mitra and Niakaros delve into the causal impact of the Horizon 2020 programme on firm-level financial outcomes, including employment, assets, and revenue. Specifically, their paper explores the causal impact of receiving Horizon 2020 funding:

- as a whole;
- differentiating by sector.

Their analysis draws upon administrative records from CORDA and financial data from ORBIS, spanning from 2010 to 2022. The study's core sample comprises approximately 40 000 unique privately owned companies that applied for Horizon 2020 grants. To infer causality, the authors rely on the Difference-in-Differences (DiD) approach, accounting for staggered treatment timing and heterogeneous treatment effect.

The policy assessment reveals that EU R&I funding successfully achieves its 'additionality' goals by offering tangible EU value. Companies receiving Horizon 2020 grants experienced an average increase of about 20% in employment levels, and a notable 30% rise in both total assets and revenues in subsequent years (see Figure 5.1-2). However, this positive outcome is predominantly observed in firms operating within the *Information and Communication* and *Professional, Scientific, and Technical Activities* sectors. Firms in other sectors did not exhibit significant changes following the receipt of Horizon 2020 funding.

Figure 5.1-2 Causal impact of Horizon 2020 grants on beneficiary companies

Science, research and innovation performance of the EU 2024

Source: Mitra, Alessio and Niakaros, Konstantinos (2024). Note: The y-axes indicate the average treatment effect (ATT) of receiving a Horizon 2020 grant for a beneficiary firm compared to a non-beneficiary firm. The dots (or point estimates) represent the magnitude of the impact, while the bars (or confidence of intervals) indicate if the impact is statistically different from zero or not. The x-axes indicate the number of years before or after the receipt of the Horizon grant by the recipients.

2. R&I and green growth

Climate change and environmental degradation pose a critical threat to Europe and the globe. The European Green Deal is poised to address these challenges by revolutionising the EU into a modern, resource-efficient and competitive economy. Its goals are ambitious yet clear: achieve net-zero greenhouse gas emissions by 2050, foster economic growth independent of resource consumption, and ensure inclusive progress that leaves no person or community behind (COM/2019/640). This comprehensive plan is not just an environmental strategy, but also a path to equitable and sustainable economic development.

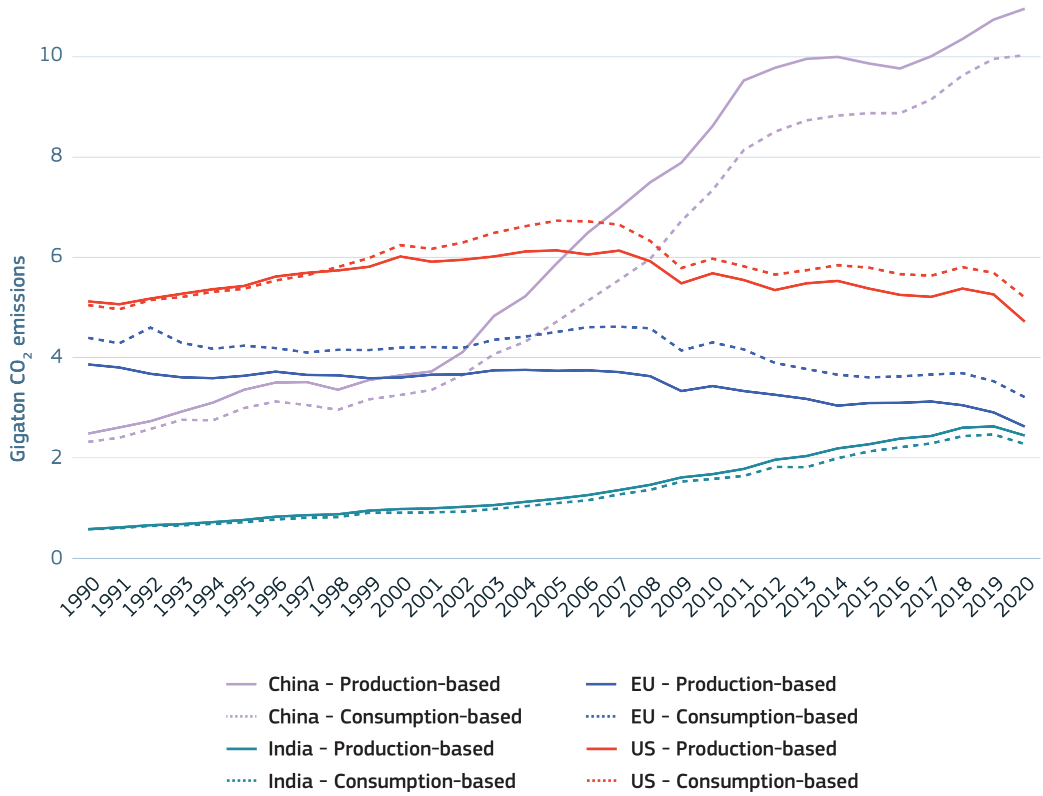
R&I are key drivers in Europe's ambitious journey to redefine its economic growth model. This new paradigm seeks to harmonise economic growth with the urgent need to respect planetary boundaries. In this context, productivity and economic growth maintain their policy importance as they are not just goals, but essential tools for boosting competitiveness, socio-economic development and addressing poverty (Dollar and Kraay, 2002; Isaksson et al., 2005; Beugelsdijk et al., 2018). Economic growth enables nations to invest in policies and ambitious programmes that lead to socially desirable outcomes such as health and education (Acemoglu, 2008). By generating the necessary resources, it enables substantial investments in green and digital technologies. These technologies are crucial for tackling the contemporary challenges we face, such as climate change and an ageing population.

While the EU has made strides in addressing climate change, it cannot tackle the issue in isolation. Multilateralism is important. Effective global collaboration with other major economies is imperative. Indeed, even after accounting for trade-adjusted CO_2 emissions (consumption-based emissions), China's annual CO_2 output is approximately triple that of the EU (Friedlingstein et al., 2022). Figure 5.1-3 charts the CO_2 emissions of key economic players from 1990 to 2021, tracking both production[1] and consumption-based[2] emissions. The data reveals a surge in China's emissions, contrasted by a decline in those of the EU and US. Notably, for manufacturing-driven countries like China, production emissions exceed consumption emissions due to the export of goods to Western countries. Conversely, the EU and US display higher consumption than production emissions, reflecting their importation of goods produced elsewhere, carrying the embedded carbon manufacturing costs.

1 Production-based emission: territorial emissions, which do not account for emissions embedded in traded goods.

2 Consumption-based emission: emissions generated in the production of goods and services according to where they were consumed, rather than where they were produced. Consumption-based emissions equals production-based emissions, minus emissions embedded in exports, plus emissions embedded in imports.

Figure 5.1-3 Global CO_2 emission trend



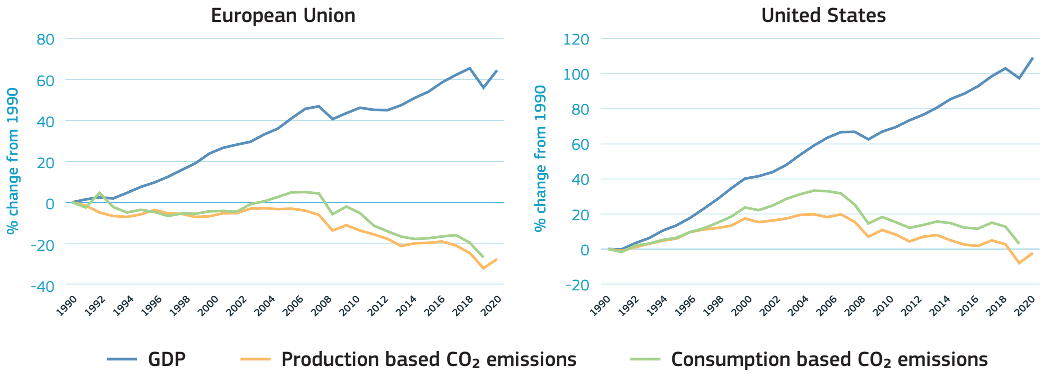
Science, research and innovation performance of the EU 2024

Source: Global Carbon Budget (2022). Note: CO_2 consumption represents CO_2 adjusted for trade. If a country's consumption-based emissions are higher than its production emissions, it is a net importer of carbon dioxide. If its consumption-based emissions are lower, then it is a net exporter.

In the past, there was a direct link between a nation's wealth and its CO_2 emissions. Higher incomes typically led to greater emissions due to increased energy consumption, much of which was derived from fossil fuels. This pattern has now shifted, particularly in high-income countries that are channelling investments into green technologies and striving for a decarbonised economy. These efforts have begun to break the traditional bond between economic prosperity and environmental impact (Kasperowicz, 2015; Agbugba et al., 2019).

Today, many high-income countries have decoupled economic growth from CO_2 emissions, even if we take offshored production into account. Figure 5.1-4 compares GDP, production-based CO_2 and consumption-based emissions, highlighting the relationship between economic growth and CO_2 emissions. In the EU and US, GDP has grown or remained stable, while both production-based and consumption-based CO_2 emissions have declined.

Figure 5.1-4 Economic growth decoupling from CO_2 emissions



Science, research and innovation performance of the EU 2024
Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit's own elaboration, based on World Bank and Global Carbon Budget (2022) data.
Note: Gross Domestic Product (GDP) figures are adjusted for inflation. CO_2 consumption represents CO_2 adjusted for trade.

Emissions have fallen in many high-income countries thanks to the replacement of fossil fuels with low-carbon energy and the transition toward a more intangible economy. This indicates that with the support of robust political will and the adoption of technological innovations and sustainable practices, economic progress can be achieved without a proportional increase in CO_2 emissions (Ritchie, 2021). A key question is whether we can decouple fast enough, and across more countries.

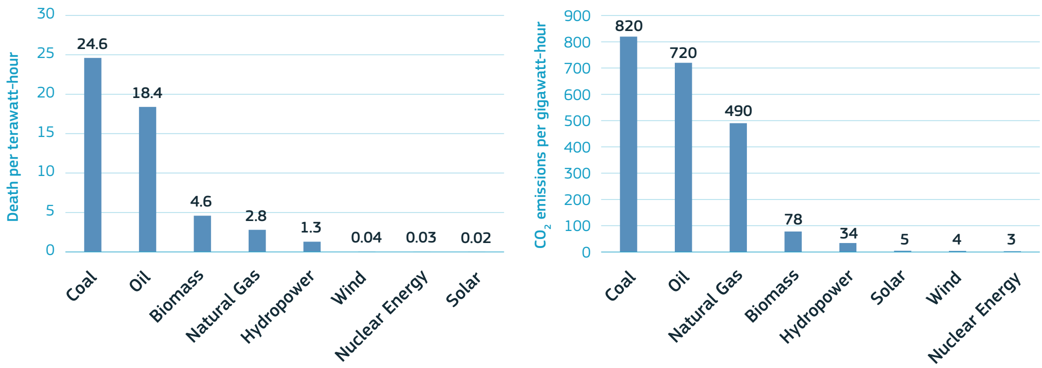
R&I plays a crucial role in accelerating economic growth decoupling from resource use by fostering the current decline in the cost of low-carbon technologies, as well as their deployment across the world. Indeed, while the costs of fossil fuels and nuclear power depend on the price of the fuel burnt and the power plant's operating costs, the cost of renewable power is defined mostly by the cost of the technology itself, as operating expenses are comparatively low, and there are no fuel costs.

A beneficial feedback loop drives the affordability of renewable technologies. As deployment expands, technological learning reduces costs, making these technologies economically viable for a broader range of applications. This expansion in applicability spurs further demand, propelling a cycle of increased deployment and continuous price declines. This self-reinforcing mechanism mirrors the learning curves observed in technological advancements like Moore's Law, a pattern not exhibited by fossil fuel technologies (Roser, 2020). Hence, renewable technologies not only benefit from, but also contribute to, an escalating cycle of affordability and accessibility.

Renewable energy sources and nuclear power stand as markedly safer and cleaner alternatives to fossil fuels (Kharecha and Hansen, 2013; Ritchie, 2020). Figure 5.1-5 underscores this by contrasting the estimated mortality rates attributable to various energy sources per electricity unit produced. When considering the consequences of air pollution and catastrophic events, it becomes clear that fossil fuels – particularly coal – are responsible for substantially more deaths per electricity unit than nuclear power and modern renewables. Figure 5.1-5 further highlights coal as the most polluting energy source per electricity unit produced, emitting vastly more greenhouse gases than its counterparts of nuclear, solar and wind energy. While oil and gas also surpass nuclear and renewables in terms of emissions, their impact is somewhat less severe than that of coal.

The vivid impact of nuclear accidents like Chernobyl and Fukushima starkly contrasts with the less visible, yet more deadly, effects of fossil fuel pollution. This discrepancy highlights a common behavioural bias called an 'availability heuristic', where the slow and steady impact of a hazard is often underestimated in comparison to more dramatic – but less statistically deadly – events. This bias can skew public perception, undervaluing the broader and more persistent threat posed by fossil fuel emissions relative to the rarer, albeit catastrophic, risks associated with nuclear energy.

Figure 5.1-5 Cleanliness and safety of different energy sources

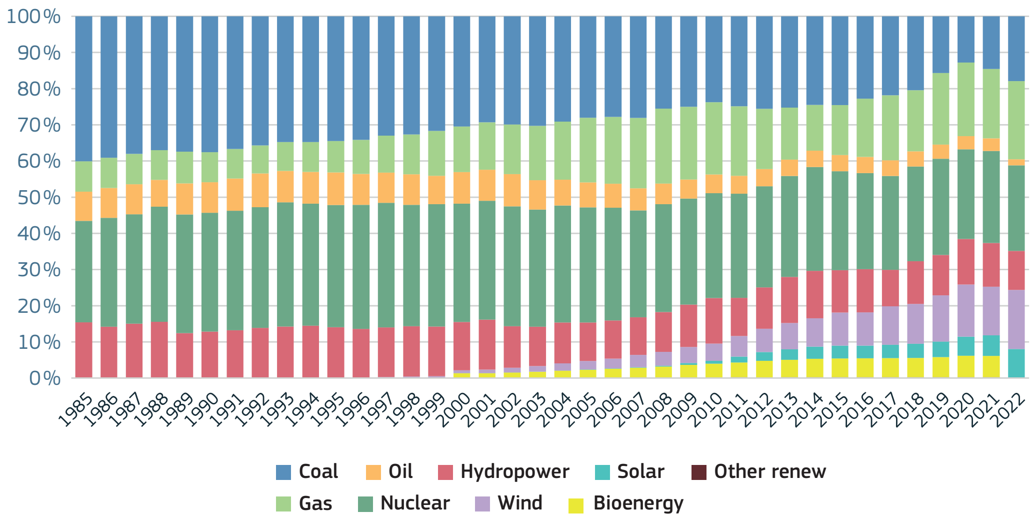


Science, research and innovation performance of the EU 2024

Source: Max Roser (2020), Hannah Ritchie (2020). Note: Deaths from accidents and air pollution per terawatt-hour of energy production. Greenhouse gases emitted per unit of electricity production include the burning of fuels, but also the mining, transportation and maintenance over a power plant's lifetime.

The prevalence of fossil fuels as the primary energy source has historically been underpinned by their lower costs compared to alternatives. Figure 5.1-6 shows the historical trends of electricity production by source in the EU. To shift the global energy paradigm towards safer and cleaner options, R&I must be leveraged to drive down the costs of these alternatives. This strategy has already borne fruit in numerous high-income countries where renewable energy sources are now more economically viable than fossil fuels, demonstrating the potential for a broader, cost-effective energy transformation.

Figure 5.1-6 Electricity produced by source in the EU



Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit's own elaboration, based on Ember's Yearly Electricity Data; Energy Institute Statistical Review of World Energy (2023).

Simultaneously, advancements in production efficiency, driven by ongoing R&I, significantly boost the output yield per unit of energy. This enhancement not only optimises energy utilisation, but also paves the way for increased production capabilities. As a result, a wider array of goods and advanced technologies can be developed and manufactured, either by maintaining the current level of energy consumption or, more impressively, by reducing it. This shift not only reflects a leap in efficiency, but also marks a critical step towards sustainable production practices. By integrating cutting-edge R&I, industries can contribute more effectively to environmental conservation efforts, while also meeting the growing demands of a rapidly advancing technological era.

3. AI and the productivity slowdown of advanced economies

Despite expectations that digital technology would boost productivity, growth has stagnated over recent decades. This paradox has sparked extensive research seeking answers. Robert Solow famously remarked in 1987, 'You can see the computer age everywhere but in the productivity statistics.' Figure 5.1-7 illustrates the deceleration in productivity growth within the Euro area and the United States from 1950 to 2019. It depicts three distinct measures of productivity: growth in GDP per capita, labour productivity and Total Factor Productivity (TFP). Each of these metrics shows a trend of decline followed by a period of stabilisation, which is particularly intriguing given the rapid advancements in technology and heightened investment in R&D during this period.

Likely explanations are low technological diffusion, high human capital and organisational uptake costs for laggard firms and declining business dynamism. Indeed, while digital technologies boost individual productivity at the firm level (Hubbard, 2003; Bartel et al., 2007), this doesn't always translate to larger scale economic growth, often due to dynamic market and organisational factors. In fact, implementing ICT effectively is challenging, requiring complementary investments in human capital and managerial practices (Pilat, 2005). The digital transformation turns out to be particularly difficult for non-frontier firms, with non-trivial adjustment costs, organisational changes and new skills required, potentially leading to negative returns during the process of adjustment and experimentation (Brynjolfsson et al., 2019). Declining business dynamism, including the increase of 'zombie firms' and resource misallocation, also contributes to the productivity slowdown (McGowan and Millot, 2017). Moreover, a decrease in productivity growth through capital-embodied technical change, with variations seen in how US and EU firms convert R&D into productivity improvements, can be added to the list of culprits (Schubert and Neuhäusler, 2018). Further explanations include measurement difficulties in a service-based, intangible-heavy economy, and the long lag time for new technologies to diffuse and impact productivity (McGrattan, 2020).

This trend prompts the pertinent inquiry into whether the unfolding revolution of generative AI can overcome the enduring Solow Paradox. The resolution of this question remains to be seen. There are, however, many reasons to think that AI will bring a different digital revolution. Indeed, the AI revolution has broken the limitations of earlier digital technologies, significantly broadening their scope. It has transcended the boundaries of merely codifiable tasks – those routine operations that could be condensed into exact instructions – thereby demonstrating the potential to handle more complex and nuanced activities (Manyika and Spence, 2023).

Prior to the recent advancements in AI, digital machines were incapable of executing tasks that were not easily codifiable, such as recognising a cat in a picture. Before the advent of AI, the digital revolution had a profound impact in its sphere: automation quickly permeated various sectors, with machines replacing human tasks in areas such as bookkeeping, filing, accounting, banking and the management of supply chains. This shift marked a significant transformation in how these functions were traditionally executed. Concurrently, the shift to digital information storage and transfer made data more accessible and affordable. This, coupled with a surge in

Figure 5.1-7 Productivity growth slowdown, 1950-2022

Science, research and innovation performance of the EU 2024

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.

inexpensive online services, reshaped consumer behaviour and social interaction. However, the economic effects of these changes were not universal. Numerous tasks remained beyond the reach of automation, thus limiting the digital revolution's full impact. Notably, sectors centred on knowledge and creativity, including fields like medicine, law, advertising and consulting, were largely unaffected. In these industries, the inherent value lies in specific expertise and the execution of nonroutine tasks, which technology could not replicate (Manyika and Spence, 2023).

Large Language Models (LLMs) powered by deep learning, such as the famous OpenAI ChatGPT, are now capable of engaging in non-codifiable tasks. These include finding and assembling facts and insights, detecting logical and conceptual structures embedded in language, synthesising and reprocessing information, and drawing on experience, expertise and tacit knowledge to provide answers to complex and nuanced questions (Ghosh, 2023).

While the digital revolution automated routine tasks, the AI era demands a more nuanced and collaborative approach to workforce development and education. The digital revolution, marked by the automation of routine tasks, led to a significant shift in the labour market. In particular, it sparked a decline in jobs and income for some low and middle-class earners, a trend referred to as 'job and income polarisation' (Acemoglu and Autor, 2011). This shift necessitated a change in educational focus towards critical thinking and creativity (Deming, 2017; Deming and Kahn, 2017). With the advent of modern AI, the landscape is changing further. Adapting to an AI-assisted work environment requires new skill sets, prompting the need for partnerships between government, industry and educational institutions (Bouschery et al., 2023). Policies aimed at ensuring AI augments rather than replaces human labour are crucial. Additionally, AI research should prioritise enhancing human productivity rather than simply substituting it (OECD, 2023) (see Chapter 5.2 for more).

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CHAPTER 5.2

SKILLS AND HUMAN CAPITAL FOR R&I

Key questions

- Is digitalisation driving labour market polarisation around the world?
- What are the demanded and supplied skills in the EU?
- How is gender distributed across different occupations and economic activities?
- What are the most important skills that will drive future breakthrough technologies?

Highlights

- Technological advancements such as automation and computerisation, bundled with international trades, are spurring job polarisation by boosting demand for high-skilled labour and reducing routine, medium-skilled roles.
- Employment in the EU is predominantly concentrated within the manufacturing sector, in contrast to the US, where there is a greater focus on human health services. Additionally, the information technology (IT) and financial sectors in the US are significantly larger compared to those in the EU.
- In 2022, EU female graduates still predominantly pursue fields such as education, arts and humanities, social sciences, and health and welfare, whereas their male counterparts are more concentrated in Information and Communication Technologies (ICT), engineering, manufacturing and construction.
- From 2010 to 2022, there has been a significant increase in the proportion of employment in high-technology sectors across Europe. Female employees continue to represent a minority.
- Skills in physics, engineering and technology, computer electronics, mathematics and critical thinking are the most poised to propel the advancement of groundbreaking technologies in the future, catalysing economic growth.
- AI skills are highly valued in the job market, offering a substantial wage premium due to their versatility across multiple knowledge domains. These skills necessitate a blend of technical expertise in fields such as statistics, computer science and software engineering, as well as crucial soft skills including leadership and communication.

Policy insights

- The promotion of STEM skills development, coupled with communication and leadership skills, will likely give a competitive advantage over other nations and spur economic growth.
- Women are underrepresented in crucial areas like ICT, engineering and high-tech industries, limiting workforce diversity and size.
- Reskilling and upskilling – inclusive of underrepresented groups – is important to avoid the digital transformation further exacerbating inequalities and wage gaps.

In this chapter, we explore the evolving job market, shaped by technological advancements and global trade, highlighting a shift towards high-skilled labour and a decline in routine jobs. We examine differences in employment sectors between the EU and the US, and then deep dive in the EU graduates and employment statistics by field and economic activity, differentiating by gender. Gender disparities in education and employment persist, with women and men choosing traditionally gendered fields. Despite a rise in high-tech sector employment in Europe, women remain underrepresented.

We spotlight essential future-ready skills, including those in AI, which are increasingly valuable across multiple sectors. The chapter concludes with policy insights advocating for STEM and soft skill development to drive economic growth and addressing the gender gap in critical tech-driven fields. The emphasis is on reskilling and upskilling to prevent widening inequalities and wage gaps in the face of digital transformation.

1. Job polarisation in developed countries

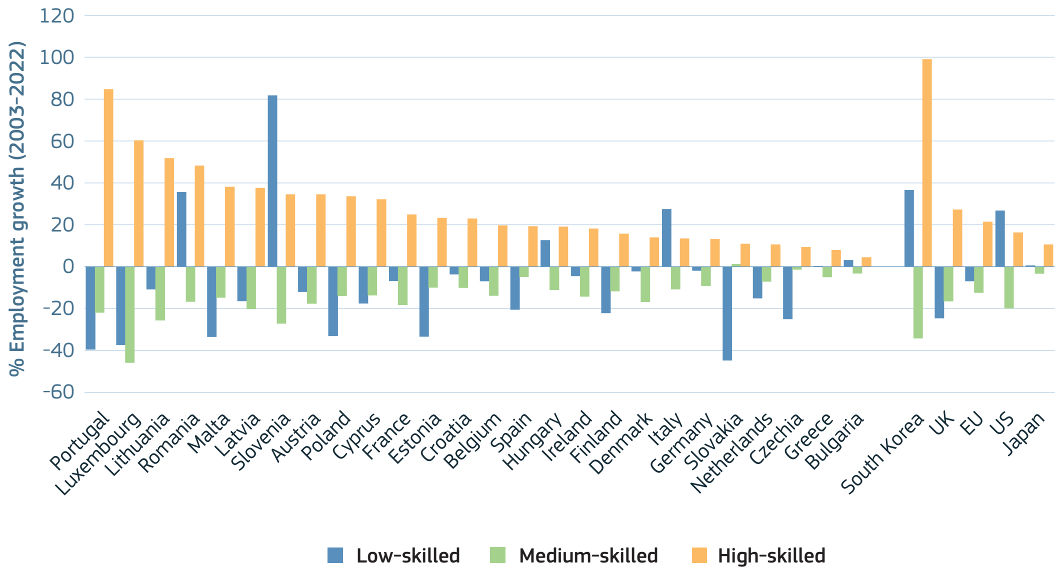
Digital transformation spurs job polarisation by boosting demand for high-skilled labour and reducing routine, medium-skilled roles, splitting the job market. Figure 5.2-1 showcases this trend across most developed countries. From 2003 to 2020, the share of high-skilled workers in the EU grew by 21%, while medium-skilled declined by 12%, and low-skilled by 7%. In the US the phenomenon appears more radical, with an increase of 16% in high-skilled workers, a decline of 20% in medium-skilled, and a rise of 27% in low-skilled.

The EU's share of high-skilled jobs has experienced steady growth in most years from 2003 to 2022. The annual growth rate for low-skilled jobs has worsened, while the medium-skilled growth rate is negative and steady. Interestingly, high-skilled jobs is the only category that continued to grow during the COVID-19 pandemic, showcasing superior resilience (Figure 5.2-2).

This shift is primarily fuelled by advancements in technologies such as automation and computerisation, which substitute for less-skilled workers and complement more highly-skilled ones. The deepening of digital technologies integration in the economy, which tends to require complex problem-solving and advanced cognitive abilities that high-skilled professionals possess, streamlines workflows and optimises processes, automating many repetitive tasks that have traditionally been the domain of medium-skilled workers. The result is a skill-biased alteration in labour demand, driving a wedge between the wage and employment prospects of high- and low-skilled workers (Acemoglu and Autor, 2011; Acemoglu and Restrepo, 2019).

International trade intensifies this polarisation, with developed economies tending to import products made with unskilled labour and export those requiring skilled labour. This global exchange pattern exacerbates the domestic shift towards high-skilled labour demand, potentially inflating the wage premium for skilled workers and contributing to a global redistribution of jobs (Mankiw, 2013).

Figure 5.2-1 **World structural change trends in skills**



Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit's own elaboration based on ILO LFS data.

Note: Employment growth represents the growth from 2003 to 2022 in the employment share of total employment of low/medium/high-skilled workers. This approach allows for fluctuations in total employment levels.

Figure 5.2-2 **EU trend in job polarisation**

Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit's own elaboration, based on ILO LFS data.

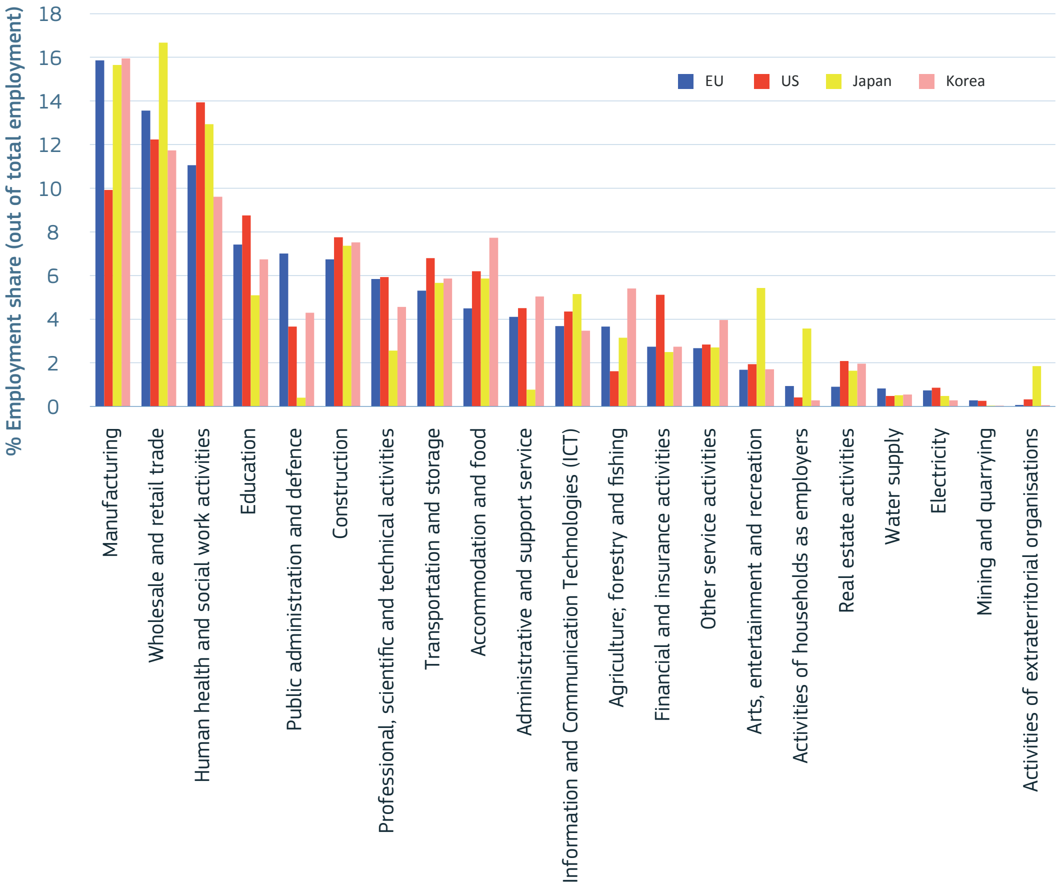
Note: Employment growth represents the growth from one year to the next

The concept of human capital further elucidates disparities in labour outcomes. Indeed, workers who accrue more human capital generally command higher wages, but when the supply of such workers lags behind demand, wage inequality can surge, reflecting an imbalance in the labour market.

This shift in the labour landscape elevates the value of and the need for workers with advanced technical training, analytical skills and the ability to innovate. The resultant structural change trends in skills requirements pose significant challenges to societal equity and economic stability, calling for strategic interventions that can facilitate workforce transitions through upskilling and education.

In 2022, the EU and the US displayed significant structural differences in the distribution of employment across the different economic activities. The EU's highest share of employment resided in the manufacturing sector, while in the US, it is in human health and social work activities. Furthermore, the EU's employment share in ICT is 15% smaller than that of the US, with financial and insurance activities being 47% smaller (Figure 5.2-3).

Figure 5.2-3 Labour market structural differences between EU and international competitors (2022)



Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit's own elaboration based on ILO LFS data.

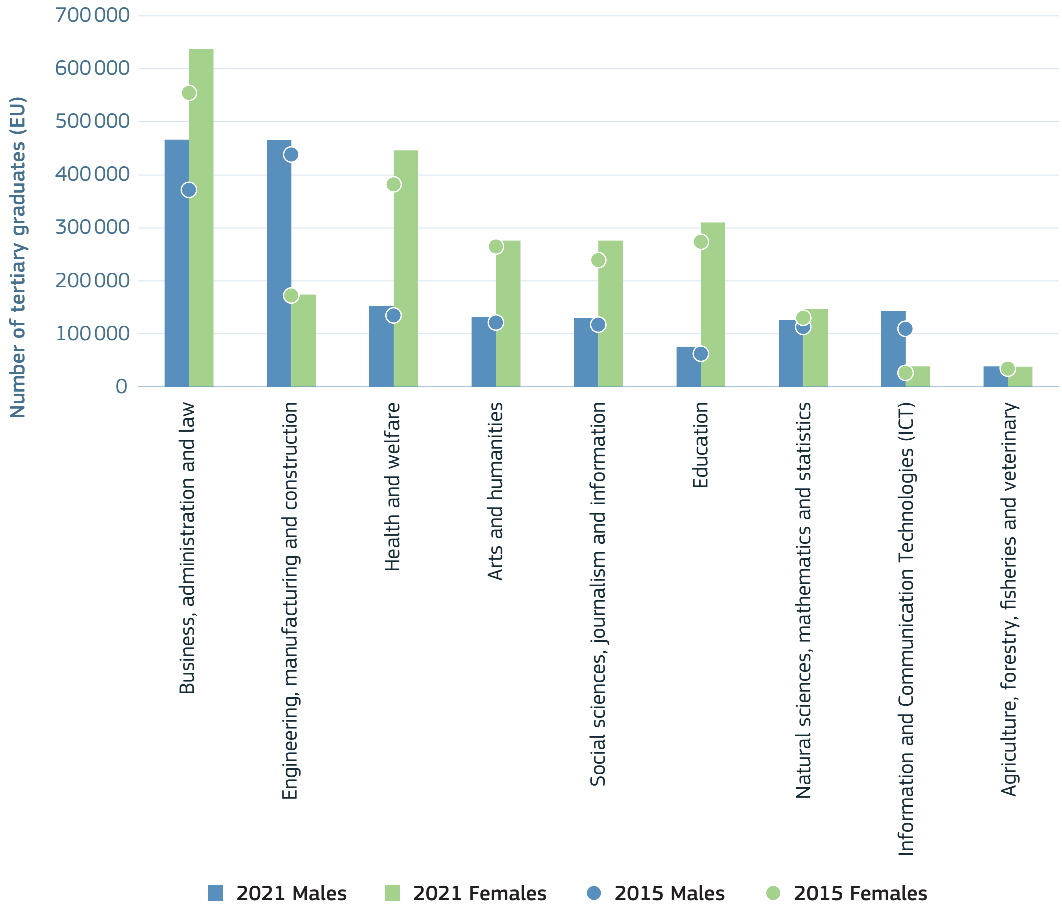
Note: Data on Japan refers to 2020. Economic sectors ranked by EU shares in decreasing order.

2. Skills allocation across the EU

Tertiary graduates represent an important skills supply measure. In the EU, business, administration and law hold the highest share of graduates, with engineering, manufacturing and construction ranking second, and health and welfare placing third. ICT experienced the highest growth in graduates from 2015 to 2021 (Figure 5.2-4).

Female graduates are concentrated in the fields of education, art and humanities, social sciences and health and welfare, while their male counterparts are predominant in ICT and engineering, manufacturing and construction. Notably, male graduates of ICT were around four times that of female graduates in 2022, and almost three times in the fields of engineering, manufacturing and construction. Such a gap is not closing, with the increase in male graduates from these fields higher than that of females. Conversely, female graduates are double that of male graduates in art and humanities and social sciences, four times in education, and three times in health and welfare (Figure 5.2-4).

Figure 5.2-4 Graduates by sex and field of education (EU)



Science, research and innovation performance of the EU 2024

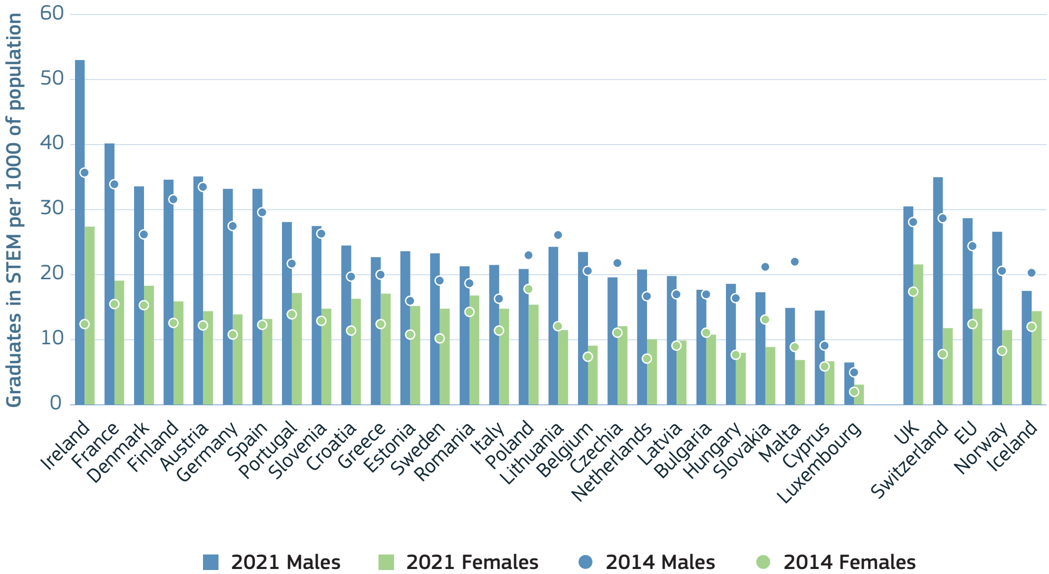
Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit's, based on Eurostat (Online data code: educ_uoe_grad04).

Note: Field of education ranked in 2021, decreasing total order (males + females).

Across Europe, the number of tertiary graduates in science, mathematics, computing, engineering, manufacturing and construction is increasing for both males and females. Yet, the gap is still substantial – in many countries, sometimes even increasing. The EU Member States with the highest overall graduates per capita in the aforementioned fields are Ireland, France, Denmark, Finland, Austria and Germany (Figure 5.2-5).

The rising demand for STEM skills in our tech-driven economy highlights the urgency for policies that encourage and support women to pursue STEM education. Initiatives such as scholarships, mentorship programs and campaigns that dismantle stereotypes are crucial not only to bridge the gender gap in these vital areas, but also to ensure a diverse and competent STEM workforce capable of driving innovation and addressing future challenges.

Figure 5.2-5 **Graduates in science, mathematics, computing, engineering, manufacturing and construction, by sex**



Science, research and innovation performance of the EU 2024

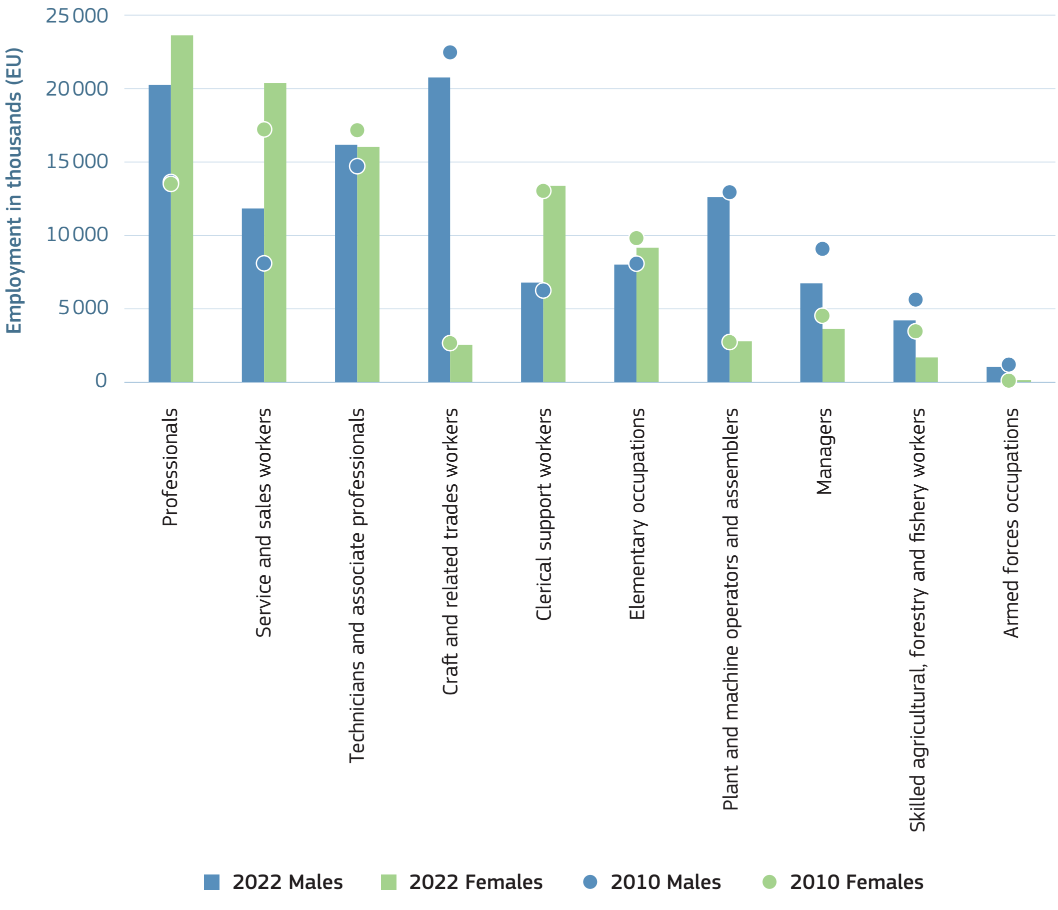
Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit's, based on Eurostat (Online data code: educ_uoe_grad04).

Note: For 2021, the UK data refers to 2019, the France data refers to 2015, and the Netherlands data refers to 2017. Countries ranked in 2021 decreasing total order (males + females).

Employment represents a relevant skills demand measure. In the EU, the occupational class of professionals holds the highest share of employment, followed by service and sales workers, and technicians and associate professionals. Regardless of the sex of workers, both professionals and service and sales workers enjoyed the largest growth from 2010 to 2022 (Figure 5.2-6).

Female employment is concentrated in the occupational classes of professionals, clerical support workers and service and sales workers, while its male counterparts are predominant in that of managers; skilled agricultural, forestry and fishery workers; plant and machine operators and assemblers; and armed forces occupations. Across 2022 in particular, male employment in the occupational class of managers was almost double that of females, eight times in that of craft and related trades workers, and four times in that of plant and machine operators and assemblers (Figure 5.2-6).

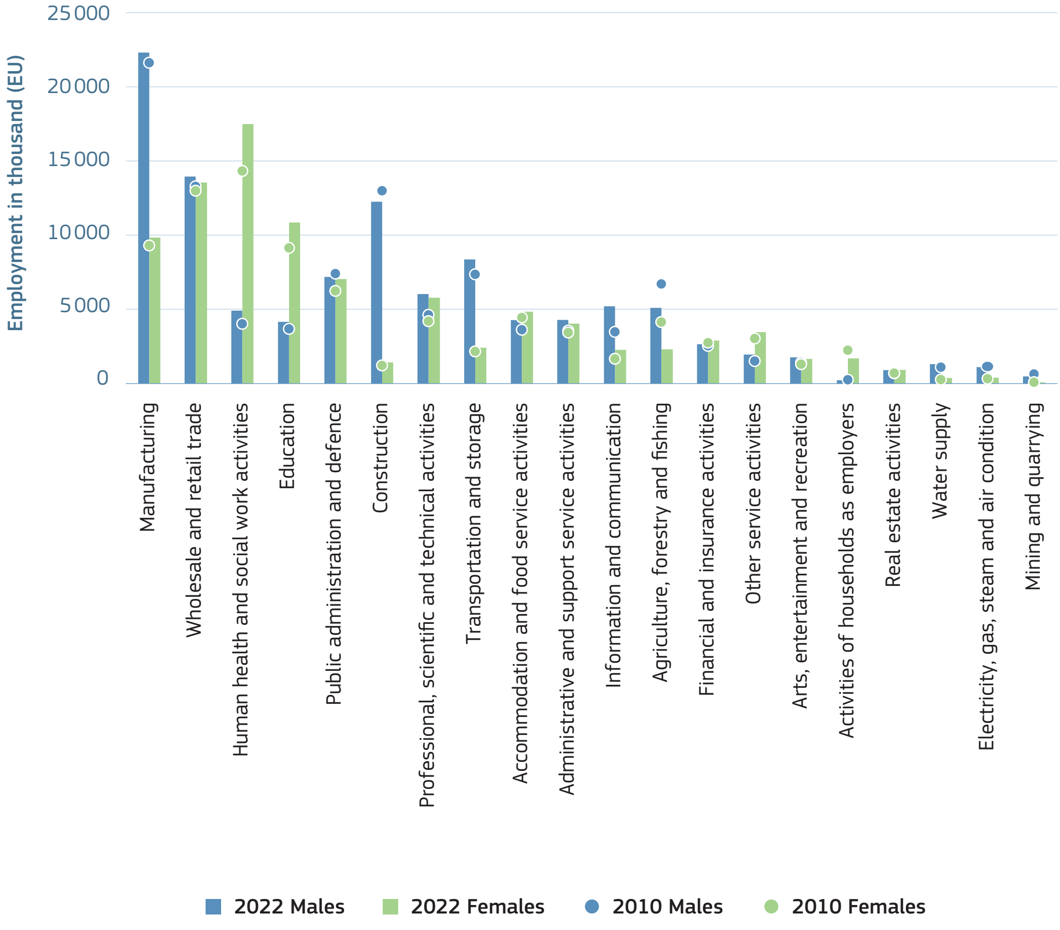
Figure 5.2-6 Employment by sex and occupation class (EU)



Science, research and innovation performance of the EU 2024
Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit's based on Eurostat (Online data code: lfsa_eisn2).
Note: Occupation classes are defined using ISCO08 codes. Occupational classes ranked in 2022 decreasing total order (males + females).

Manufacturing represents the largest economic activity in the EU, employing the largest share of the EU workforce in 2022. The economic sectors of ICT; professional, scientific and technical activities; and human health and social work activities observed the largest employment increments from 2010 to 2022. Similarly to previously highlighted statistics, men are heavily predominant in economic activities such as agriculture, forestry and fishing; mining and quarrying; manufacturing; electricity, gas, steam and air conditioning; water supply; construction; transportation and storage; and ICT, while females represent a strong majority in education and human health and social work activities (Figure 5.2-7).

Figure 5.2-7 **Employment by sex and economic activity (EU)**



Science, research and innovation performance of the EU 2024

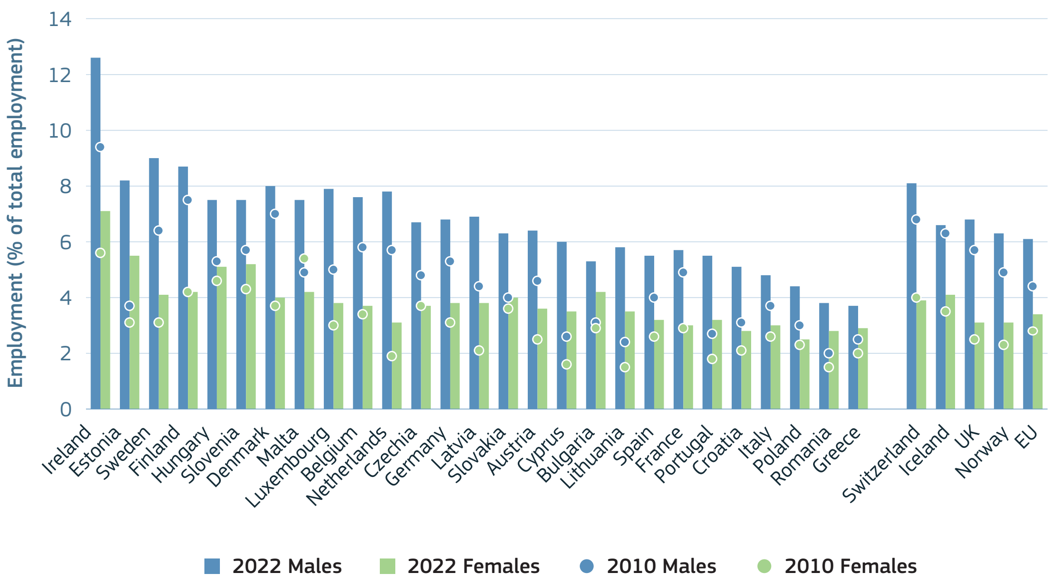
Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit's, based on Eurostat (Online data code: lfsa_eisn2).

Note: Economic activities are defined using NACE codes. Economic activities ranked in 2022 decreasing total order (males + females).

Across Europe, the share of employment in high-technology sectors out of total employment rapidly rose from 2010 to 2022. Ireland, followed by Finland and Sweden, showcase the highest rate of overall employment in high-technology sectors. Notably, female participation in high-technology sectors increased from 2010 to 2022, despite still representing a minority (Figure 5.2-8).

In our modern economy, the increasing demand for workers in the technology and knowledge-intensive sectors also underscores the critical need for policies to incentivise and facilitate women's participation in technology-intensive industries. Such policies are vital for harnessing the full potential of the workforce in these rapidly growing and evolving sectors.

Figure 5.2-8 Employment in technology and knowledge-intensive sectors by sex



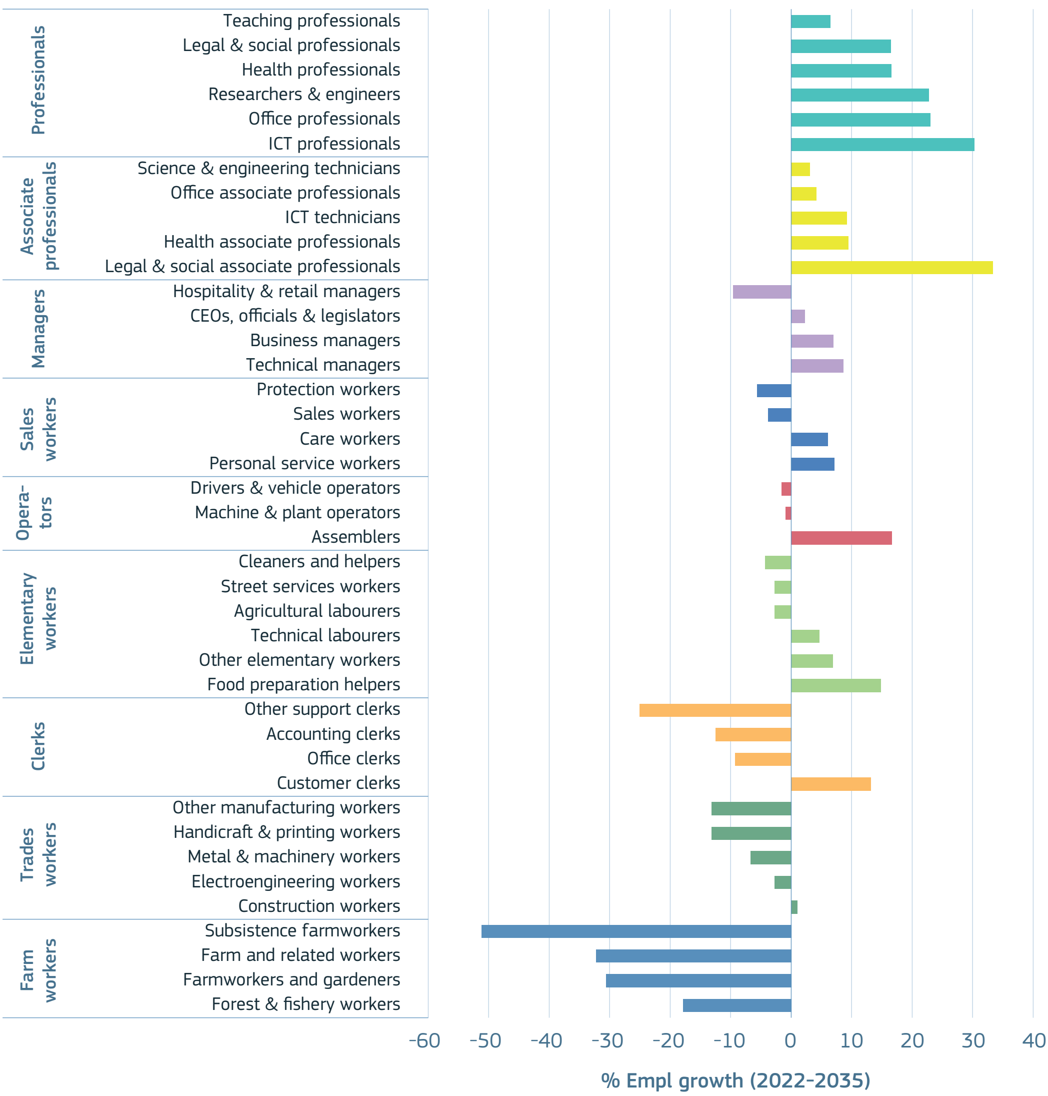
Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit's, based on Eurostat (Online data code: htec_emp_nat2).

Note: Countries ranked in 2022 decreasing total order (males + females).

Looking toward the future, employment in technology and knowledge-intensive sectors is likely to continue its rise. The European Centre for the Development of Vocational Training (Cedefop) estimates a remarkable increase in the EU's future employment growth across 2022 to 2035 for professionals, ICT experts, researchers, engineers and so on. Conversely, employment in sectors such as agriculture, fishing and mining is expected to decline. (Figure 5.2-9).

Figure 5.2-9 **Future employment growth (%) by occupations in EU in 2022-2035**



Source: Cedefop future jobs database.
Note: Due to the unpredictable nature of the labour market and associated external factors, estimations are to be taken with caution.

3. STEM and social skills for technological breakthroughs

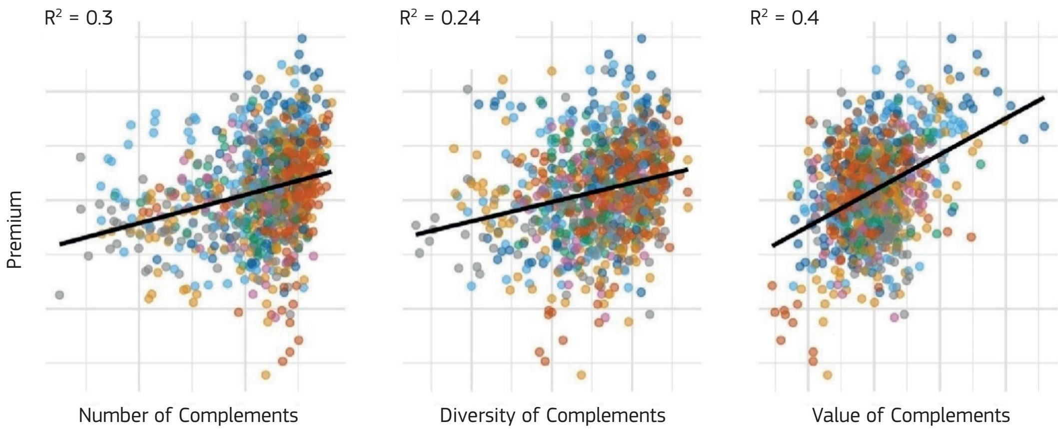
The analysis of modern breakthrough technologies and labour market challenges starts with understanding the complexity of production and its implications for economic growth. Indeed, highly sophisticated goods, which require diverse and exclusive production capabilities, are central to an economy's advanced development. This complexity is linked to the diversity[1] and ubiquity[2] of the labour skills and knowledge involved in producing these goods (Hidalgo and Hausmann, 2009).

Physics, engineering and technology, computer electronics, mathematics and critical thinking skills appear to be more complex[3] and are the core resources behind the production of sophisticated goods. Regions with higher occupational complexity also experience greater economic growth. This points to the strategic importance of fostering these skills for long-term economic competitiveness (Turco and Maggioni, 2022).

Complementarity is another fundamental aspect in assessing a skill's worth, defined as the ability of a skill to enhance and synergise with other skills. Firstly, a skill that can be combined with a wide range of other skills tends to be more valuable. Secondly, the diversity of the 'neighbourhood' of skills that can be paired with a particular skill adds to its value. And thirdly, if a skill complements other high-value skills, its individual worth is enhanced. Beyond complementarity, the demand relative to the supply of skills in the workforce also plays a significant role in determining their value. Skills that are in high demand but have a relatively low supply naturally command a higher value. Figure 5.2-10 showcases the positive relationship between skills premium and the complementarity associated with such skills (Stephany and Teutloff, 2024).

1 Defined here as relating to the variety of necessary skills and knowledge.
2 Defined here as concerning the rarity of such skills and knowledge.
3 See Box 1 of chapter 2.2 for a formal definition of 'complexity'.

Figure 5.2-10 Skills premium and complementarity



Science, research and innovation performance of the EU 2024

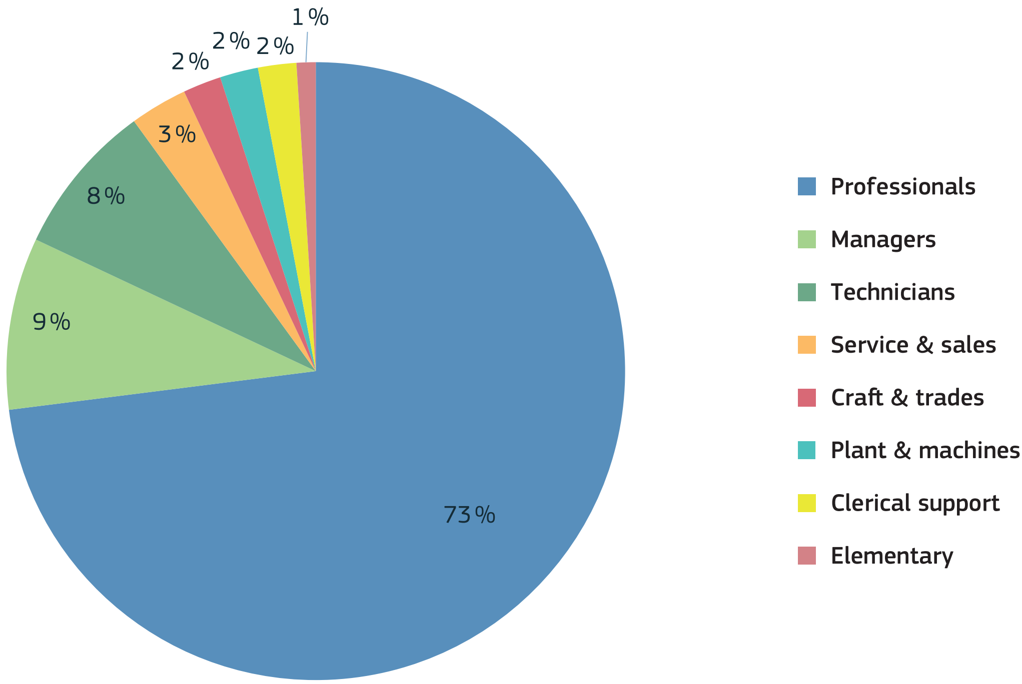
Source: Stephany and Teutloff (2024).
Note: Different colours represent different sectors in the economy. Time period of reference: 2014–2022. Estimates computed using US labour market data.

AI skills enjoy a significant wage premium. This higher value can be attributed in part to their complementarity; AI skills can be effectively combined with a diverse set of capabilities across various knowledge domains, making them highly adaptable and valuable in multiple contexts. Additionally, skills complementary to AI are often of high economic value in and of themselves. Finally, the sustained high demand for AI skills, coupled with a comparatively lower supply, further boosts their market value. (Stephany and Teutloff, 2024)

AI skills are in demand across all occupational classes, with the largest majority being requested from that of professionals. Indeed, from 2019 to 2022, around 73% of online vacancies in the EU requiring AI skills were aimed at professionals (Figure 5.2-11). This highlights how the impact of AI in the labour market is likely to be different compared to that of robotisation and early digitalisation technologies. Prior to the recent advancements in AI, digital machines were incapable of executing tasks that were not easily codifiable, limiting their profound impact to routine medium-skilled jobs such as book-keeping, filing, accounting, banking and the management of supply chains (Manyika and Spence, 2023). However, recent advancements in machine learning, deep learning and natural language processing are changing this, with AI technologies increasingly complementing and augmenting the capacities of highly skilled workers (Felten and Seamans, 2019; Bachmann et al., 2022).

AI jobs require not only a high mastery of technical skills such as statistics, computer science, data analysis and software engineering, but also soft skills such as leadership and communication. Job listings calling for AI professionals indicate not only an expectation for high-level technical skills, but also the possession of competitive prowess in more social and qualitative skills (Borgonovi et al., 2023). This will likely put highly skilled individuals who only possess social and qualitative skills at a comparative disadvantage to those also possessing quantitative ones.

Figure 5.2-11 Online job vacancies requiring AI skills in selected European countries, by occupation (2019-22)



Science, research and innovation performance of the EU 2024

Source: Borgonovi et al. (2023).
Note: 'European countries' refers to Austria, Belgium, France, Germany, Italy, the Netherlands, Spain, Sweden and Switzerland.

Box 5.2: Labour shortages in high-skilled occupations in the EU

By Gralek Karolina and Caisl Jakub, DG EMPL F.4

The *Employment and Social Developments in Europe 2023 Review*[4] analyses labour shortages that have persisted over time. By combining different available approaches, it identifies 14 occupations (at ISCO 3-digit level) and 16 sectors (at NACE 2-digit level) facing persistent labour shortages in the EU. In particular, the report underlines that next to cyclical fluctuations, labour shortages strongly depend on structural drivers, such as skills shortages and mismatches, declining or inactive labour force, labour market segregation, labour mobility and migration, and working conditions. It also discusses relevant policies to address persistent labour shortages, as the impact of various drivers varies significantly across occupations and sectors.

Labour shortages could hinder the EU in reaping the full spectrum of benefits from technological advancements. For example, the economic activity and innovative capacity of companies may be limited, potentially weakening the competitiveness of the EU in the medium and long term. While persistent labour shortages are found across all skill levels, this box presents the main findings from the report focusing on high-skilled shortage occupations[5], given that the digital transformation is expected to especially boost the demand for high-skilled labour. Among the high-skilled occupations in particular, medical doctors, nursing and midwifery professionals, and software and applications developers and analysts are found to face persistent labour shortages over time.

Skills shortages and mismatches are driving persistent labour shortages in high-skilled occupations. For instance, even when controlling for different characteristics of occupations, high-skilled occupations with persistent labour shortages are more likely to have higher upskilling and digital skill needs, compared to high-skilled non-shortage occupations. They also face a higher demand for better-educated workers and greater job complexity. While the digital intensity of work is relatively low for most of the occupations with persistent labour shortages, this is not the case for software and applications developers and analysts, with around one-third of all required skills being digital.

4 https://op.europa.eu/webpub/empl/esde-2023/index.html

5 For the purpose of Box 1, high-skilled occupations include occupations that fall under categories 1) Managers, 2) Professionals and 3) Technicians and associate professionals (at ISCO 1-digit level).

High-skilled occupations with persistent labour shortages are characterised by high degree of gender segregation. This is especially the case for nursing and midwifery professionals (90% of women in 2021) and software and applications developers and analysts (82% of men). Medical doctors represent a rather gender balanced occupational group (54% of women), but available evidence indicates that there may be strong gender segregation by certain medical specialisations. Differences in study fields of qualifications are found to explain sizeable shares of gender gaps in those occupations. In addition, even when holding an ICT-related qualification, women are less likely than men to work in an ICT occupation, pointing to other relevant factors such as gender stereotypes or the gender divide in advanced digital skills, thereby contributing to persistent gender segregation.

Poor working conditions in some occupations and a low share of migrant workers also contribute to persistent labour shortages in high-skilled occupations. The 'job strain' indicator calculated using Eurofound's *European Working Conditions Telephone Survey 2021* refers to difficult work environments, organisation and time. While software and applications developers and analysts enjoy the lowest job strain (7.8%) across all shortage occupations, nursing and midwifery professionals report the highest job strain (60.5%). The job strain for medical doctors (42.8%) is also above the EU average (30.3%). As concerns migrants born outside the EU, they tend to be concentrated in lower skilled occupations, with only 4% working in high-skilled shortage occupations. This points to a limited contribution of migrants in alleviating persistent labour shortages in those occupations.

Looking forward, high-skilled occupations are projected to face high labour shortages by 2035. Future shortages are projected based on the Cedefop's 'future shortage indicator', which is constructed using information on labour market imbalances, expansion demand and replacement demand drawn from the Cedefop's Skills Forecast. According to this indicator, future shortages in high-skilled occupations will be strongly driven by expansion and replacement needs. Next to high-skilled occupations already experiencing persistent labour shortages, additional high-skilled occupations are projected to face high labour shortages in the future. Namely, these include chief executives, senior officials and legislators; production and specialised services managers; legal, social and cultural professionals; business and administration associate professionals; and legal, social, cultural and related associate professionals. While many of those occupations are expected to be highly exposed to AI, its impact on labour shortages remains unclear.

A comprehensive set of policies is needed to alleviate persistent and future labour shortages in high-skilled occupations in the EU. These include promoting skills anticipation and upskilling/reskilling; investing in adult learning; improving the matching between job requirements and candidate competences; increasing financial incentives to work (e.g. by reviewing tax-benefit systems); removing barriers to people entering the labour market (e.g. by expanding childcare access to help mothers to engage in paid work, or easing the recognition of migrant qualifications); improving work and pay conditions and social protection coverage; reducing stereotypes and discrimination; implementing policies to attract workers from abroad into jobs facing shortages; and strengthening social dialogue. In line with these findings and as a follow-up to the Val Duchesse Social Partners Summit of January 2024, in March 2024, the Commission has come forward with an action plan to tackle labour and skills shortages in the EU.[6] Addressing labour shortages could also contribute to reaching the EU headline 2030 targets set in the *European Pillar of Social Rights Action Plan*, and to prepare the EU economy for the advent of new technologies.

6 https://ec.europa.eu/commission/presscorner/detail/en/ip_24_1507

4. High-technology sector and AI: opportunities for competitiveness and challenges for inequality

The EU labour market is currently at a crossroads, marked by rapid technological advancements and changing social dynamics. Two of the most pressing issues in this landscape are the polarisation of the labour market and persistent gender disparities, especially in STEM fields. These challenges are further complicated by the rise of the high-technology sector and AI, which, while driving innovation and economic growth, also pose the risk of exacerbating wage inequality and gender gaps. Yet, if the first digital revolution was marked by the automation of routine tasks, sparking a decline in jobs and income for some routine middle-class earners, the advent of modern AI (also capable of automating non-routine, high-skill tasks) may change the landscape further (see Chapter 5.1 'R&I and productivity' for more).

While the rise of the high-technology sector and AI offers numerous benefits, it also carries the risk of fostering wage inequality. High-skilled workers with expertise in these areas command premium wages, further widening the economic divide within the workforce. This burgeoning inequality poses a risk of social instability, as large segments of the population may find themselves economically marginalised. For this reason, it is vital to create policies ensuring AI complements rather than replaces human labour, with a focus on enhancing human productivity.

Compounding this issue is the gender disparity prevalent in STEM fields. Women are significantly underrepresented in areas like ICT, engineering and high-tech industries – sectors that are crucial to the future economy and are witnessing rapid growth. This underrepresentation not only limits the diversity and potential of the workforce, but also means that women are less likely to benefit from the opportunities and higher wages offered by these booming sectors. As the demand for skills in these areas grows, the gender gap in STEM could lead to a broader wage gap between men and women. Age differences in the familiarity and ease of learning new digital skills may also contribute to the socio-economic divide, as compared to older workers, young people are more likely to benefit from the newly emerging technologies.

To counter these trends, there is an urgent need for reskilling and upskilling initiatives. The focus should be on equipping the workforce – including underrepresented groups such as women – with the technical skills required in high-tech and AI-driven industries. However, preserving and enhancing soft skills such as leadership, communication and creative problem-solving is equally important. These skills are crucial for driving innovation and ensuring that technological advancements are effectively integrated into the workplace.

From an economic perspective, addressing these challenges is vital for the EU's competitiveness on the global stage. A workforce that is diverse, technologically adept and equipped with a balance of technical and soft skills is better positioned to drive productivity growth and innovation. By fostering a labour market that is both fair and competitive, the EU can ensure sustainable economic growth and social stability.

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CHAPTER 5.3

BUSINESS DYNAMISM AND ACCESS TO FINANCE

Key questions

- What is the state of business dynamism in the EU, and how has it responded to recent crises?
- What are the latest trends in the EU's venture capital (VC) markets?
- What are the future challenges to financing innovation in the EU?

Highlights

- Business dynamism experienced a resurgence after the COVID-19 crisis, but investor appetite is falling with the latest economic outlook, posing new challenges for European tech companies.
- After the positive performance registered in 2021, VC activity in the EU is cooling down, with a more pronounced slowdown for late-stage investments.
- The financing gap with the US persists, especially in the scale-up phase. Nevertheless, the EU's VC market has shown resilience to short-term fluctuations, as well as considerable untapped potential.
- The European tech ecosystem has experienced an important increase in the scale of capital invested in clean and climate technologies, but has not fully unlocked its capacity to attract higher investments in strategic net-zero technologies.

Policy insights

- Establishing a conducive environment for companies to innovate remains at the core of the EU's strategy to enhance productivity, competitiveness and resilience. Efforts need to ensure that investments keep flowing to EU companies (particularly from EU-based investors) at the required scale to accelerate the roll-out of strategic technologies.

- Policies also need to account for the diverse nature of innovation activities, selecting the financial instruments that most suitably support different types of innovation.

- Making the EU more attractive to talent remains key, as new company formation in the European tech ecosystem is largely driven by more experienced individuals, with companies able to raise large rounds of funding typically run by experienced founders and/or managers with prior experience in successful tech firms.

- Addressing the still persistent gender gap in VC funding is important to guarantee social justice and boost economic impact.

An important interplay exists between finance, innovation and growth. Countries with better functioning financial intermediaries and markets tend to grow faster, thanks to the effective allocation of capital, higher quality of financial intermediation, capital flows and investment monitoring (Levine, 2005). Furthermore, finance is at the heart of any innovation-led economy, as firms need to collateralise their ideas to procure the funding necessary to finance their research and development (R&D) activities (Akcigit and Van Reenen, 2023).

Because of the forward-looking nature of innovation activities, recent crises and geopolitical turmoil are set to produce a significant impact on innovative firms and their financing opportunities. Recent geopolitical tensions and their economic effects have contributed to increasing inflation rates globally. In response, central banks have raised interest rates to temper demand and slow the inflationary pressure. The consequent increase in the cost of capital is likely to affect the path of future aggregate growth and innovation, creating new challenges for tech start-ups and VC markets.

1. Challenges for business dynamism in Europe

Recent shocks have produced heterogeneous effects on the European innovation ecosystem, hitting small firms the hardest. The COVID-19 crisis determined a significant drop in aggregate demand and increasing uncertainty, which put innovative companies under considerable pressure due to a severe lack of liquidity and disruptions along global supply chains (Criscuolo, 2021). Small businesses were those most negatively affected, relying on less diversified supply chains compared to larger companies. At a global level, about 30% of small and medium-sized enterprises (SMEs) appeared to have experienced negative profits during the first half of 2020 against the 17% of large firms, although heterogeneous effects have been observed across different countries (Brault, 2023).

Start-ups and young firms also appear to be more exposed to adverse business cycle conditions. The challenges these types of businesses typically face include a lack of easily accessible financing resources, and competition from incumbents, which can rely on pre-established customer bases. These aspects make start-ups and young companies more sensitive to economic disruptions, with significant repercussions on their survival ability and growth capacity.

Nevertheless, economic crises can also act as a driving force for innovation. Periods of significant distress can serve as a springboard for new businesses to refine their processes, pushing entrepreneurs to adapt to the changed economic environment by pursuing new opportunities and undertaking fresh innovation activities.

Overall, European businesses showed a good ability to adapt to the COVID-19 pandemic shock (aided considerably by substantial public economic support), although with significant heterogeneity across countries. The number of business establishments in the EU fell sharply in the first half of 2020 (European Commission, 2022a). However, the drop in business registrations was mostly short-lived, quickly followed by an increase in the number of entries in the years following the COVID-19 outbreak. The magnitude of the decline varied considerably across different countries. As an example, France, Hungary and the Netherlands reported a drop between 5% and 20%, but also experienced a rapid and sustained recovery characterised by high entry growth relative to pre-crisis levels.[1] On the contrary, countries like Sweden and Norway showed no decline, but nonetheless experienced a significant increase in the number of limited liability companies.[2] Yet, economies such as Italy, Portugal and Spain were hit harder, reporting a drop in business entries higher than 40% in the second quarter of 2020, and a slow and delayed recovery thereafter.[3]

The increase in business registrations also protracted into 2021 and the first quarters of 2022. As reported in Figure 5.3-1, the number of new business registrations in 2021 was significantly higher than the pre-crisis performance in several European countries. Norway and Sweden reported a 30% surge compared to 2019 levels, followed by France with 25%, Hungary with 20%, and the United Kingdom and the Netherlands with 12% each. Such a pattern has also been observed in the US, where the increase in new business applications with a higher likelihood of converting into employers was followed by an overall increase in job creation (Decker and Haltiwanger, 2023).

Although this boom represents an encouraging sign of a potential revival of business dynamism[4], uncertainty remains on whether this will hold in the long term.[5] After the surge experienced in 2021, business registrations have again begun to decline in several countries, sometimes reverting to the pre-crisis levels.[6] This suggests that the resurgence of business dynamism may be only transitory, and additional analyses are needed to clearly assess whether the observed positive pattern is merely the result of public support injections, as opposed to genuine company resilience.

1 Results from the Organisation for Economic Co-operation and Development (OECD) Project BRIDGE, based on the OECD Timely Indicators of Entrepreneurship by Enterprise Characteristics database, focusing on limited liability companies.

2 Focusing on limited availability companies has the potential to provide a better approximation of firms with growth potential. Entrepreneurs' motivation to start new ventures can be driven either by opportunity or necessity. While firms are created to capitalise on a business opportunity, necessity entrepreneurship is triggered by a lack of viable alternatives on the labour market, and is typically counter-cyclical. The activity of limited liability companies is more likely to be driven by opportunity considerations, thereby allowing them to better capture the creation of more growth-oriented businesses.

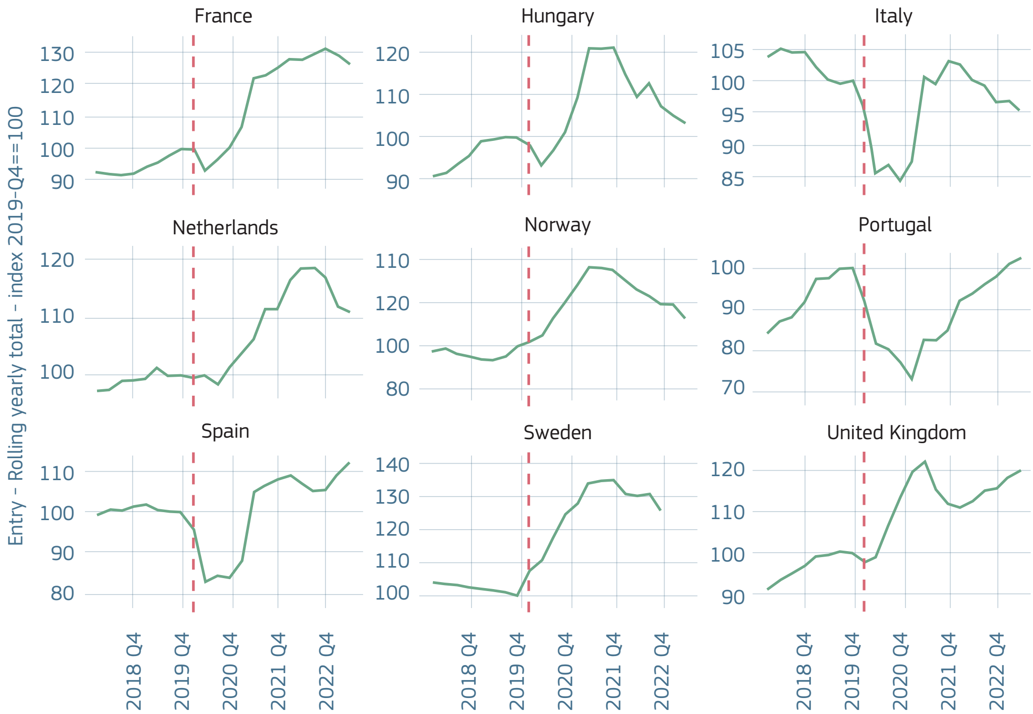
3 Results from the OECD Project BRIDGE, based on the OECD Timely Indicators of Entrepreneurship by Enterprise Characteristics database, focusing on limited liability companies.

4 In the context of this chapter, we focused exclusively on business registrations and bankruptcies as primary metric for assessing business dynamism. Nevertheless, other key indicators include, among others, job creation and destruction rates, and economic churn.

5 Financial Times. "How long can the entrepreneurship boom last?" October 6, 2023. Available at: https://www.ft.com/content/a9b68387-db34-4c69-85d8-1d28e9930adf.

6 Results from the OECD Project BRIDGE, based on the OECD Timely Indicators of Entrepreneurship by Enterprise Characteristics database, focusing on limited liability companies.

Figure 5.3-1 Change in rolling total number of registrations of limited liability companies, 2018 Q1-2023 Q2, selected countries



Science, research and innovation performance of the EU 2024

Source: OECD project BRIDGE based on the OECD Timely Indicators of Entrepreneurship by Enterprise Characteristics database.

Notes: The red line indicates the start of the COVID-19 pandemic. The figure plots for each country the evolution of a rolling yearly total number of registrations of limited liability companies, and is based on an index, normalised to 100 in 2019 Q4, of the total number of registrations in the last four quarters. Data generally refers to the total economy. Owing to methodological differences, figures may deviate from officially published national statistics.

Concerning the evolution of business bankruptcies, numbers remained low compared to 2019, mostly due to the massive support packages deployed in the aftermath of the crisis. The COVID-19 pandemic led to an unprecedented response from EU institutions, including the creation of the Next Generation EU Programme and the Recovery and Resilience Facility. The adoption of important support measures raised concerns over the risk of a "zombification" of the economy, contributing to the survival of unproductive companies and the slowdown of productivity-enhancing reallocation (European Commission, 2022a). Nevertheless, recent analyses suggest that while resource reallocation slowed down during the COVID-19 pandemic, its productivity-enhancing aspect continued (Calligaris et al., 2023). Furthermore, the latest evidence indicates that business bankruptcies are starting to revert to pre-pandemic levels as the support measures are lifted, although the increase observed in 2022 is likely to be due to the uncertainties linked to the difficult global conjuncture.

While innovative companies typically show good resilience to external disturbances, the ability of tech companies to thrive as others struggle seems to have reduced as a result of recent economic shocks. The change in the global economic outlook is putting tech companies under duress. Starting from the end of 2021, stock markets began to experience a decline (with digital firms being hit the hardest[7]), which was the first sign of various large-scale economic changes. These changes continued to negatively impact investor confidence and the distribution of capital, causing the decline to persist without clear signs of recovery (Atomico, 2022).

These changes are driven by several factors. On the one hand, digital markets are maturing and, converse to the past, are now also becoming vulnerable to economic cyclical shifts. Additionally, digital markets are also experiencing a shift in market dynamics, where tech firms are more frequently expanding into each other's business areas, thereby further increasing the degree of interconnection between differing segments.[8]

These structural changes are emerging amidst fast-changing geopolitical scenarios and increasing uncertainty, which are shifting investors' appetite. The unjustified Russian invasion of Ukraine, and the associated change in the macroeconomic environment and geopolitical situation, have represented a new turning point for the European entrepreneurial finance sector. Overall, the perceptions of the fundraising environment are worse than during the COVID-19 crisis (Kraemer-Eis et al., 2023). High interest rates and inflation rank highest among the main macro risks perceived by investors in the European tech ecosystem (Atomico, 2022), shifting the investor focus from rapid-growth companies to those that grow efficiently and generate strong cash flows.

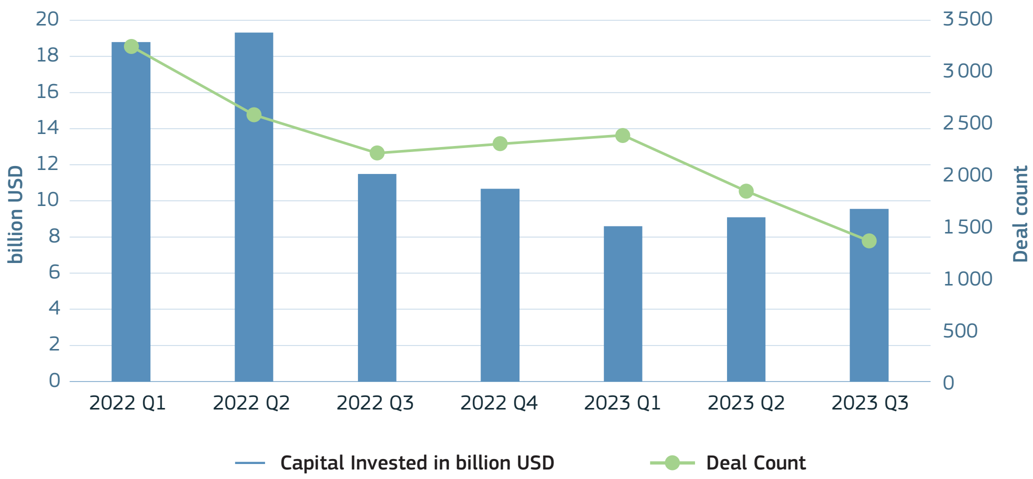
7 See https://www.economist.com/business/2022/12/24/how-techs-defiance-of-economic-gravity-came-to-an-abrupt-end.
8 Ibid.

2. The slowdown of VC investments and the strengths of the EU tech ecosystem

During the COVID-19 pandemic, VC investments in the EU underwent a cycle of rapid growth and subsequent decline. The global VC industry experienced unprecedented growth during the peak of the COVD-19 pandemic, with record deal counts and investment amounts across diverse sectors. The average size of VC investment in the EU grew across all funding stages.[9] However, 2022 marked a shift, as resources were reallocated to address post-pandemic challenges, leading to reduced market activity. The effects of government initiatives to foster technology commercialisation and workforce development are still emerging, and are expected to shape the industry's future trajectory (PitchBook, 2023a).

After the positive performance registered in 2021, VC activity in the EU is cooling down. The good performance reported in 2021 carried over into the first half of 2022. In 2022 Q2, investments amounted to USD 19.3 billion (Figure 5.3-2), in line with the performance registered at the end of 2021. Nevertheless, VC market activity in the EU started to cool off in the second part of the year, when VC investments dropped by about 40.5 % in Q3 compared to the previous period. At the end of 2022, VC investments were about 41.7% less than what was reported in 2021 Q4.[10]

Figure 5.3-2 VC[(1)] invested and deal counts in the EU, 2022 Q1–2023 Q3



Science, research and innovation performance of the EU 2024

Source: PitchBook data, as of 20th of November 2023.

Notes: (1) Investment values are calculated considering the headquarters country of the company involved in completed deals.

9 The OECD BRIDGE project, based on the OECD Start-Up Database, based in turn on Crunchbase and Dealroom.

10 DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit based on PitchBook data, November 2023.

The same pattern protracted into 2023. In 2023 Q1, VC capital invested kept decreasing, presumably as a result of the difficult economic outlook. Historically, low interest rates made VC an attractive investment option, but with rates increasing, investors are diversifying their portfolios, potentially moving away from VC activity (PitchBook, 2023a).

The value of VC deals towards the end of 2023 was lower than in 2022. In 2023 Q3, VC deal value in the EU amounted to USD 9.5 billion (Figure 5.3-2), about 17 % lower than what was reported in the same period of 2022. However, deal value in the EU has increased during the first three quarters of 2023, although this recovery is not sufficient to match the performance of the previous two years.

Nevertheless, the deal value registered in 2023 is in line with those pre-2020. This suggests that the VC activity has undergone structural growth over a longer time horizon (PitchBook, 2023b). The VC invested in the EU in 2019 was USD 27.8 billion, slightly less than the USD 31.7 billion reported in 2023.[11] This indicates that the EU's VC market has shown resilience to short-term fluctuations, and a strong underlying growth trend.

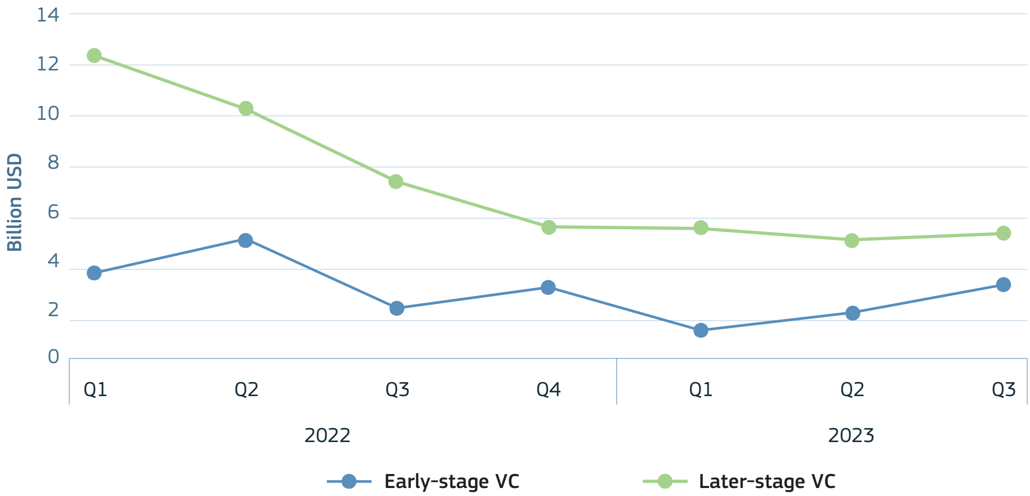
The slowdown in investment activity was more pronounced for later-stage[12] VC investments. In 2022, later-stage VC investments in the EU dropped more significantly than early-stage investment, decreasing from USD 12.4 billion in the first quarter of 2022 to USD 5.5 billion in the same period on 2023, and remaining broadly stable thereafter (Figure 5.3-3). The slowdown in late-stage investments is also reflected in the significant decline of VC rounds of more than USD 100 million (Atomico, 2023). Conversely, early-stage[13] investments started to recover as of the beginning of 2023, after the smaller contraction reported in the second half of 2022.

11 Data as of 20th of November 2023.

12 PitchBook database defines a later-stage VC deal as a Series C to Series D round, or a round that occurs more than five years after the company's founding date.

13 PitchBook database defines early-stage VC as a Series A to Series B financing round founded within five years of the company's founding date.

Figure 5.3-3 Early- and later-stage VC investments in the EU, 2022 Q1-2023 Q3



Science, research and innovation performance of the EU 2024

Source: PitchBook data, as of the 20th of November 2023.
Notes: (1) Investment values are calculated considering the headquarters country of the companies involved in completed deals.

Exit activity also remains weak. During the first three quarters of 2023, the deal value of exit activities (including both Initial Public Offerings [IPOs] and acquisitions) reached USD 7.6 billion, about 72 % less than what was observed over the same period of 2022.[14]

The VC market remains significantly larger in the US than in the EU. US VC funds are historically larger than their European counterparts. In 2021, the amount of VC capital invested in the US was almost six times higher than that observed in the EU, with USD 442.92 billion and USD 75.12 billion, respectively.[15] The US advantage partly decreased in 2022, when VC investment dropped by around 42%, against the 14% reduction observed in the EU.[16]

The financing gap between the EU and the US is observed at all development stages, but remains more prominent in the scale-up phase. In 2023, VC investments in the US exceeded those in the EU by a factor of 5 at the seed stage[17], and by a factor of 4 at early-stage financing. The largest gap is observed for scale-up operations, with the US VC investments at later-stage financing amounting to USD 103.3 billion, against the USD 18.2 billion reported in the EU (Figure 5.3-4).

The significant gap in late-stage financing between the EU and the US is also confirmed when looking at VC investments by deal size. As of November 2023, the US exhibits a larger number of VC investments across all deal sizes compared to the EU (Figure 5.3-4). The disparity is more

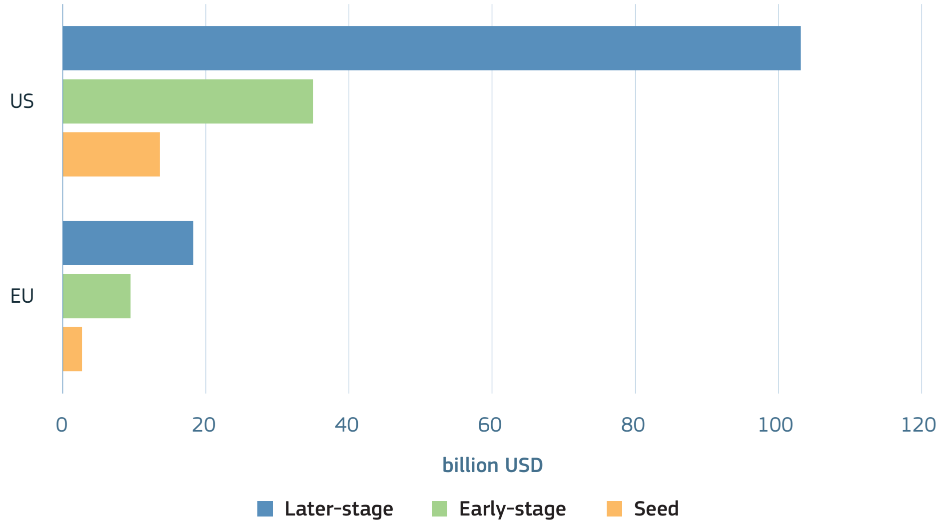
14 DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit based on PitchBook data, as of 20th November 2023.

15 PitchBook data, as of 20th November 2023.

16 DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit based on PitchBook data, as of 20th November 2023

17 A seed deal is when any investor type provides the initial financing for a new enterprise that is in the earliest stages of development.

Figure 5.3-4 VC investments[1] by development stage in the EU and US, 2023



Science, research and innovation performance of the EU 2024

Source: PitchBook data, as of 20th of November 2023.
Notes: (1) Investment values are calculated considering the headquarters country of the companies involved in completed deals.

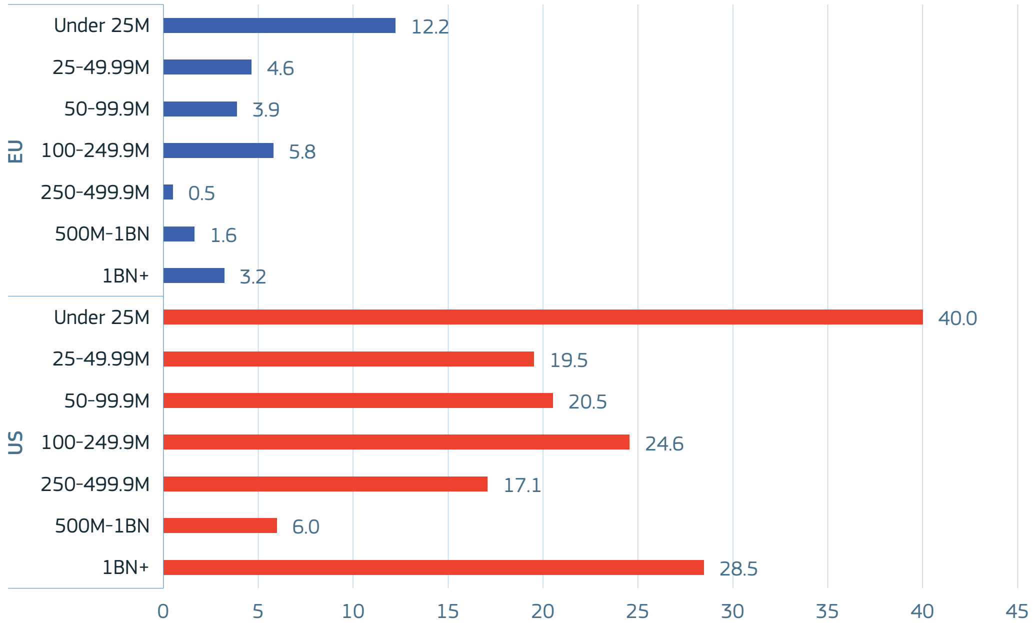
pronounced as the deal size increases, with the US showing a significantly higher volume of deals above USD 100 million. The gap becomes especially marked in the highest investment tiers, particularly for deals over USD 250 million. Specifically, for funds exceeding USD 1 billion, the US outnumbers the EU by a factor of more than 5.

Furthermore, the US tech ecosystem consistently offers a wider pool of start-up[18] companies for investors to back. Up to November 2023, the number of VC-backed start-ups in the US was more than twice that of the EU.[19]

18 Start-ups are defined using the PitchBook business status definition of start-up: a company in its formative stage/very early stage, with very few employees (such as lacking a full management team) and typically VC-backed. 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 (Vandresse et al., 2023). As such, it is extremely challenging to provide a comprehensive overview of the European landscape, using a unique definition.

19 DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit based on PitchBook data, as of 20th November 2023.

Figure 5.3-5 Venture capital investments by round size in the EU and the US, 2023 (billion USD)



Science, research and innovation performance of the EU 2024

Source: PitchBook data, as of 20th of November 2023.
Notes: (1) Investment values are calculated considering the headquarters country of the companies involved in completed deals.

The largest share of VC-backed start-ups operates in the information and technology (IT) sector[20] and in the healthcare industry[21], and are mostly concentrated in France and Germany, accounting for more than 30% of the VC-backed start-up population in the EU.[22] Additionally, **60% of all global scale-ups are based in North America, while only 8% in EU countries**, with Germany and France again in the lead (Startup Genome, 2023).

Nevertheless, the number of new tech startups founded each year in Europe has exceeded that observed in US over the last five years. On average, around 15 200 new tech start-ups have been founded per year in Europe, compared to 13 700 in the US (Atomico, 2023), signalling that other factors are at play limiting the scaling-up of the EU start-up ecosystem.

20 The IT sector includes all companies whose primary focus is the development of software, hardware, or related computer peripherals, and all companies whose primary focus is on IT consulting, outsourcing or database management. This includes both business-facing companies and consumer-facing companies.

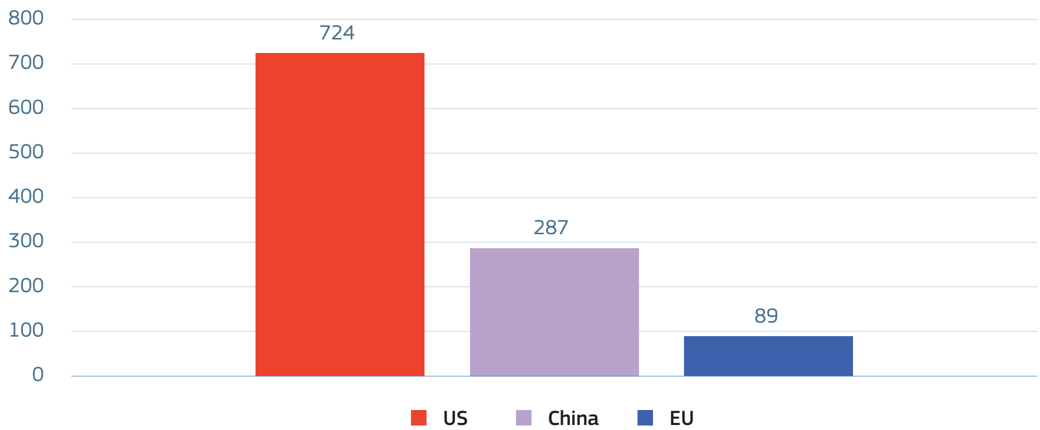
21 The healthcare sector refers to all companies providing medical products or services. This includes consumer facing organisations such as hospitals, health insurance companies and business-facing organisations that provide specific healthcare services, enterprise products or research and development.

22 DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit based on PitchBook data, as of 20th November 2023.

Additionally, the role of institutional investors in the EU remains highly underdeveloped compared to the US. In 2021, government agencies accounted for a substantial share of total funds raised in the European VC market, although in decline compared to 2020 (European Commission, 2022b). On the contrary, institutional investors like pension funds and insurance companies play a minor role. Between 2020 and 2023, the amount of capital committed by pension funds and insurance companies accounted for about 31 % of the money flowing to VC funds, against the 67 % observed in the US.[23]

The EU also keeps lagging behind in terms of unicorn firms. As of November 2023, the number of companies holding the status of unicorns[24] in the US and China exceeded that in the EU by a factor of 8 and 3, respectively (Figure 5.3-6). Furthermore, the number of newly minted unicorns has significantly reduced, with only five new companies reaching a valuation of at least USD 1 billion.[25] This is in stark contrast with the performance observed in 2021, when more than 40 EU companies were able to attain unicorn status.[26] Nevertheless, when looking at the number of active unicorns, the performance of the EU has kept improving (even if only marginally), despite the difficult economic conjuncture.[27]

Figure 5.3-6 Number of active unicorns across world regions per headquarter, up to November 2023



Source: PitchBook data, as of 20th of November 2023.
Notes: A unicorn is defined as a venture-backed company that has raised a venture round with a post-money valuation of at least USD 1 billion. An ‘active’ unicorn is one that has not been exited, meaning that it is/was venture-backed as of the year shown.

23 DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit based on PitchBook data, as of 23rd November 2023.

24 PitchBook defines a unicorn as a venture-backed company that has raised a venture round with a post-money valuation of at least USD 1 billion. An ‘active’ unicorn is one that has not been exited, meaning that it is/was venture-backed as of the year shown.

25 PitchBook data as of 20th November 2023.

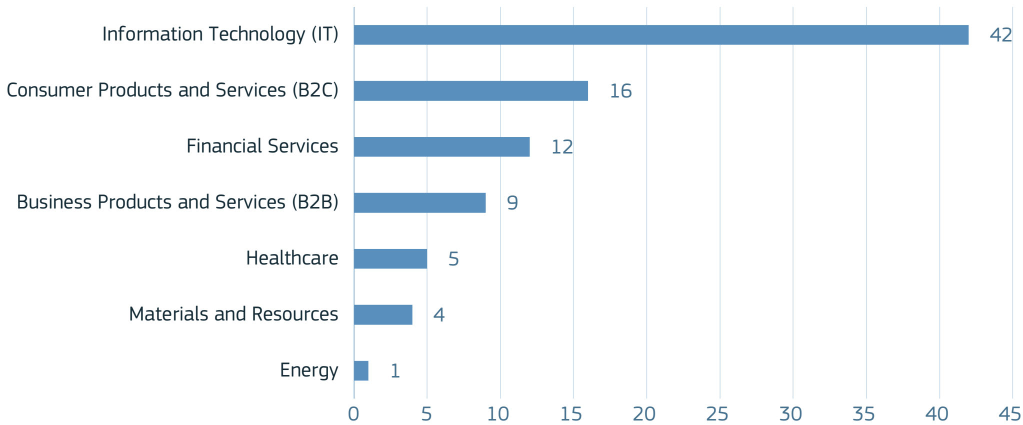
26 PitchBook data as of 20th November 2023.

27 PitchBook data as of 20th November 2023.

The EU's unicorns are mostly concentrated in the IT sector[28]. As of November 2023, there are 42 unicorn companies operating in the IT sector. The consumer products and services sector[29] ranks second with 16 unicorns, followed by the financial service sector[30] with 12 unicorn companies (Figure 5.3-7).

Despite lagging behind the US, the European tech landscape shows considerable untapped potential. Although the amount of capital raised by VC funds in the EU has been decreasing since the positive performance registered in 2021, the "dry powder"[31] available remains significant. This trend is evident in Figure 5.3-8, showing that the cumulative overhang in the EU has not decreased post-2021, but rather, has continued rising. This pattern may be the result of a more conservative approach by VC investors due to economic uncertainties, such as those prompted by geopolitical tensions or market fluctuations. As of November 2023, the amount of dry powder in the EU amounts to USD 66.9 billion, signalling the presence of readily available funds to invest in new opportunities or to support existing investments through additional funding rounds.

Figure 5.3-7 Number of active unicorns in the EU by industry sector in 2023



Science, research and innovation performance of the EU 2024

Source: PitchBook data, as of 20th of November 2023.
Notes: A unicorn is defined as a venture-backed company that has raised a venture round with a post-money valuation of at least USD 1 billion. An 'active' unicorn is one that has not been exited, meaning that it is/was venture-backed as of the year shown.

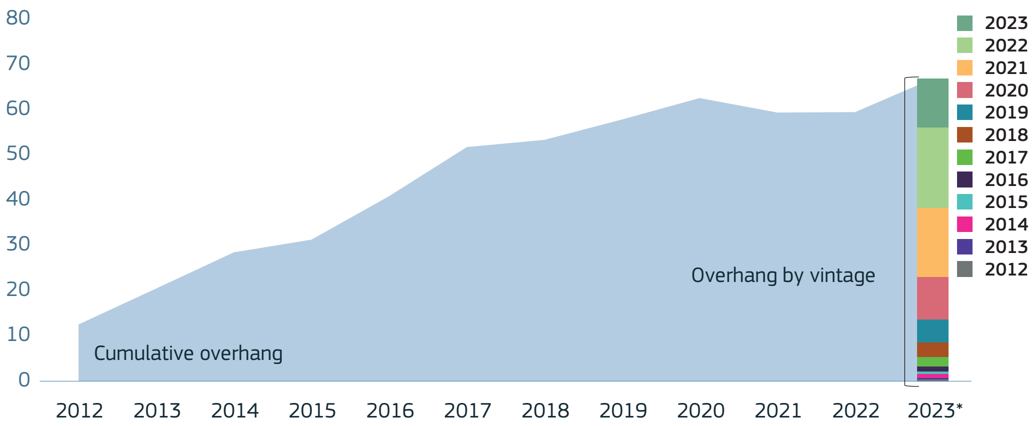
28 According to PitchBook, the IT sector includes all companies whose primary focus is the development of software, hardware or related computer peripherals, and all companies whose primary focus is on IT consulting, outsourcing or database management. This includes both business-facing companies and consumer-facing companies.

29 Business-to-consumer (B2C) refers to product or service transactions that are conducted between a business and a consumer, rather than between a company and a business or an individual consumer and another consumer. This includes companies engaged in the sale of clothing, accessories and related appeal products directly to consumers; companies engaged in sales of durable and non-durable products; companies providing media-based products and services directly to consumers; companies offering consumer media services not classified elsewhere; companies engaged in consumer retail, both via digital and brick and mortar locations; companies providing consumer-facing non-financial services, and companies providing customer-facing transportation services and products.

30 Professional services involving the investment, lending and management of money and assets for both businesses and individual customers.

31 Dry powder, or capital overhang, refers to the remaining amount of capital that can be called down to use for investment purposes.

Figure 5.3-8 VC dry powder in the EU, 2012-2023 (billion USD)(1)



Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on PitchBook data.

Notes: (1) As of 2023 Q3.

Furthermore, funds raised remain highly concentrated within the Union. The European tech ecosystem is characterised by many different hubs and sub-regions, all at different stages of maturity. Germany and the Netherlands alone account for around 52% of total VC capital raised in 2023[32], but only 30.4%[33] of the EU GDP. This indicates that VC fundraising is disproportionally distributed across the Member States, and new investment opportunities may arise from territories currently underrepresented.

32 DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit based on PitchBook data, as of November 2023.

33 DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit based on Eurostat data (online data code: nama_10_gdp__custom_9450868).

Box 5.3-1: The Importance of Governmental Venture Capital

Ramon Campano and Giuseppina Testa

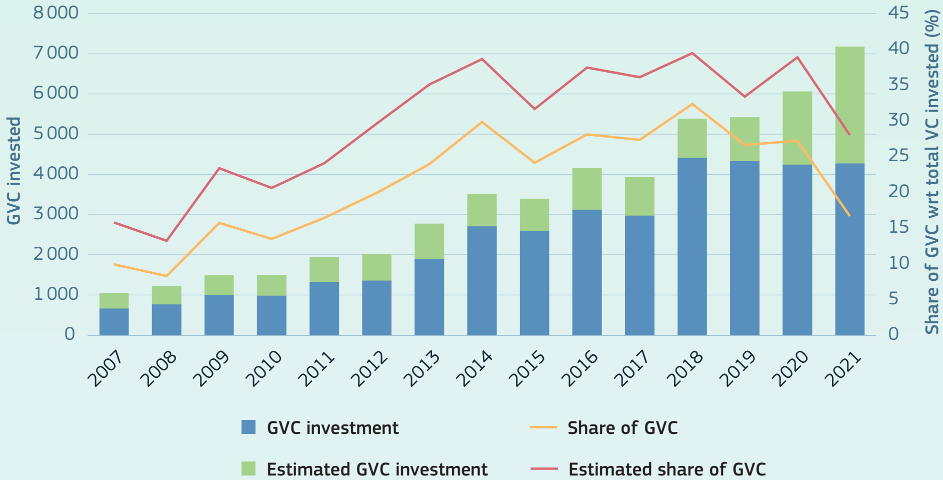
Promising start-ups have the potential, when properly funded, to contribute disproportionally to employment, innovation and economic growth. They are innovative and often operate in high-tech sectors. However, their market and technological characteristics make them likely to suffer from financial constraints, hindering their growth (Berger and Udell, 1988). For this reason, regional, national and supra-national governments all over the world intervened via "**Government Venture Capital programmes**", i.e. VC funds financed with public money and often managed by public agencies to support innovative companies.

Government intervention is justified by the presence of a market failure in the venture capital market (when the level of VC investments is suboptimal, i.e. too low, from a societal perspective) and **serves both to bridge the equity capital gap of promising start-ups and to foster the development of the venture capital market** (Colombo et al., 2016).

To understand the role and positioning of governments in the VC market in Europe, we gathered data on 128 national and regional government venture capital (GVC) institutions located in eleven high-income EU economies, including information on their founding year, ownership, geographical mandates, and policy mix. Additionally, we collected data on 392 GVC funds, such as their type of intervention, committed capital, annual disbursement, duration, management, and investment criteria. This data was obtained from annual reports published on the websites of GVC institutions and press releases. We also validated the data with the respective managers of the GVC funds. This comprehensive approach allowed us to gain a deep understanding of the implementation of GVC funds since their inception. Based on such official accounts we estimate that **over the period from 2007 to 2021, the collected GVC initiatives invested a total of EUR 36.6 billion, with an average annual disbursement of EUR 2.4 billion** (Figure 5.3-9).

Governments have steadily increased their VC investments over time. Between 2007-2021, the estimated amount of GVC investments accounted for 30.9% of the total VC investments. Furthermore, the share of GVC on total VC investments significantly increased over the same period, from 10% in 2007 to nearby 40% in 2020, with a decline in 2021 (Figure 5.3-9). In absolute terms, we calculated GVC investments to be EUR 36.6 billion in the period 2007-2021, compared to EUR 165.4 billion in total, according to the European VC association, Invest Europe (Testa et al., forthcoming).

Figure 5.3-9 Trends in GVC investments in absolute terms and as a percentage of total VC investment (million EUR)



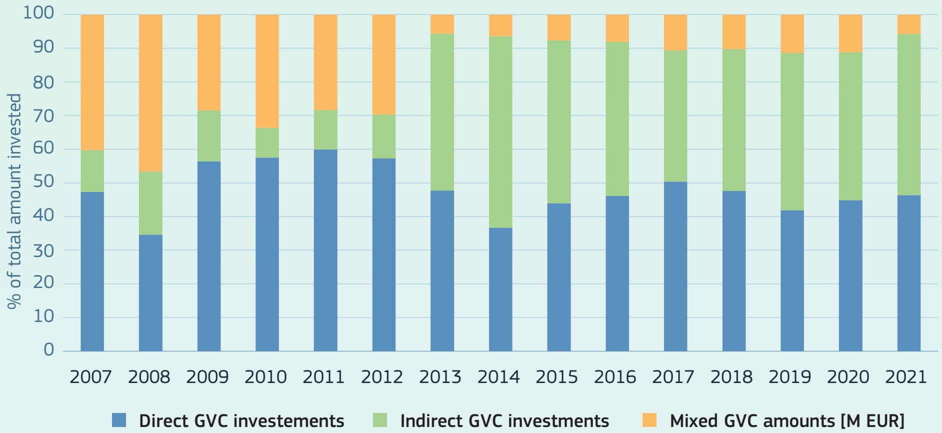
Science, research and innovation performance of the EU 2024

Source: Testa et al., (forthcoming).
Notes: The filled bars indicate collected data, while the dashed bars referred to the estimated data.

GVC funds differ significantly in terms of their investment strategy private investor involvement, budget management, size, and investment process. Examples of different investment strategies are that governments can invest directly (alone or/and alongside private investors) in companies (direct GVC funds), or they can set up funds (that are entirely or partially financed by the public sector and either managed by public officials or private sector managers) that invest in companies (indirect GVC funds). In the selected EU countries, the significance of direct, indirect, and mixed GVC funds has evolved over time in terms of the total investment amount (Figure 5.3-10). Direct GVC investments were predominant in the early years of the analysis. However, since 2013, there has been **a notable increase in indirect GVC investments**, which account for approximately half of the total GVC investments in recent years. Mixed initiatives are gradually declining.

In relation to their industry focus, the majority of GVC funds in the sample are "generalist", i.e. have no general industry regulations or restrictions regarding their investments. **About 81% of our GVC funds are closed-end funds**, indicating that they focus their investment activities on a limited period of time, after which they are 'closed' to new investments performing 'follow-on' investments, only. Closed-end funds on average have a lifetime of about 8 years (values range min = 1; max = 21), suggesting that they are not particularly patient (for comparison average private VC funds have typically a lifetime of 10 years, with the possibility to extend by two additional years). **The consequence of this is that there might be the risk of missed opportunities to invest in deep-tech and groundbreaking technologies that require longer periods to develop marketable products.**

Figure 5.3-10 Total GVC investments by type of initiative and year (million EUR)



Science, research and innovation performance of the EU 2024

Source: Testa et al., (forthcoming).

There exists a **great deal of variation in terms of characteristics of GVC institutions**, such as ownership, experience, geographical focus, stated objectives and policy mix. These institutions have different multiple objectives, ranging from stimulating economic growth, innovation, increasing employment to fostering VC market.

GVC institutions have shifted from providing one-time financial support to a wide range of financial instruments to support SMEs and start-ups throughout their entrepreneurial journey. All this suggests the importance of public sources in the financing of promising start-ups dynamically. While in the economic literature (e.g. Alperovych et al., 2020; Munari and Toschi, 2015) GVC institutions have been highly criticized for their underperformance, particularly when compared to private sector VC investors, we believe, as argued by other scholars (Owen, 2019; Bertoni et al, 2019), that there is often a lack of appreciation for their different role, and their policy goals, such as tackling socio-economic challenges, environmental concerns, and/or mitigating regional disparities, which goes beyond the maximization of financial returns.

International investors have become progressively more involved in the European tech ecosystem (especially in later-stage financing), although a slowdown has been observed in recent years. Domestic funding remains the predominant source of finance in the European VC market, especially in early-stage rounds where domestic investors still account for around 80% of VC invested in rounds less than USD 20 million (Atomico, 2022). Nevertheless, the role of international investors appears more important in later-stage rounds. Indeed, the European tech ecosystem experienced significant capital injection into later-stage rounds in recent years, leading to a rapid increase in the number of investors in rounds above USD 100 million (Atomico, 2022). Among these new investors from outside Europe, those originating from the US hold the highest share, although their number has declined since 2021 (Atomico, 2022), presumably as a result of the difficult economic conjuncture.

Furthermore, the European tech ecosystem has experienced a significant increase in the scale of capital invested in clean[34] and climate tech[35]. The amount of capital invested in these two segments has significantly increased over the last five years. As of November 2023, clean and climate technologies accounted for 39% of total VC invested in the EU.[36] The surge in green companies has been accompanied by a significant slowdown in fintech investment, which accounted for only 10% of the resources invested in 2023.[37]

VC investments in the clean energy domain proved to be more resilient in the EU than in the rest of the world. In 2022, the EU's VC investments in the clean energy domain reported a 42% increase compared to 2021, reaching EUR 7.4 billion (European Commission, 2023). Early-stage investments in EU clean energy start-ups more than doubled in 2022, increasing at a much faster rate than in the US, but less than in China. This growth was mostly driven by deals in industries related to green steel production, renewable carbon products and clean energy generation (small modular nuclear reactors and installation services for solar PV). Later-stage investments in EU clean energy scale-ups also increased between 2021 and 2022 (by a factor of 1.3), as opposed to the significant drop observed in both the US and China (-10% and - 29%, respectively) (European Commission, 2023).

However, the EU has still not fully unlocked its capacity to attract higher growth deals when looking at strategic net-zero technologies as defined in the Net-Zero Industry Act (NZIA) (except for batteries). Global VC investment in strategic net-zero technologies increased from EUR 19.5 billion in 2021 to EUR 20.8 billion in 2022 (European Commission, 2023). Nevertheless, the EU's increase was lower than observed at a global level, particularly in the US, which recorded a 41% increase against the EU's 2.3%. US growth was primarily driven by investments in renewable hydrogen and fuel cells, sustainable biogas/biomethane, heat pumps and geothermal (European Commission, 2023).

34 In PitchBook, clean tech companies include developers of technology which seeks to reduce the environmental impact of human activities, or to significantly reduce the amount of natural resources consumed through such activities.

35 In PitchBook, the segment of climate technology includes companies developing technologies intended to help mitigate or adapt to the effects of climate change. The majority of companies in this vertical are focused on mitigating rising emissions through decarbonisation technologies and processes. Applications within this vertical include renewable energy generation, long-duration energy storage, the electrification of transportation, agricultural innovations, industrial process improvements, and mining technologies, among others.

36 DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit based on PitchBook data, as of 20th November 2023.

37 DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit based on PitchBook data, as of 20th November 2023.

To meet the NZIA target of manufacturing at least 40% of the EU's annual deployment needs of strategic clean technologies (solar PV, wind, batteries, heat pumps, electrolysers, and CCS), at least EUR 92 billion investments over the period 2023-2030 will be needed. Out of these, between EUR 16 billion and EUR 18 billion are expected to come from public investments, while EUR 25 billion are expected to be raised from private investors given the current rate of private investments in these technologies (Cleantech for Europe, 2024). This implies a financing gap of EUR 50 billion over the period 2023-2030, and calls for a coordinated approach to secure sufficient and swift funding to compete on the global stage.

The share of total investment captured by Artificial Intelligence (AI) is also increasing. Despite the global economic downturn, the amount of capital invested in companies operating within the AI realm[38] has shown more resilience than other segments. According to PitchBook data, 2022 investments in companies linked to AI and machine learning technologies remained close to the 2021 levels, with AI's share in total investment at around 16% in 2023.[39]

38 According to PitchBook, this category refers to companies developing technologies that enable computers to autonomously learn, deduce and act through the utilisation of large data sets. The technology enables the development of systems that collect and store massive amounts of data, and analyses that content to make decisions based on probability and statistical analysis. Applications for Artificial Intelligence & Machine Learning include speech recognition, computer vision, robotic control and accelerating processes in the empirical sciences where large data sets are essential.

39 DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit based on PitchBook data, as of 20th November 2023.

Box 5.3-2: Deep tech innovation in Europe

Deep tech innovation is rooted in cutting edge science, technology and engineering, often combining advances in the physical, biological and digital spheres and with the potential to deliver transformative solutions in the face of global challenges. Deep tech innovation differs from other forms of technological innovation by finding its source in a deep interaction with the most recent scientific and technological advances (including in the fields of materials and biology), and by seeking to produce a profound impact in the targeted application areas that also help address the most pressing challenges, such as the green transition.

Deep tech start-ups have a different risk profile compared to traditional companies. Deep tech innovations typically have strong disruptive potential, but face specific issues such as higher development costs, longer time spans to move from discoveries to market, and technological risks. The technological risk is linked to the very nature of deep tech innovation, which entails the development of game-changing technologies completely new to the market, whose development is, thus, characterised by a significant degree of uncertainty (European Commission, 2022a).

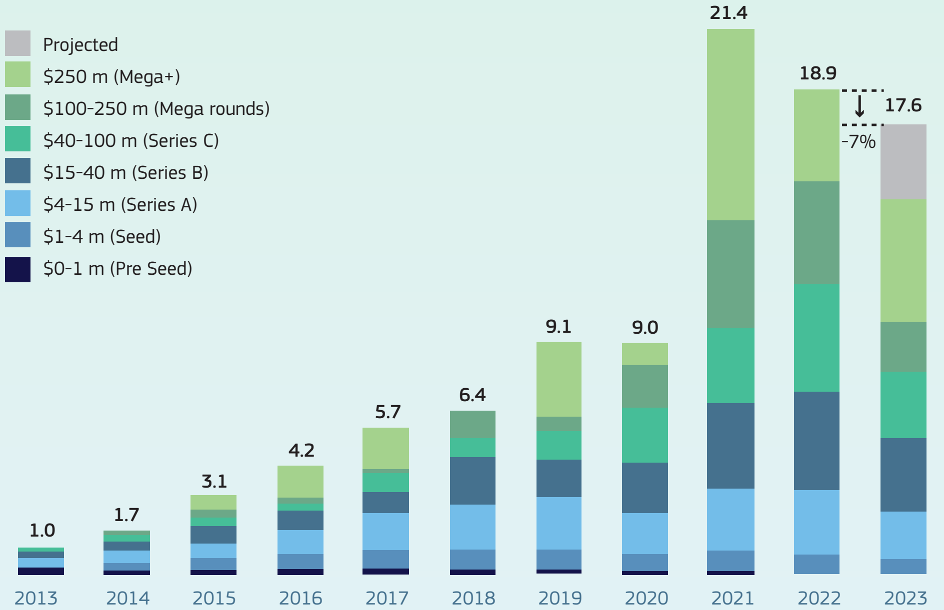
Nevertheless, deep tech start-ups also face lower market risk. Deep tech companies are typically built around advanced technologies that are not easy to replicate or replace, thereby providing significant barriers to entry for potential competitors. Additionally, deep tech start-ups can rely on highly skilled personnel, whose expertise allows to maintain a competitive edge in developing and improving cutting-edge technologies (Dealroom, 2023).

Deep tech innovation is critical for navigating the green and digital transitions, to accelerate the EU's open strategic autonomy, to find alternatives technologies in disrupted markets, from renewable energy to agri-tech, and address health emergencies. Deep tech spans many industries and technology segments, including novel AI (e.g., autonomous driving, privacy enhancing technologies, explainable AI); space tech (e.g., launch, earth observation, in-space manufacturing); novel energy (e.g., hydrogen, fusion, new battery chemistry); computational biology and chemistry (e.g., AI-enabled drug discovery, protein design, biofuels); and quantum innovations (Dealroom, 2023).

In 2023, the level of VC investment in European deep tech companies was close to that of 2022, as opposed to regular tech companies. Deep tech showed significant resilience to the recent economic downturns, maintaining relatively high investment levels across the different funding stages (Figure 5.3-11).

Nevertheless, the share of capital coming from European investors dropped to half at later-stage of funding, posing a potential threat to Europe's technological independence. At the initial (pre-seed) phase, deep tech VC in Europe

Figure 5.3-11 VC investments in European Deep tech start-ups by stage, 2016-2023 (billion USD)



Science, research and innovation performance of the EU 2024

Source: Dealroom, (2023).

is predominantly sourced from within the region. However, at more mature funding stages, almost half of the investment comes from the US and Asia (Dealroom, 2023). Efforts are thus needed to increase the attractiveness of deep tech investments for domestic investors. In this regard, the **European Innovation Council (EIC)**, with its EUR 10 billion, is increasingly recognised as the largest deep tech investor in Europe (see Box 3). Separately, **the European Tech Champions Initiative**, structured as a fund-of-funds, aims to allocate EUR 3.75 billion to tackle the European scale-up gap, providing growth financing to European tech champions in their late-stage growth phase (European Commission, 2022b). Additionally, the Strategic **Technologies for Europe Platform (STEP)** initiative aims to boost investments in critical technologies, including deep tech.

Attracting talents represents another important challenge for deep tech companies in Europe. Deep tech technologies require a unique skillset. High quality education and attractive working conditions are key to attracting and ensuring a flow of highly skilled and talented individuals, which can contribute to achieving wider policy priorities such as the twin transitions, and a competitive edge in strategic value chains. Furthermore, skilled growth investors, able to assess transformational technologies and support companies in building their businesses, are needed to increase growth investments in the years to come (Dealroom, 2023).

3. Policy initiatives to scale up the EU's tech ecosystem

Financial frictions represent a significant constraint for innovation. Innovative ideas are the engine of economic development, and the creative disruption they trigger is a key driver of companies' and industries' dynamics. From the moment a new idea manifests to its potential use within the production process and future arrival on the market, inventors face several inefficiencies. In particular, financial constraints not only affect the size and the quality of the innovator pool, but can also impact the speed and efficiency at which new ideas are integrated into production (Ackigit and Van Reenen, 2023).

Furthermore, the financing of innovation differs significantly from that of tangible assets. The challenges linked to financing innovation are related to the non-rival and non-excludable nature of innovation outcomes, which prevent firms from ensuring full returns on their R&D investments. Additionally, the intangible nature of technological knowledge and the inherent risks and uncertainties of innovation projects create financial frictions in securing external investment (European Commission, 2022a).

Therefore, establishing a conducive environment for companies to innovate lies at the core of the EU's strategy to enhance productivity, competitiveness and resilience. In this regard, the EU's capital markets remain considerably fragmented, with resources heavily concentrated in few regions and significant untapped potential across the entire EU. This calls for increasing efforts to progress and complete the Capital Markets Union (CMU), whose role remains key to providing additional and alternative funding opportunities. This is particularly relevant to ensure that investments keep flowing to the EU's companies at the required scale to accelerate the roll-out of strategic net-zero technologies. STEP, established in June 2023, aims to earmark public funding for allocating and distributing financial support to investments in critical technologies, such as deep and digital technologies, clean technologies and biotechnologies. This initiative is designed to mitigate the risks associated with innovation investments, bridge the divide between project developers, corporate and institutional investors, and ultimately facilitate increased private-sector investment (European Commission, 2023).

Policy actions also need to account for the different nature of innovation activities, as the suitability of different financial instruments varies depending on the types of innovation firms undertake (Mitra et al., 2023). Due to the constraints faced in accessing external financing, innovative firms in the EU still largely rely on internal resources to finance their innovation activities (European Commission, 2022a). Nevertheless, grants are among the financing instruments showing the largest positive association with firms' likelihood to innovate, confirming the key role of grant schemes for the EU's innovation performance, as well as the importance of the EU's Framework Programme for R&I, which employs grants as primary financing instruments to promote and foster innovation within the EU (Mitra et al., 2023).

Furthermore, improving access to non-banking financing remains high in the EU's innovation agenda. Equity and venture capital financing are key to creating growth opportunities in the EU. This is particularly relevant for deep-tech companies, which have strong disruptive potential and are set to play a pivotal role in navigating the green and digital transitions (European Commission, 2022b).

The "New European Innovation Agenda" (NEIA) aims to foster a new wave of deep-tech innovation, which requires breakthrough R&D and large capital investment in the EU. The NEIA is currently in its implementation phase, with 24 of the 25 core actions announced either completed or ongoing. These actions aim to improve access to finance, enable innovation through experimentation spaces (e.g., regulatory sandboxes), help strengthen and better connect innovation players across Europe, attract and retain talent, and improve the European innovation policy framework (European Commission, 2022b).

In this regard, the EIC has a central role to play. The EIC focuses on deep-tech innovations where significant funding is needed over a long timeframe before returns can be generated. It is designed to identify ground-breaking ideas and bridge **two critical financing gaps** that innovative companies face in their growth journey to create scalable deep tech propositions: the transition phase from the laboratory to the market, and the scale-up phase for high-risk innovations.

Box 5.3-3: Access to Finance – the EIC

Sivasegaram Manimaaran

The EIC, a flagship initiative of the Commission's Horizon Europe programme, was established to provide a one-stop-shop for breakthrough innovators at all stages of development, ensuring a pipeline of ideas and companies that are either ripe for investment now, or will be in the future. Support for companies through the EIC comes in the form of both non-dilutive grant funding and investments in individual startups and SMEs. With long time horizons and a high-risk tolerance, investment through the EIC is designed to crowd in essential private investment.

Through such syndication, the EIC leverages the domain knowledge and expertise of more specialised funds, and in turn, ensures that EIC beneficiaries will be viewed as credible propositions by the market when seeking additional future financing. To date, over 500 startups and SMEs have gained support through the EIC Accelerator and its investment arm, the EIC Fund, which has been fully operational since October 2022. To date[40], over EUR 1.3 billion in investments in over 200 deep-tech companies have been approved, and over a hundred of these approved investments have resulted in investment agreements that have crowded-in approximately 3.5 euro of additional equity investment for every euro of investment via the EIC, thus contributing to the emergence of a single market for innovative risk capital in Europe.

Importantly, the EIC has also consistently sought to support female led companies, now representing over 19% of the portfolio[41], **and has increased its reach to companies from less developed regions**, now standing at over 20% of applicants. The resulting portfolio of projects under the Accelerator now features scaling companies, including well over 100 that have achieved centaur status[42] or higher valuations, in critical technology areas such as Biotech, Energy Storage, Hydrogen, Semiconductors and Quantum Technologies, amongst many others.

Support from the EIC also goes beyond the pure provision of funding. Its Business Acceleration Services, which include connections to large corporate and public procurers, also help startups and SMEs make connections that are essential to gain market traction.

40 End of January 2024.

41 Companies with female CEOs.

42 A centaur is defined as a private, technology-based company valued at more than EUR 100 million.

Making the EU more attractive to talent is also crucial to competitiveness. High quality education and working conditions are key to attracting and ensuring a flow of highly skilled and talented individuals, which can contribute to achieving wider policy priorities such as the twin transitions, and a competitive edge in strategic value chains. The EU appears to be losing the global race for talent, with skilled researchers and potential academics more often moving from the EU to the US (see Chapter 3.2).

A deep talent pool is a key ingredient to a successful innovative ecosystem. Companies able to raise large rounds of funding and thus quickly scale up are more likely to be run by experienced founders and/or managers (Atomico, 2022). Furthermore, new company formation in the European tech ecosystem is largely driven by individuals who have previously worked in unicorn companies (Atomico, 2023). These founders can leverage the extensive knowledge and networks gained from their experiences in successful tech companies, giving them a substantial advantage in establishing their ventures. In Europe, around 9 000 new companies have been initiated by alumni of exited unicorns founded in the 2000s (marking a 50 % increase compared to those from the 1990s) (Atomico, 2023). This trend emphasises the key role of strong network effects in fostering innovation and growth within the industry, with important implications for the future trajectories of Europe's tech sector.

Furthermore, as the EU's VC market and tech industry continue to grow and mature, it is important to ensure a more inclusive development trajectory. Despite the fluctuations observed in recent years, 75 % of all VC funding in Europe in 2023 was raised by companies with male founding teams. On the contrary, only 7 % of the rounds raised were captured by all-women founding teams (Atomico, 2023).

There exists a significant disparity between the number of deals secured by teams led solely by women and the actual funding they receive, with a gap ranging from 2 to 6 times depending on the year (Atomico, 2022). This indicates that even when all-women teams are successful in raising funds, they tend to receive smaller amounts compared to their male counterparts, and this trend appears to be worsening over time. Concerning mixed-gender teams, the share of funding rounds obtained in 2022 was only 10 %, in decline compared to the 12 % registered in the previous year. Nevertheless, the overall percentage of funding allocated to these teams has slightly increased, suggesting that the average funding amount per deal for mixed teams is trending upwards (Atomico, 2022).

Addressing the gender gap in VC investment remains essential, not only for social justice, but also to boost economic efficiency. Diverse teams, including those led by women, bring unique perspectives that can catalyse further innovation, which is vital for a dynamic and competitive market. Moreover, by unlocking the full potential of female entrepreneurs, the EU can tap into a largely underutilised resource, boosting overall economic productivity and innovation.

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CHAPTER 5.4

R&I VALORISATION AND THE UPTAKE AND DIFFUSION OF INNOVATIVE OUTPUT

Key questions

- How is the EU performing in terms of knowledge diffusion and innovation uptake?
- What is the role of policy in supporting knowledge valorisation and the uptake of R&I results?

Highlights

- The EU's innovation performance has been improving over time, and the adoption of digital technologies by EU companies is increasing, reducing the gap with the US. Nevertheless, more efforts are needed to maximise the returns to R&I through knowledge diffusion and valorisation, boosting the take-up of innovative solutions, for example by strengthening collaborations between academia, public and private sectors.
- Increasing the speed at which scientific findings are converted into commercial and societal applications is crucial for maintaining the EU's competitive edge and sustain its path towards the Sustainable Development Goals (SDGs).
- Thanks to its pan-European approach and broad set of instruments, the EU's Framework Programme for R&I plays a central role in supporting market and societal take-up of innovative results at different stakeholder levels.

Policy insights

- A systemic approach to knowledge diffusion and valorisation in R&I policy is critical for designing policies effectively promoting the societal and market uptake of innovation. Such an approach needs to take into account the dynamics of diffusion across actors, and create framework conditions to steer the uptake of innovation towards desired socioeconomic goals.

- A strategic approach to intellectual assets management which combines economic interests and societal benefits is also essential to improve access to knowledge and to support competitiveness through increased value creation while advancing societal progress.

- Strengthening collaboration across academia, industry and government helps to enhance and accelerate the transformation of research into practical applications.

- An adaptable regulatory framework and a proactive standardisation strategy remain key to foster innovative activities. In this regard, the EU's focus on regulatory sandboxes and its Standardisation Strategy aims to streamline the integration of research into the market, while ensuring the legislative agility needed to keep pace with rapid technological advances.

In the EU, **the diffusion of knowledge and the uptake of innovation are pivotal to maintaining economic competitiveness and driving sustainable growth**. Effective knowledge valorisation and dissemination ensure that research findings are transformed into practical applications, fuelling innovation across various sectors and enhancing productivity. Moreover, embracing innovation is key to addressing societal issues driving societal progress, thereby fostering an inclusive and forward-looking economy. This process is essential for the EU to respond to global challenges, harness new market opportunities and sustain its position in the global economy.

In this context, **knowledge valorisation is central to transforming R&I findings into practical applications, catalysing economic growth, societal evolution and innovation**. Knowledge valorisation involves transforming data, expertise and research results into viable products, services and solutions, as well as formulating knowledge-based policies that yield social and economic benefits (European Commission, 2022a). By creating linkages across different domains and sectors, knowledge valorisation maximises the impact of R&I results, ensuring that investments from both government and the private sector in research are not only recouped, but also leveraged to generate tangible societal advantages. This approach is key to transforming theoretical knowledge into practical, sustainable innovations that drive progress and address societal needs.

1. The need to boost the take-up of innovation and the diffusion of knowledge

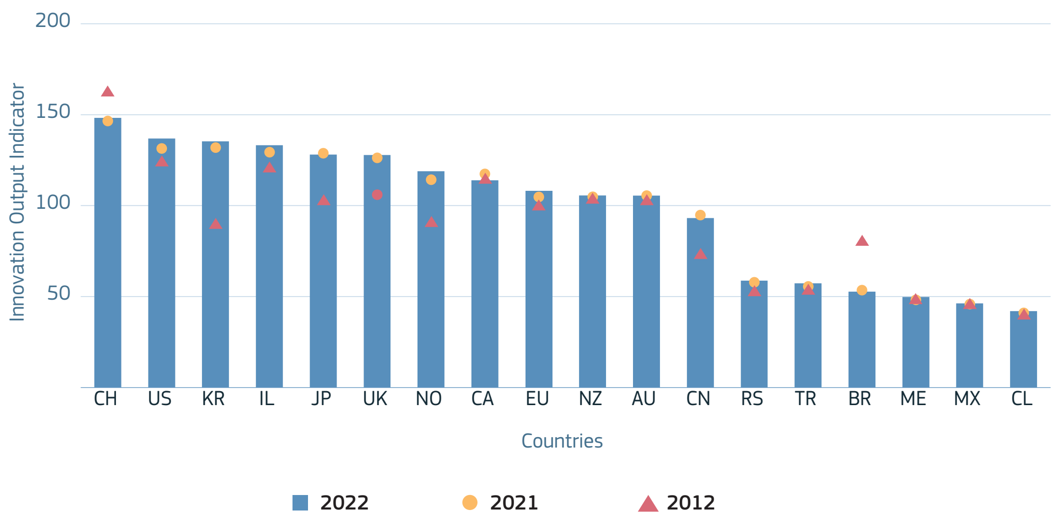
The innovation performance of the EU has consistently increased over the last decade. Since 2016, the European performance as measured by the European Innovation Scoreboard (EIS) has improved by 8.5 percentage points (p.p.), keeping the EU among the top innovation performers worldwide (European Commission, 2023a).[1] A similar positive trend is also confirmed by the Innovation Output Indicator (IOI)[2], which reports the EU's score as increasing from 100 to 115 between 2012 and 2022. This increase places the EU ahead of China[3] (Figure 5.4-1), although still trailing behind the US, South Korea and Japan (Bello et al., 2024). Sweden tops the Member States' IOI ranking, followed by Germany, Finland and Ireland. On the contrary, Romania, Latvia, Poland and Bulgaria show a lower performance (Bello et al., 2024).

1 A decline was observed only in 2020 due to the economic disruptions triggered by the COVID-19 pandemic (for more details, please refer to Chapter 4.1).

2 The Innovation Output Indicator (IOI) is a composite indicator which has been developed by the European Commission since 2013. Its objective is to support policymakers by offering an output-oriented metric of innovation performance at the country and EU levels. The IOI measures countries' capacity to derive economic benefits from innovation by tracking the extent to which innovative ideas reach the market, create knowledge-intensive jobs and increase technological capability.

3 The score of non-EU countries, and in particular China, needs to be interpreted with caution, considering the presence of missing indicators that could lead to an underestimation of the performance.

Figure 5.4-1 The IOI indicator



Source: Bello et al., (2024).
Note: The score is normalised to the EU 27 International score in 2012.

In 2020, more than 50% of active companies in the EU undertook innovation activities.[4] The propensity of EU firms to innovate is higher among large companies. The share of large companies (more than 250 employees) that reported innovation activities was about 79%, against the 60.2% observed for companies of medium size (between 50 to 240 employees) and the 42.5% of companies with less than 50 employees.[5]

However, the technological take-up and socio-economic impact of innovation remains weak. Although an increase has been observed in the degree of technological adoption worldwide (with more people having access to internet, improved access to safe sanitation and a surge in electric vehicle sales), the speed of technological take-up still appears low to promptly address pressing global challenges (WIPO, 2023).

The adoption of digital technologies by EU companies has been increasing in recent years, and the digital divide between the EU and the US is shrinking. In response to the COVID-19 pandemic, over half of EU companies have prioritised investments in digitalisation, reducing the gap with their US counterparts in adopting cutting-edge digital technologies. From the 11 p.p. gap recorded in 2019, the share of EU companies adopting advanced digital technologies rose to 70% in 2023, closely approaching the 73% observed in the US (EIB, 2024).

Nevertheless, successfully managing the digital transition continues to pose several challenges. As an example, in 2021, 61.6% of European enterprises decided against the adoption of AI technologies due to lack of relevant expertise, while 43.7% did not proceed with the

4 Eurostat/CIS Survey 2020 [inn_cis12_inact__custom_8898623].
5 Eurostat/CIS Survey 2020 [inn_cis12_inact__custom_8898623].

purchase of cloud computing services because of insufficient knowledge of this technology.[6]

Knowledge diffusion is essential in facilitating the take-up of innovative results. It contributes to the widespread circulation of new ideas, encouraging the creation of new collaborations and fostering interdisciplinary advancements. Furthermore, it facilitates technology adoption, increasing awareness and understanding of new available technologies. Facilitating the access and sharing of intellectual assets such as patents, know-how and data is pivotal in this respect. According to the Global Innovation Indicator (GII) 2023, any national intellectual property policy should be aligned or even integrated into the national innovation policy (WIPO, 2023).

The share of the EU's high-tech product exports to non-EU countries is stalling. The share of high-tech exports over total trade not only helps measure the technological competitiveness of an economy, but also reflects the ability to commercialise and disseminate the results of R&I products (European Commission, 2022b). Although the value of high-tech product exports in the EU increased by 16% between 2021 and 2022, (reaching EUR 446 billion), their share over total trade slightly decreased from 17.6% to 17.3%.[7]

Knowledge transfer also plays a crucial role in strengthening the presence of innovative companies in an economy. It involves sharing knowledge and expertise across different actors, thereby facilitating the flow of cutting-edge ideas and technologies from research entities to businesses, and fuelling the development of new products, processes and services essential for a competitive and dynamic economic landscape.

In 2019, the link between patent activities and science in the EU was lower than the world average. Non-patent literature (NPL) citations can be used as a proxy for understanding the link between patent activity and scientific research, as they refer to existing scientific and technical knowledge relating to patented inventions. In 2019[8], the average number of EU NPL citations was around 10% lower than the global average.[9] The same performance was observed in China, while in the US, the link between patent activities and science appears stronger[10] (around 40% higher than the world average).

6 Technology Adoption Dashboard, Technology adoption dashboard (bruegel.org).

7 DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit based on Eurostat data [online data code: ds-018995__custom_9278739].

8 Data refers to the most available information available at the time of writing, considering the limitations linked to the patent granting process and the typical 5-years window available for citations to be edited.

9 DG Research and Innovation – Common R&I Strategy and Foresight Service – Chief Economist Unit based on Fraunhofer data on patent applications filed under EPO.

10 It should be noted that US patent applicants are bound by particular legal mandates, requiring the inclusion of a comprehensive list of citations associated with the patent in their filing request. As such, the better performance of the US must be read considering the potential bias that the US patent filing process may create.

While knowledge transfer aims to ensure the diffusion of information, skills and expertise, knowledge valorisation refers to the process of extracting economic or social value from knowledge. Moving beyond the simple transfer of knowledge, valorisation involves a high degree of co-creation between R&I actors and translating research findings or academic knowledge into industrial applications that produce economic and societal benefits (European Commission, 2022b). In particular, efficient collaboration between industry and academia is a key driver of innovation and of competitiveness for the European industry and economy.

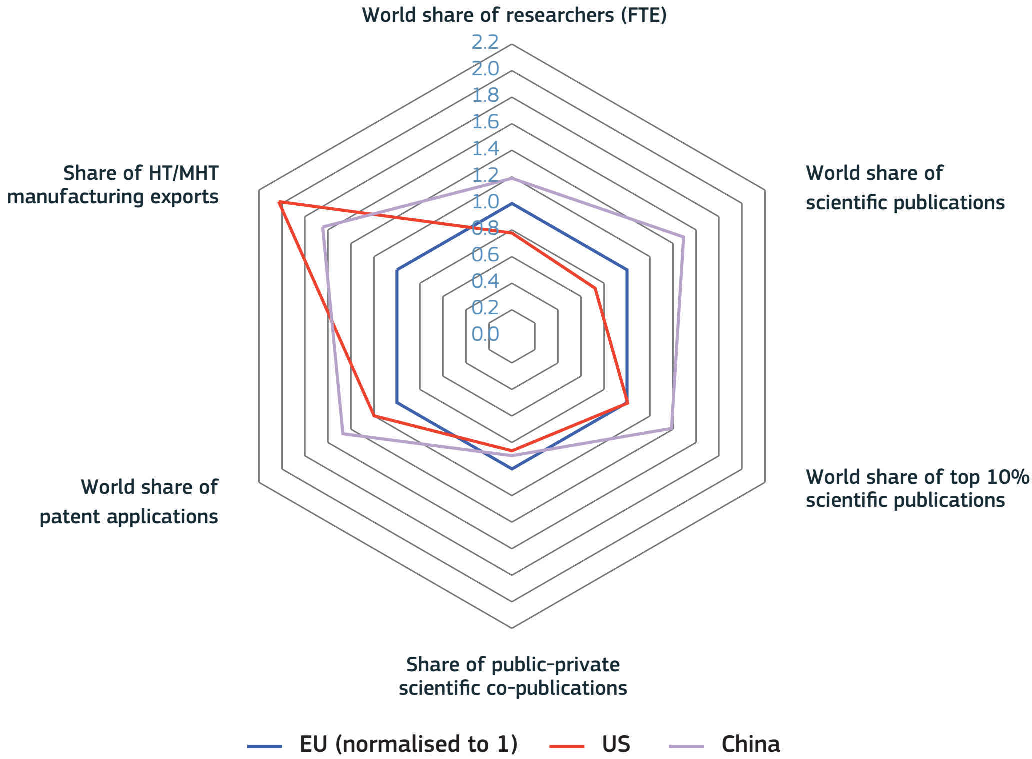
Many elements come into play to measure knowledge valorisation. Capturing the multifaceted and complex nature of knowledge valorisation requires the use of different indicators to ensure a comprehensive assessment of its economic, social and technological impacts. Current indicators, which primarily focus on the transfer and dissemination of knowledge, fall short in capturing the intricate relationship between knowledge creation, diffusion and valorisation. To address this gap, research methods such as social network analyses of university-industry collaborations (Wickramasinghe, 2022) could be leveraged to enable a more precise mapping of these interactions. Nevertheless, despite these data constraints, available evidence still offers important insights into the state of play of knowledge valorisation in Europe.

Despite a demonstrably strong research workforce and ties between academia and the business sectors, the EU continues to lag behind the US and China across several dimensions. As reported in Figure 5.4-2, the two global innovators outperform the EU both in terms of patent applications and share of high-tech exports, for which the gap with China is particularly pronounced. Furthermore, the EU fails to excel in scientific production, especially compared to China, which boasts a substantial advantage in terms of scientific quality (Figure 5.4-2).

Collaborations between public research performing institutions and the business sector are one of the most important channels for both knowledge diffusion and valorisation. It boosts private investments in research, leads to more inventions and to the creation of intellectual assets such as patents, know-how, data and prototypes, and facilitates the flow of knowledge and talent into companies. This synergy not only enhances researcher skills and their understanding of market needs, but also nurtures their entrepreneurial culture. The outcome is a significant improvement in the competitiveness of the European industry and the R&I ecosystem, supporting the development of green, innovative and digital solutions for society (Wickramasinghe, 2022).

The extent to which universities and businesses collaborate on R&D activities varies considerably across Member States. According to the GII 2023, only nine of the EU's Member States ranked among the top 20 countries in terms of university-industry R&D collaborations. Among these, only the Netherlands showed a better performance than China (sixth in the ranking), although remaining below the US (second), while Belgium reported the second highest performance among the EU's Member States, holding the ninth position (WIPO, 2023).

Figure 5.4-2 **Knowledge valorisation approach, latest available year**



Science, research and innovation performance of the EU 2024

Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on Science-Metrix, Eurostat, JRC (INNOVA VI), OECD and UNESCO.

Public Research Organisations (PROs) and Higher Education Institutes (HEIs) also play a crucial role in the diffusion and valorisation of knowledge. PROs act as bridges between academic research and practical applications, facilitating knowledge diffusion between research agents and industry (Vega-Jurado et al., 2021). HEIs hold the potential to enhance the economy's human capital through their educational activities, leading to higher levels of employment and income (Pastor et al., 2018). Furthermore, the research and knowledge transfer initiatives undertaken by HEIs are key to creating scientific and technological advancements, contributing to an increase in technological capital.

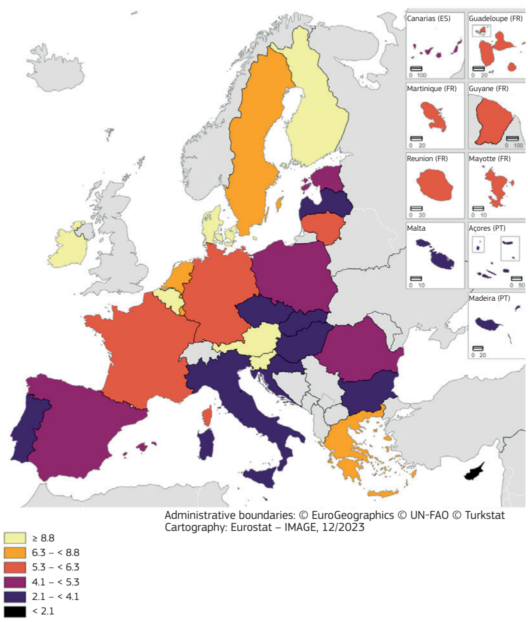
Innovative companies in the EU tend to collaborate more with universities than with research entities, showing important differences across Member States. The share of companies collaborating with HEIs and PROs has been stalling or declining in most European countries (Andriescu and Collier, 2023). According to the Community Innovation Survey (CIS), in 2020, only 5.5% and 10.5% of the EU's innovative companies cooperated on R&D and other innovation activities with research organisations and HEIs respectively.[11] Ireland ranks first at the Member State level, with 13.3% of innovative firms collaborating with research entities, followed by Slovenia, Austria, Finland and Belgium.

11 Eurostat/CIS Survey 2020 [online data code: inn_cis12_coop].

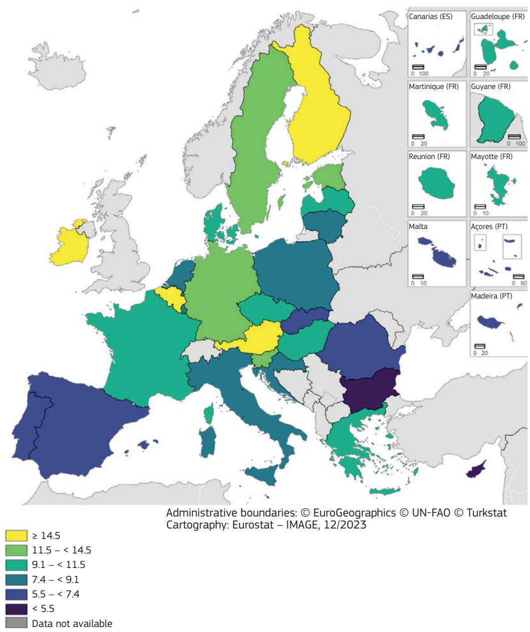
Conversely, Cyprus, Bulgaria, Slovakia and Malta report the lowest performance, significantly below the EU's average (Figure 5.4-3A). In terms of collaborations with HEIs, Finland, Austria and Ireland show the best performance, with a share of collaborations above 14 % (Figure 5.4-3B). By contrast, Bulgaria, Romania and Cyprus significantly underperform as compared to the EU average, with shares between 4 and 5.5 %.[12]

Figure 5.4-3 Share (%) of the EU's innovative enterprises collaborating with research institutes and universities and higher education institutes, 2020

A. Research Organisations



B. High Education Institutes



Science, research and innovation performance of the EU 2024

Source: Eurostat/CIS Survey 2020 [online data code: inn_cis12_coop].

12 Eurostat/CIS Survey 2020 [online data code: inn_cis12_coop]

2. From scientific results to concrete solutions for higher EU competitiveness

Enhancing competitiveness calls for the adoption of a robust 'from-lab-to-fab' strategy, which is key to ensuring efficient innovation chains and knowledge spillovers from research to commercialisation. Knowledge diffusion and valorisation are critical for the process of creative destruction, which drives economic development. Innovations, stemming from new knowledge and its applications, disrupt established industries and stimulate the development of new ones. This cycle leads to the continuous renewal of the economic landscape, where old technologies are replaced by new, more efficient ones, thereby fueling economic growth, competitiveness and progress.

Europe has long struggled with the problem of translating scientific results into market-viable solutions. Such a phenomenon is typically referred to as the "European Paradox": the idea that despite the quality and volume of European scientific production being on par with its major global competitors, the EU's capacity to innovate and, thus, its competitive edge remain hampered by difficulties associated with converting this scientific capacity into innovative output (Argyropoulou et al., 2019; Nagar et al., 2023).

Nevertheless, the question of the validity of the European Paradox remains. Significant concerns have been raised regarding Europe's actual scientific power – particularly when compared to that of the US (Rodríguez-Navarro and Narin, 2018) – and the availability of conflicting evidence makes it difficult to confirm the actual strength of the European research output (for more details, please see Chapter 3.1). Less disputed, however, is Europe's lack of entrepreneurial capacity to transform research excellence into innovation, growth, wealth and jobs (Argyropoulou et al., 2019).

The EU's scientific research value is partly realised when it successfully transitions to the market, a crucial step for enhancing welfare and economic gains (European Commission, 2023a). On average, it takes about 20-25 years for scientific findings to reach the market, whereas products available in the market today often incorporate technology that was developed over a decade ago (European Commission, 2022b). These extended timeframes exceed the usual duration of policy cycles, posing significant challenges for policy evaluation and strategic planning (European Commission, 2023b).

However, new technologies and market-based solutions alone may not be sufficient to address societal challenges. Science is expected to drive the creation of solutions to current and future societal challenges, such as climate change, ageing population, biodiversity loss and increasing inequalities. The essence of knowledge valorisation lies in the ability to focus on more traditional technology-based solutions to these issues, along with how technologies and non-technology solutions can be embedded in broader societal systems, thereby triggering a transformative change in current practices. Furthermore, the rapidly evolving geopolitical environment calls for a more strategic approach to R&I activities and, in turn, to knowledge diffusion and valorisation. In this context, it is crucial to foster a strategic approach to the management of intellectual assets such as patents, know-how and data in international collaborations.

Therefore, closing the divide between research, innovation and their market and societal applications poses challenges at both the micro and macro levels. Micro-level challenges centre around individual researchers, start-ups and small businesses, and relate to the journey of transforming ideas into marketable products. Conversely, the macro level involves broader systemic and structural factors, with governments and large institutions shaping policies and creating environments conducive to innovation and commercialisation, as well as societal uptake. The interplay of these micro and macro dynamics is essential to ensure the effective conversion of scientific research into societal and economic advantages (Pinto et al., 2023).

Limited funding resources and potential skill gaps are some of the difficulties experienced by researchers and innovative companies. Access to skilled personnel remains critical to the uptake of innovative output, as exemplified by the higher adoption of advanced digital technologies by companies operating in regions where the population has above-average digital skills (EIB, 2024). At the same time, financial constraints and limited R&D investments represent a critical challenge, as they stifle the creation of new knowledge and the improvement of existing technologies, can reduce opportunities for collaborative networking, and slow down technology transfer, thereby delaying the commercialisation of new technologies and their subsequent diffusion.

Furthermore, the successful development and diffusion of new products and services (especially those addressing grand societal challenges) often require significant changes in societal norms, values and expectations. As such, the effective design of policy interventions needs to take into account practices, norms and embedded values characterising the societal systems adopting novel products, processes and technologies (Warneryd and Karltorp, 2020; Lopolito et al., 2022). An example of this is social innovation. The collaborative, experimental and problem-solving nature of social innovation initiatives has a positive impact on innovation uptake and diffusion. By bringing together diverse perspectives, fostering experimentation and addressing real-world challenges, social innovation initiatives create an environment where knowledge is more readily shared and translated into action, thus potentially contributing to a faster uptake and diffusion of innovative solutions (Purtik and Arenas, 2019).

While grassroots approaches such as social innovation can effectively drive innovation, they may not always be enough to ensure the widespread adoption of technologies that rely heavily on contextual factors, such as clean energy and transportation technologies. These technologies often need to be integrated into existing energy systems (including standards and regulations) and infrastructures, which can be challenging without a more coordinated approach. To better support the diffusion of these technologies, it is important to consider a wide range of factors that co-develop over time, creating positive feedback loops that can accelerate adoption and diffusion (Palm, 2022). These factors include aligning policies, building infrastructure, attracting early adopters and creating value chain modules.[13]

13 Policy alignment involves ensuring that regulations, standards and practices are supportive of new technologies. Infrastructure development involves creating the necessary facilities and networks to support their adoption. Early adopters are individuals or businesses that take on new technologies early on, helping to create a critical mass of demand and demonstrate their feasibility. Value chain module formation involves creating the early building blocks of the industry that support new technologies, such as specialised manufacturing facilities or service providers (Palm, 2022).

Box 5.4-1: Values, Learning and Knowledge in Solar PV Adoption – A Case Study

Bianca Cavicchi

Warneryd and Karltorp (2020) explore the **interplay of values, learning and knowledge acquisition in driving the expansion of the solar photovoltaic (PV) niche, particularly in the context of large building adoption.** The authors delve into the motivations and experiences that have propelled solar PV uptake and diffusion in Sweden.

The study underscores the **central role of values in shaping the niche expansion of solar PV**. Owners of solar PV systems on large buildings are drawn to the technology's alignment with their values, such as sustainability, fair costs and induced innovativeness. These values translate into positive experiences, fostering a desire to assume new roles and contribute further to the niche's growth. Values also contribute to the establishment of a strong social identity within the niche, shaping a positive narrative that attracts new actors and influences policy decisions.

The installation of solar PV plants has increased the engagement of organisations in their local electricity system. This engagement has spread to members and employees, who have learned more about the energy system and the prospects for reduced energy costs and energy self-sufficiency provided by solar PV technology. The process has also led to the development of new business models for the adoption of solar PV, which can contribute to further upscaling.

The positive experiences within the solar PV niche enable knowledge transfer to mainstream energy system stakeholders, attracting them to exploit the benefits of a more decentralised energy system. For instance, energy utilities are shifting their focus to customer value and housing regime stakeholders integrating electricity infrastructure development as a core activity. The study showed that solar PV adoption can lead to knowledge acquisition and transfer, thus fostering a change in routines, values, increased engagement in the energy system, and a greater understanding of the role of solar PV in sustainability transitions.

Therefore, creating an ecosystem conducive to innovation and able to support the translation of research and innovation into societal and market solutions represents a multifaceted challenge, calling for policies able to act on different fronts. Good framework conditions positively affect business investment decisions, ease market access for new and innovative companies, contribute to reallocating resources towards more productive and innovative activities and increase societal trust (European Commission, 2023b). This calls for increased engagement with policy makers to co-create policies that provide the necessary infrastructure to boost innovation development, diffusion and uptake; promote collaborations across different actors; and develop an innovation-friendly regulatory framework.

An innovation ecosystem able to foster a culture of collaboration between academia, industry and government entities is critical to boost knowledge valorisation. Multi-actor approaches in innovation projects allow for the bringing together of diverse perspectives and expertise from businesses, researchers, policymakers and end-users. Such approaches enhance problem-solving capabilities and facilitate the translation of theoretical knowledge into practical solutions through more interactive tools and models of collaboration. Such a multi-actor approach applied to R&I projects was developed in Horizon 2020 and has been implemented in a multitude of calls in Horizon Europe Pillar II (especially in Cluster 6), aiming at ensuring the involvement of all relevant actors and making the R&I process more demand-driven (European Commission, 2023b). Additionally, the Commission Recommendation on the Code of Practice on industry-academia co-creation for knowledge valorisation provides further guidance for R&I actors to improve stakeholder collaboration and co-creation.[14] The creation of enabling environments and the management and valorisation of the outputs of such partnerships are covered by the Code of Practice, which interestingly outlines the importance of intermediaries (e.g., scientific associations) in fostering and developing co-creation between industry and academia.[15] In parallel, this has inspired stakeholders to create dedicated practices for specific actors, such as small and medium-sized enterprises (SMEs).[16] The Code of Practice on intellectual assets management[17] and on standardisation[18] for knowledge valorisation also provide relevant guidance to support the valorisation of results arising from industry-academia joint-activities.

Furthermore, developing this collaborative culture calls for a deeper reflection on how different stakeholders – especially the public – interact. On the one hand, the multi-actor approach could be further deepened, focusing more on the performance of different actors and their ability to function in a network (Wickramasinghe, 2022). On the other hand, the concept of co-creation suggests engaging diverse actors throughout innovation processes. However, questions remain regarding the effects on public engagement. Although co-creation offers new participation opportunities, it also tends to favour economic benefits over social justice (Ruess et al., 2023). This approach often conflates the roles of

14 Commission Recommendation (EU) 2024/774 of 1 March 2024 on a Code of Practice on industry-academia co-creation for knowledge valorisation C/2024/601 OJ L, 2024/774, 5.3.2024, ELI: http://data.europa.eu/eli/reco/2024/774/oj

15 *Ibid*.

16 For example, the SIXLabs Playbook supporting knowledge valorisation process of SMEs by Puurtinen, Hanna-Greta; Pohjola, Petri (2023) https://urn.fi/URN:NBN:fi-fe20231004138761

17 Commission Recommendation (EU) 2023/499 of 1 March 2023 on a Code of Practice on the management of intellectual assets for knowledge valorisation in the European Research Area, OJ L 69, 07.03.2023

18 Commission Recommendation (EU) 2023/498 of 1 March 2023 on a Code of Practice on standardisation in the European Research Area, OJ 69, 07/03/2023

citizens, consumers and users, blurring the line between self-motivated opportunity and fair democratic participation (Ruess et al., 2023). Therefore, deepening the understanding of how the government and public interact is crucial to ensure that policy development remains both inclusive and reflective of diverse societal needs, ultimately leading to more effective and equitable outcomes. The Code of Practice on citizen engagement for knowledge valorisation[19] outlines the key role of citizens in this regard, where "knowledge valorisation" is expected to "benefit society". It addresses the issue through a comprehensive approach integrating organisational frameworks, skill enhancement and cross-sectoral collaboration, while prioritising social inclusion, diversity and gender equality as central pillars of the enrichment of knowledge. The Code of Practice also contains recommendations for the management of these actions, both to support the scalability of citizen projects, and to sustain their efforts in the long term.[20]

An efficient regulatory framework[21] also plays a pivotal role in knowledge valorisation by creating an environment conducive to innovation and attracting investments. Effective regulations are key to ensuring the protection of intellectual property rights and fundamental for innovators and researchers to feel confident in investing time and resources into developing new ideas. At the same time, a strong regulatory framework helps build trust among key stakeholders (e.g., investors, entrepreneurs and consumers) by ensuring that new products and services meet quality and safety standards. This trust is essential for the successful commercialisation and widespread adoption of innovations. Moreover, effective regulation is instrumental in facilitating collaborations across different sectors and countries, which are crucial for the exchange and application of knowledge.

Nevertheless, providing an adequate environment that maximises the appropriation of science is particularly challenging. Various obstacles hinder the effectiveness of the EU's regulatory framework as catalysts for innovation. These include the absence of flexible regulatory tools that can proactively adapt to the speed of innovation, the prolonged duration of legislative procedures, the potential for market fragmentation due to inconsistent treatment of the same innovation across different Member States, and challenges in the national-level implementation of EU regulations (European Commission, 2023b).

In this regard, experimental approaches represent an important tool in the design and implementation of efficient R&I policies. In a fast-changing world, policymakers need to be able to adapt quickly to new challenges and opportunities. Experimental approaches are used to evaluate novel solutions or different business models within a controlled real-life setting prior to their market introduction. As such, policy experimentation allows policymakers to test new policies on a smaller scale and within a controlled environment before widespread implementation, thereby helping to identify and mitigate potential risks and unintended consequences.

19 Commission Recommendation (EU) 2024/736 of 1 March 2024 on a Code of Practice on citizen engagement for knowledge valorisation C/2024/600 OJ L, 2024/736, 5.3.2024, ELI: http://data.europa.eu/eli/reco/2024/736/oj

20 *Ibid.*

21 E.g., well-designed laws, regulations, and guidelines that effectively support and promote innovation while ensuring safety, quality, and fairness in the market. Specific principles include comprehensiveness, proportionality, coherence, stakeholder participation, basis in evidence, transparency and learning from experience, as outlined by the Better Regulation Guidelines https://commission.europa.eu/document/download/d0bbd77f-bee5-4ee5-b5c4-6110c7605476_en?filename=swd2021_305_en.pdf

Central to experimentation approaches are regulatory sandboxes and experimentation clauses. Current regulatory sandboxes[22] in the EU are designed for innovations expected to benefit both consumers and society. They grant regulators a certain level of flexibility, enabling them to uphold regulatory norms while adapting to new developments. Additionally, regulatory sandboxes are instrumental in fostering an environment of learning, keeping pace with sector-specific advancements, and reinforcing connections among regulators across diverse policy fields. They find legal support in experimentation clauses, which enable authorities responsible for applying and enforcing legislation to exhibit a degree of pliancy when dealing with innovative technologies, products or methodologies, even when they do not fully align with existing legal requirements (European Commission, 2023b).

The efficient management of intellectual assets is essential to derive more value from knowledge. The Code of practice on the management of intellectual assets for knowledge valorisation[23] helps stakeholders to successfully approach the various steps of intellectual assets management and address the challenges linked to the adequate control and sufficient leverage of intellectual assets. It promotes a strategic approach to intellectual assets management where both economic interests and societal benefits are taken into account.

Standardisation is also important to the creation of a well-functioning and resilient innovation ecosystem. Developing new standards, coupled with the EU's increased participation in international standardisation bodies, is essential to the success of Europe's digital and green transition, and to boosting the competitiveness and resilience of European industry (European Commission, 2023b).

European standardisation needs to adapt to rapid innovation, delivering timely yet high-quality standards. These standards not only facilitate knowledge sharing among various stakeholders, but also bridge the research-market gap, increasing the market uptake of technological innovations. Additionally, standardised methods for evaluating technology impacts throughout their lifecycle are crucial for promoting innovation across industries, benefiting both policymakers and businesses (European Commission, 2023b).

22 Regulatory sandboxes are defined as concrete frameworks which, by providing a structured context for experimentation, enable where appropriate in a real-world environment the testing of innovative technologies, products, services or approaches, for a limited time and in a limited part of a sector or area under regulatory supervision ensuring that appropriate safeguards are in place, Regulatory sandboxes and experimentation clauses as tools for better regulation: Council adopts conclusions - Consilium (europa.eu)

23 Commission Recommendation (EU) 2023/499 of 1 March 2023 on a Code of Practice on the management of intellectual assets for knowledge valorisation in the European Research Area, OJ L 69, 07.03.2023

Standardisation also plays a crucial role in research and R&I investment agendas, facilitating the widespread deployment of new and strategic technologies. The EU Standardisation Strategy[24] highlights the untapped potential of EU-funded, pre-normative research in shaping future standardisation trends, allowing new technologies to create opportunities for industries.

In this regard, the role of Horizon Europe remains key, as it entails the anticipation of standardisation needs and strong linkages between strategic priorities and pre-normative research[25] (see Box 2 for more details on the initiatives around standardisation policy in the EU).

Box 5.4-2: Standardisation

Gergely Tardos

Since 2022, the Commission has proposed **a handful of initiatives to support the valorisation of research results through standardisation and to find answers on what is the effective strategy to bring R&I results closer-to-market**. Standardisation is a key policy instrument to help valorise research results across the European Single Market and internationally. Driving stronger and more systematic integration of R&I and standardisation to deliver greater social, economic and environmental impact from R&I activities is one of the main pillars of the European Standardisation Strategy[26].

The strategic role of standards is underlined by the **Council Recommendation on the guiding principles for knowledge valorisation[27], where measures and policy initiatives were adopted for improving knowledge valorisation in the Union by broadening the scope of actors and focusing on the entire R&I ecosystem**. The guiding principles respond to the needs of knowledge valorisation actors and provide a common reference to improve knowledge valorisation in the EU.

26 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022DC0031
27 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32022H2415&qid=1670573108748

24 Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions on An EU Strategy on Standardisation: Setting global standards in support of a resilient, green and digital EU single market https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A52022DC0031

25 Pre-normative research (PNR) is research necessary to establish norms and standards in the deployment of a new technology. It is necessary to cover the knowledge gaps, to define adequate uses and safety levels, ensure level playing fields for both incumbents and newcomers, especially in the development and market uptake of new technologies. Research undertaken during the standardisation process is named co-normative research, which often follows up on further research needs determined after the pre-normative phase. https://www.biobasedeconomy.eu/research-knowledge/

Their implementation is supported by the **Code of Practice on Standardisation**[28] **which promotes standardisation as a powerful and currently under-utilised knowledge valorisation tool**. The Code of Practice contributes to the successful synchronisation and systematic integration of R&I and standardisation, raises awareness among researchers and innovators, and facilitates a consistent approach to standardisation activities. Its recommendations guide beneficiaries of public R&I funds on how best to valorise project results through standardisation. Further, the Code of Practice lays a particular emphasis on the involvement of Standard Development Organisations in R&I projects, needs assessment, synchronisation of different timelines of R&I projects and standardisation processes, stakeholder management, and liaising intellectual assets management and standardisation needs of R&I projects.

The Code of Practice was developed on the basis of a scoping study that singled out 40 Horizon 2020 projects as best practice cases renowned for valorising their results by means of standardisation. Almost all areas of Horizon 2020 are represented by the best practice cases, including ICT, transport, security, health, construction and circular economy (Radauer et al., 2022).

With the aim to support researchers and innovators participating in Horizon projects, **HS Booster**[29] **connects projects with standardisation bodies and provides hands-on guidance to help projects valorise their results through standardisation**. It has two main objectives: firstly, to develop an engaged community of European standardisation experts and increase the participation of research performers. Secondly, service design and delivery for projects, including a Standards Training Academy.

A European Standardisation Panel Survey was launched in October 2023 with the objective to identify industry's demand for standards as results of R&I projects. Survey results support the assessment of **how Horizon programmes tackle the standardisation needs of industry and raise awareness of the importance of the standardisation potential of R&I projects, which is indispensable for market uptake**. The analysis of the 3700 responses to the survey highlights how industry urges a stronger link of standardisation and R&I through the efforts of all innovation ecosystem players. One of the survey findings is that while there is untapped potential to bring innovation into the standards-development process, company standardisation and innovation/strategy departments are very often not coordinated.

28 https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32023H0498&qid=1678171117168
29 https://www.hsbooster.eu/

3. Horizon Europe as a central player for a better take-up of innovative results

Thanks to its pan-European approach, the scale of its support and its strong networks with all R&I players, the EU Framework Programme for R&I plays a unique role in supporting the development of the EU's R&I system. The Framework Programme covers a wide spectrum of measures and programmes intended to boost the uptake of R&I results by encouraging academia-industry collaboration, enhancing knowledge valorisation and supporting the commercialisation of innovative technologies. It also inherits and builds upon the success of its predecessor, the Horizon 2020 programme, which had a marked impact on the EU economy (European Commission, 2024).

Several policy instruments and initiatives under Horizon Europe aim to bring together organisations from business, higher education and research sectors. As an example, the European Institute of Innovation and Technology (EIT) has created Europe's largest innovation ecosystem, with over 3 000 partners. It focuses on supporting entrepreneurial education, developing innovative projects, business creation and acceleration, as well as on creating new innovative solutions to address global challenges in areas of climate change, digitisation, sustainable energy, raw materials, manufacturing, food production, healthy living, urban mobility, and culture and creativity (European Commission, 2023b). Other initiatives intended to promote industry-academia collaborations include supporting individual researchers in their research endeavours; promoting innovative training, exchanges and mobility; and encouraging the development of joint research programmes.[30] **The European missions of Horizon Europe are also set to play a key role in fostering innovation throughout the EU**, aiming to connect all relevant actors through new forms of partnerships for co-design and co-creation (European Commission, 2023b).

Horizon Europe also offers specific tools to maximise the impact of research projects and foster collaborations between research actors and users. The Horizon Results Booster provides tailor-made support to both closed and ongoing projects, thus enhancing their societal and economic impact. The Horizon Results Platform serves as a dissemination tool for project beneficiaries, helping to improve the connection with potential partners for commercialisation. Additionally, the Competence Centre on Technology Transfer at the European Commission offers expertise in technology transfer, including capacity building and innovation ecosystems.

The European Research Council (ERC) is the premier European funding organisation for excellent frontier research. Established in 2007, the ERC aims to encourage the highest quality research in Europe and to support investigator-driven frontier research across all fields based on scientific excellence.[31]

30 Respectively: the Marie Skłodowska-Curie Actions, the Innovative Training Networks (ITN), the Research and Innovation Staff Exchange (RISE), and Individual Fellowships

31 https://erc.europa.eu/about-erc/erc-glance

It plays a pivotal role in fostering innovations as it is particularly suitable for generating knowledge spillover and thus driving subsequent inventive activities. Recent evidence further suggests that ERC science holds the same innovative potential as non-ERC funded European research of comparable quality, and that publications originating from ERC projects are more likely to inspire inventions with significant technological and commercial potential (Nagar et al., 2023).

Nevertheless, despite the robust spillover effect generated by ERC science on inventive activities, Europe keeps grappling with the challenge of fully capitalising on the benefits derived from this spillover. The inventive capacity inspired by ERC science appears to be primarily concentrated in entities located in the US, confirming its capacity for assimilating and exploiting high-level scientific research for innovation (Nagar et al., 2023). In terms of the European Paradox, this evidence seems to confirm the European ability to produce research of excellent quality, but calls for increasing efforts to strengthen the European innovation ecosystem and invest in the absorptive capacity necessary to leverage local scientific excellence (Nagar et al., 2023).

In this regard, the European Innovation Council (EIC) is instrumental in identifying and fast-tracking the commercialisation of breakthrough technologies. It was designed to bridge two critical funding gaps that innovative companies face in their growth journey: the transition phase from laboratory to market, and the scale-up phase for high-risk innovations (European Commission, 2023b).

In doing so, the EIC supports the most talented and visionary European researchers and entrepreneurs, adopting a bottom-up approach that enables the proposal of revolutionary ideas across diverse scientific and technological domains, potentially impacting multiple sectors and applications (EIC, 2022).[32]

Lastly, the Framework programme also provides tools for boosting the diffusion and uptake of its results by interacting with complementary policy areas. In this regard, it contributes to the production of evidence-based policy by feeding the lessons learned from its projects and methodological insights into the EU's policy. As an example, specialised tools, such as the Feedback to Policy mechanism, support the European Commission in its commitment to create more effective policymaking (as part of the Better Regulation agenda[33]). This also includes the evaluation of existing policy frameworks and the consideration of diverse viewpoints and foresights, as seen in initiatives like the Horizon Europe Foresight Network. Furthermore, it promotes innovative policy development through experimental approaches and pioneering formats, including mission-based policies.

32 For more details on the EIC, please refer to Chapter 5.3.
33 Better regulation - European Commission (europa.eu).

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PART II

CHAPTER 6

THE PUBLIC RESEARCH SYSTEM AND THE ISSUE OF DIRECTIONALITY: CONDITIONS, PROCEDURES AND POLICY IMPLICATIONS

Dominique FORAY
Ecole Polytechnique Fédérale de Lausanne

Abstract

This chapter addresses "directionality" in public research, focusing on guiding innovation to meet societal and industrial challenges. It contrasts research universities (RUs) and government research laboratories (GRLs), advocating tailored strategies for each to achieve targeted innovation outcomes. The analysis introduces directional adjustment costs (DAC) as key to understanding the trade-offs in redirecting research. It proposes two approaches: one that emphasises flexibility and low DAC, suitable for RUs, and another that involves more directive, higher DAC strategies for GRLs, aiming at precise technological advancements. The chapter suggests empowering RUs for broader societal impact whilst recommending a streamlined, accountable approach for GRLs to focus on specific goals. It calls for a strategic reassessment of how public research is directed, emphasising the importance of RUs in adapting to societal needs and the role of GRLs in achieving targeted innovations.

1. Introduction

One new buzzword in research and innovation (R&I) policy circles is 'directionalities'. Defined as a policy to encourage innovation in a specific direction, its application extends across multiple contexts, from addressing societal challenges (climate change, global health) to industrial policy issues (sectoral transition or modernisation, establishment of a new industry, strategic autonomy). While a certain rate of innovation may be found sufficient for sustaining productivity growth in the economy in general, it can be insufficient in certain domains where accelerating the production and application of knowledge is an imperative for particular reasons. In these circumstances, the policy goal is not merely to address market failure and incentivise R&I in the general economy, but to do so in a specific way within certain domains or in certain *directions*[1].

This chapter addresses the problem of 're-directing' public research. The public research sector is not homogenous; it is characterised by a diversity of institutions and incentive mechanisms and, therefore, the issue of re-directing public research needs to be contextually addressed in accordance with this heterogeneity. In particular, the public research sector includes two main models: the research university (RU) and the government research laboratory (GRL). These two models comprise different institutions and respond to different types of incentives. As such, the problem of directionality needs to be tackled using an alternate modality.

In the next section, some conceptual clarifications are discussed. In section 3, a framework to capture the abovementioned challenge of heterogeneity is then developed. Based on the main findings of the so-called 'new economics of science' (Dasgupta, 1988; Dasgupta and David, 1994; Stephan, 2010; Foray and Lissoni, 2010), the main features of the public research system in terms of governance, incentives and resource allocation principles are described and analysed. From this analysis, the two essential institutional pillars of the public research system are identified: RUs and GRLs. Section 4 goes on to discuss the concept of directional adjustment costs (DAC).

The fundamental message is that although the directions of public research can be influenced through a variety of policy instruments, this influence doesn't come without costs. In a research system where decentralised and bottom-up production decisions and freedom to experiment are not only the rules but an essential ingredient for R&I success, pushing people to shift their research or innovation agenda entails DAC. In designing and deploying programmes and instruments to generate directionalities, policymakers should not ignore these costs. Based on this premise, the identification of two institutional models and on the notion of DAC, the final section explores the different modes of management and governance of public research regarding directionalities.

1 In this sense, this paper is complementary to that of Teichgraeber and Van Reenen (2022), recently published as a working paper in the R&I Paper Series (European Commission). It deals with the policy toolbox available to sustain the rate of innovation in the general economy.

This critical review is informed by the new economics of scientific institutions developed by a few giants of the economics of science (Arrow, Nelson, Dasgupta and David, Stephan) and on national research policy experiences, particularly in the Western countries and within the EU. A modern public research system – which needs to be efficient and effective in supporting countries to meet their societal Grand Challenges – should include a large sector of research universities and a much smaller sector of government research laboratories. Reasons deal with i) the capacity of research universities – having appropriate levels of resources, autonomy and leadership – to 'spontaneously' shift their educational and research agenda towards areas of high societal relevance, and ii) the spillovers they generate through research, education and international flows of students in these relevant areas. Evidence shows that most European countries have not yet reached this stage.

2. Directionalities and missions: conceptual clarifications

'Directionalities' is closely related to another policy concept, 'mission', and the differences among them are not always clearly understood.

'Mission' is a large-scale R&I policy that focuses its support on a particular technological achievement or societal objective (Juhasz et al., 2023). Such support includes not only research but also technological development, as well as complementary programmes in terms of the formation of specific human capital and the provision of specialised services and infrastructures.

2.1 The initial policy model of 'mission'

The archetypical and iconic cases include the R&D programmes organised by the US Office of Scientific Research and Development during World War II (Gross and Sampat, 2021) and Kennedy's Apollo 'moonshot' (Mazucatto, 2022). Mission principles often involve:

- centralisation of the decision process, strong leadership, and a command and control type of governance;
- a public agency which plays multiple roles of coordinator, single buyer and main operator;
- a focus on applied research, development and deployment;
- a monopsony-oligopoly market structure which rules the relationships between one single buyer and a few large suppliers;
- an exceptional and unusual enrolment of scientists and engineers towards a clear and well-identified target.

Enrolling and mobilising researchers and laboratories to achieve a specific mission creates distortions, as the key principles of academic research – freedom to experiment and decentralised production decision – are broken, and the goal of maximising knowledge spillovers becomes secondary – e.g. can be sacrificed for a superior objective which is the achievement of the mission. While acknowledging the existence of spillovers generated by the Apollo programme, Bloom et al (2019, p.179) write: "Surely, the resources used in putting a man on the moon could have been directed more efficiently if the aim was solely to generate more innovation''.

Any kind of causal identification of economic effect is obviously difficult, because any mission is a highly selected episode with no obvious counterfactual (Bloom et al., op.cit.). However, the very recent work by Kantor and Whalley (2023) on the economic effects of the Apollo programme shows both the reality of the economic effects and their limitations. They find local effects of NASA spending through a fiscal multiplier channel – an outcome that is not a strong point for this mission since it is of the same order of magnitude as the effects generated by any typical government expenditures. Furthermore, they cannot detect any local technology spillovers and productivity effects from mission contractors to neighbouring firms.

Because of these limitations, the economic or societal relevance of a mission is conditional to situations of proven crisis – where the speed for finding solutions becomes the main parameter and will justify strong coordination, top-down decisions and a focus on applied research and product development. As quoted in Gross and Sampat (2021), who document the US experience during WW2: 'The time for basic research is before a crisis, and urgency meant that basic knowledge at hand had to be turned to good account' (Conant, 1947). The point here is not so much to support fundamental research, but rather, applications.

Based on these conditions and principles, the metrics of success are clear and non-ambiguous. Missions are viewed as successful if they achieve the targets predefined by the government. Sometimes spillovers can be beneficial, sometimes they are insignificant. Always, they are a secondary objective.

2.2 Recent developments

Beyond this initial model, which was strongly related to defence and space 'missions'[2], conditions, procedures and challenges of mission-oriented public R&D policies have dramatically changed. The irruption of Grand Challenges such as adverse climate change, devastating diseases and many other formidable societal problems has triggered new policy issues and approaches (Foray et al., 2012; Mowery et al., 2010). This evolution is fundamentally characterised by the fact that numerous missions involve social and economic transformations, not only 'simple' technological and engineering objectives.

Consequently, the operational mode of such missions-oriented policy cannot be reduced to the mobilisation of an army of engineers and scientists distributed across a few organisations and conducted in some military fashion. Rather, the operational modes need to involve civil society (to transform consumption patterns and social practices) and the private markets (to fix dysfunctionalities and negative externalities). This is what the great Thomas Schelling observed already in 1996 in his work on global warming: 'Decreasing emission has to be very decentralized, very participatory, and very regulatory.

2 Mowery (2012) has provided a survey of the mission aspect of defence R&D in the US, France and Great Britain, as well as a more general analysis of 'mission-agency' R&D programmes. In the same special issue of *Research Policy*, Wright (2012) and Andrews (2021) analyse an old mission policy in the US which was NOT related to defence or space, but deployed in the area of agriculture.

It requires affecting the way people heat and cool their homes, cook, collect firewood, drive cars, consume energy-intensive aluminium, and produce steam for electricity and industrial use. Methane abatement involves how farmers feed their cattle and aerate their rice paddies. Carbon abatement depends on policies that many governments are incapable of implementing'.

Schelling identified rather a social or societal problem, where some other experts formulated an engineering or scientific problem. There is probably a bit of truth in both camps, but what is certain is that the objectives and challenges of the new missions are not merely technological. While the initial 'Apollo' model was aimed at complex problems of engineering, the new missions are facing fundamental problems of transformation involving multiple dimensions – scientifical and technological indeed, but also economic, institutional and societal. These are also missions that create winners and losers. In this perspective, the analysis of such new missions requires further refinement and more emphasis on issues of building consensus or narratives about problems (Wanzenböck et al., 2020).

The concept of 'mission' as a structuring element of R&D policies at the EU level clearly illustrates such evolution (Mazzucato, 2019; Cavicchi et al., 2023). As described in section 2.1, the concept has a larger scope and is more ample than the initial concept. Beyond the identification of societal challenges and systemic transformations, this concept emphasises the strong participation of civil society and the need for cooperation and coordination between scientists and researchers based in the various national systems of EU R&I. Several objectives are, therefore, pursued simultaneously – this can be criticised[3], – but this also provides this specific pillar of Horizon 2020 some legitimacy thanks to its role in the perpetual development of the European project.

The COVID-19 pandemic allows the observation of another more market-based (or mixed) model of 'mission'. The issue of emergency and speed was clear, but the organisation of the mission was far more decentralised and spontaneous, while featuring a strong involvement of the private sector. This different institutional setup is likely a consequence of the fact that the concerned sector of pharmaceuticals is very different in terms of how it balances market and non-market institutions than the usual 'mission-oriented' sectors of space and military. The question here is whether a Manhattan Project or a 'man to the moon' Apollo-style mission would have been a superior solution to accelerate the discovery, development and manufacturing of COVID-19 vaccines. As explained by Cockburn and Stern (2010), such a solution would have come with a great drawback – the lack of diversity and freedom to experiment – which are the key engines of innovation in life science. The life science ecosystem has never worked under centralised/top-down principles: a single R&D surge seems to have never paid off in the pharmaceutical industry, and the success of the life science innovation system has been driven i) by intellectual freedom and scientific openness, and ii) by an intense and pervasive competition throughout the value chain in life science. The success of COVID-19 vaccines are, therefore, the outcome of a process of coordination and competition involving large companies, start-ups, universities and the public sector – all working within a very decentralised and bottom-up logic – an approach that is rather far from the old Apollo model.

3 According to Rodrik (2014), multiplicity of goals does not contribute to discipline. It becomes possible to justify any range of results after the fact, by highlighting the least problematic aspects of performance.

2.3 From 'mission' to 'directionality'

'Directionality' has a different meaning to 'mission', and refers to a set of micro-R&I policies which generate new incentive structures to achieve the 'right' direction in R&I[4]. The point is not so much to mobilise and enrol in a somewhat military way, but to influence and re-direct people who are, in principle, free in their production decisions. Here, market incentives matter. Principles of strong coordination, top-down decisions and a focus on applied research don't necessarily apply. In the following sections, the issue of introducing more directionalities in public research is thereby addressed.

3. Public research systems in the EU: concept and facts

3.1 A conceptual framework

Dasgupta and David (1994) and Dasgupta (1988) analyse the public research sector, dividing it into two different types of institutions: the first consists of the 'government'[5] engaging itself directly in the production of knowledge, while the second consists of 'private agents' undertaking research, who in turn are subsidised for their effort by the public pursue. While the first arrangement characterises the so-called GRL, the second characterises RUs.

The RU solution is a decentralised mechanism, in which knowledge production decisions are independently taken by members of a self-regulating profession (academic scientists), and whose work is subsidised by the government. The GRL arrangement is closer to a kind of 'command mode of planning', such that the decision of what to produce and how much to produce it is made by the government.

GRLs and RUs form what is commonly known as the public sector research. They are related by exchanges of knowledge, personnel and finances, and they recruit scientists on the same labour market. Yet it is important to maintain the distinction between these two forms of public research, because the economic incentives and resource allocation mechanisms are fundamentally different. In other words, each institution creates for their members a fair balance of advantages and constraints, but the balance is different.

In the RU system, individuals are free to pursue research targets of their own choice, although the system of grants provides funding agencies the opportunity to prioritise a few research areas (see below). In return for financing, individuals and institutions must provide educational services such

4 A complication to the debate among economists on directionalities is that the concept of 'direction' – which was initially developed to capture a very specific feature of technical change (involving a labour-saving and factor substitution logic) and gave rise to a huge literature devoted to the impact of factors endowment on the direction of technical change in the Hicks/Salter/Ahmad tradition – is used nowadays in a much broader sense, which can create some confusion and ambiguity in policy discussions. For example, the policy discussion on artificial intelligence is based on a rather narrow concept of direction (see e.g. Trajtenberg (2019) on human-enhancing innovation *vs.* human-replacing innovation), while the policy discussion on sustainability is based on a much broader concept of directionality.

5 Government' is a broad concept embracing any ministerial institutions and public agencies that fund and drive R&I policy in a country.

as teaching and supervision. **This is the fundamental 'social contract' between research universities and society**: individuals and teams are subsidised for their research activities and they are free to decide their research agenda but in exchange they teach.[6] Modern universities' scientists receive a fixed salary for their teaching and examination tasks, in addition to other rewards (promotion, grants and increased reputation) for successful research. Perhaps research projects fail, have little relevance to societal problems or even to the advancement of knowledge, but if the RU as a whole is educating a large quantity of students who then find 'good jobs', the RU and its members have fullfilled their contract with society.

By contrast, **the GRL system exhibits a very different 'social contract'**: there is no teaching obligation. Consequently, individual scientists and teams are not free as in RUs to decide their research activities; research is organised by the state in relation to targeted objectives. GRLs are, by design, well fitted to societal, strategic or policy support missions. They are dedicated to the advancement of applied knowledge in specific fields of societal or strategic interests, or committed to generating the evidence needed to inform data-driven policymaking.

These processes are frequently fast-paced and may not always align with the more extended research periods that academic researchers are accustomed to. This necessitates a balance between the sophistication and robustness of the analysis and the timeliness of the results. For these reasons, they are often under direct ministerial supervision (such as national space agencies, institutes of health or atomic energy organisations). A successful example is the Joint Research Centre (JRC) of the European Commission, which since 1998, acts as the internal research centre of the executive branch of the European Union 'to provide EU policies with independent, evidence-based scientific and technical support throughout the whole policy cycle'. Over the past decade, JRC science for policy involved around 2 000 JRC scientists producing over 10 000 policy-support outputs, based on evidence from more than 8 000 peer-reviewed publications. As an example, JRC-backed EU energy legislation is expected save about 230 million tonnes of oil equivalent by 2030, translating to up to EUR 285 yearly savings for consumers on energy bills (Mitra A. et al., 2024).

Logically, principles of public accountability and conditionalities become very central in the management and governance of GRLs. Since the rationale for resource allocation to GRL cannot be based on education services and the training of a mass of students and is therefore only based on research and on what society can get from it, GRL must explain in great details what they are doing and how they are doing it. They must be transparent about their failures as their successes. They must also explain why they employ scientists in some specialised fields or disciplines, which seems rather far from the main 'mission' of the concerned GRL. It can be consistent with the research mission, but it needs to be explained to the public. Accountability helps legitimise the GRL's activities. The complement of accountability is resource conditionalities or discipline. Discipline requires clear objectives, measurable targets, close monitoring, proper evaluation, well-designed rules and professionalism (Rodrik, 2014; Mazzucato and Rodrik, 2023).

Historically, most countries that are now innovation leaders have experienced a slow shift from a system involving government laboratories and *teaching* universities as the main knowledge institutions to a system

6 The function of knowledge transfer and innovation is increasingly becoming fully part of the social contract between RUs and society.

characterised by the centrality of *research* universities – e.g. where both tasks of education and research are of equally high importance. Heavy reliance on GRLs can be seen as a legacy of the past: it was appropriate at a certain stage of economic development, when the main challenge for Western countries was to build a S&T infrastructure, and the fastest way to do so was to create these mission-oriented institutions[7]. However, as those countries become innovation leaders, the need for more resources in RUs is obvious. Indeed, RUs generate positive externalities in the form of both human capital and basic research that have the status of 'joint-products' (giving rise to economies of scope and internal spillovers: great scientists benefit from great students and vice versa). This explains the famous quotation by Arrow (1962, p.623): "The complementarity between teaching and research is, from the point of view of the economy, something of a lucky accident".

On the other hand, GRLs, by design, break the intimate relation between research and high education and only provide a small fraction of the total amount of positive externalities that RUs are able to provide[8]. Highlighting the double-externality argument, several economists thereby make a strong case for allocating most resources to RUs[9]. This is wonderfully explained by Zucker and Darby, two American economists:

The idea of research and technology organisations sounds very attractive, particularly in a small country that sees them as a vehicle to achieve a critical mass by concentrating the nation's best scientists in one place. In fact, we ourselves would like to have our research well funded until retirement and the opportunity to build a more permanent research group without the need to educate and train successive generations of graduate students and post doctoral fellows. Despite the personal attractions, ***we can also see how that situation might cool the entrepreneurial spirit as well as our impact on the most important objective of any knowledge institution: the generation of high quality human capital*** (Zucker and Darby, 1999; emphasis added).

Another very recent quotation is worth providing. This comes from Anne L'Huillier – a recent Nobel prize laureate in physics – who explained that she started as scientist at a French GRL (Commissariat à l'Energie Atomique or CEA) and at some point shifted to the University of Lund in Sweden, saying: « *Chercheur (au CEA), c'est formidable, on s'amuse bien, mais on se demande quand même ce que l'on fait pour l'humanité. L'enseignement c'est une récompense immédiate : on voit des jeunes gens s'éveiller devant soi, on nourrit leur enthousiasme* » (Le Monde, 4 décembre 2023). The statement accurately captures the positive impacts that teaching can have on the direction of research within RUs.

There are, thus, two models of public research organisations and their respective efficiency is conditional to how the social contract is fulfilled: RU has a crucial high education function and involves norms of academic freedom for the research aspect of the activity; and GRL has a crucial research mission in certain areas of strategic relevance for a country and strong principles of command and control and public accountability regarding the research activities need to be applied.

7 GRLs are usually created as a public research entity, not as a funding agency. However, the model evolves in many cases – combining research performance and research funding.

8 We ignore in this discussion the classical spillover effects generated by any government expenditures that materialise in some kinds of expansions of the local economy and can vary according to an estimation of the multiplier effect. We don't consider these spillovers since they are not specific to research expenditures.

9 See, e.g. Aghion, Dewatripont et al., 2009, who develop rather similar arguments on the governance and performance of RUs. In a recent paper, MacLeod and Urquiola (2020) further provide a historical analysis of the emergence of the RU's institutional form in the US.

3.2 Academic freedom: a right for any scientist?

The fact that the two models of public research – while very easily identified in the real world – are not well understood in terms of their specific contracts they have with the society, generates great confusion in discussions about academic freedom. Of course, academic freedom as a principle of free decision by individuals or teams about research objectives and methodologies is not a right that any scientist can enjoy. Researchers in corporate R&D can't claim academic freedom. This is obvious. Less obvious but equally true is the case of scientists employed in GRLs. Thus, the claim that academic freedom is a principle that should apply to all scientists working in the GRL sector is nonsensical. Scientists employed in a GRL have to develop research activities that are consistent with the strategic goals and research agenda defined by GRL's management, which in turn has to report to the government. Of course, as in any 'good job' in industry and services, research jobs are characterised by high degrees of *autonomy* in the way the work is conducted. By definition, scientists who are highly qualified and have to undertake very complex tasks need to have a high level of autonomy. But this is not academic freedom, which has a larger scope and performative impact on the way academic researchers practice their profession.

3.3 Hybrid model of RU and GRL: does it work?

Any institution that is hybrid – taking some elements of each model – raises issues of efficiency.

The Centre National de la Recherche Scientifique (CNRS) in France is a typical example of an institution which is between the two models: it is not a RU because it is not a teaching institution, and it is not really a GRL because command and control governance and public accountability are rather loose and academic freedom dominates. CNRS scientists have no teaching obligations – they can teach of course, but such obligation is not part of the labour contract – but they fully benefit from academic freedom[10]. Subsequently, the fair balance between freedom and obligation is broken, and it is difficult to consider the incentive structures which are in place as efficient. CNRS was created to provide a small number of scientists with a professional research environment that the university was unable to offer – which was by this time a fine decision – but over time, it has become a very large organisation, covering all disciplines and employing about 11 400 scientists – which now makes it an institutional anomaly. What a country can afford at small scale (an elite group of scientists with no teaching obligation and full freedom to do research) becomes unaffordable as the researcher count increases. As written by Barba Navarett et al. (1998, p.8): *Institutions for the creation and transmission of knowledge emerge and evolve endogeneously. They change according to the type of knowledge they rule, the interests they serve and the return they generate…Yet, the dynamics of institutions has inherent market failures and it is not necessarily optimal in terms of social welfare. There are many cases where institutions have been negatively affected by vested interests both related to knowledge itself, or related more generally to the regulation of society.*

10 This institutional ambiguity or confusion is reflected in the way CNRS activities are captured in public research statistics. In the French statistical public research framework, the CNRS is considered a GRL. In Eurostat and OECD studies, it is categorised under higher education!.

In Aghion et al. (2009), other cases of institutional reforms are made, where the performance of public-sector research organisations is being adversely affected by the ''rent-protecting'' behaviour of agents with vested interests. These cases are especially strong when effective subunits are 'trapped' within a larger dysfunctional system, which is typically the case of CNRS.

3.4 The European public research landscape

As first-order policy guidance, two propositions can be derived from the framework presented above:

- First, because of the double externality feature of RUs, leading countries should try to keep the GRL sector as a small fraction of the whole public research system, giving to the RUs *la part du lion*;

- Second, the remaining small GRL sector should be subject to robust accountability and discipline principles so that the research which is undertaken is aligned with the national agenda dealing with various missions, and can deliver not only knowledge, but concrete solutions.

Let us now observe the current situation in the EU member countries. The table below provides an overview of the respective weight of RUs and GRLs in the national public R&D effort.

Table 6-1 Public funds allocated to Government Research Laboratories (GRLs) vs. Research Universities (RUs) *(billion EUR)*

Sector of performance / Countries	Total (business, GRL, RU,..)	Total public research sector	GRL	%	RU	%
Germany	34	31	14	45%	17	55%
France	18	14.5	5.5	38%	9	62%
Denmark*	2.6	2.5	0.25	10%	2.2	90%
Austria	4	3.2	0.7	22%	2.5	78%
Italy	9	8	3	37.5%	5	62.5%
Sweden	4	3.7	0.7	19%	3	81%
Ireland	0.8	0.6	0.1	16.5%	0.5	83.5%
Belgium	3	2.5	0.7	28%	1.8	72%
Spain	6.4	5.5	2.3	42%	3.2	58%
Portugal	1.2	1	0.1	10%	0.9	90%
Netherlands**					-	
Finland	2	1.7	0.4	23.5%	1.3	76.5%
Greece	1.1	1	0.5	50%	0.5	50%
Czechia	1.5	1.3	0.6	46%	0.7	54%
Hungary	0.8	0.5	0.2	40%	0.3	60%
Poland	3	2.3	0.1	4%	2.2	96%
EU 27	100	87	31	35.5%	56	64%
Norway	3.7	3.2	0.9	28%	2.3	72%
Japan	21	19.5	11	56.5%	8.5	43.5%
South Korea	17	12.4	7	56.5%	5.4	43.5%
Switzerland	6	5.12	0.2	4%	5.1	96%
Turkey	2.6	2	0.4	20%	1.6	80%
USA	135.5	96.7	56.1	58%	40.6	42%

Source: Eurostat (2021).

Note: The statistics above are based on Frascati classifications and definitions. It is obviously uneasy to separate teaching and research activities in the case of universities, as the same people (e.g. professors and other teaching personnel) are undertaking both tasks. The Frascati manual provides some guidance: all education and training of personnel are excluded from R&D. However, supervision of R&D projects for student qualification and performance of own R&D projects should be counted whenever possible as a part of R&D personnel and expenditure.

In column 2 (total = business, GRL, RUs and private non-profit), the numbers correspond to the total amount of public funding allocated to the full research system. In column 3 (total public research), the numbers correspond to the amount of public funding allocated to public research. Columns 4 to 7 shows the absolute public expenditures for GRL and RU respectively. The % are the share of funding allocated to RUs and GRLs as a % of the total amount allocated to public research (column 3).

* For Denmark – data source: 2019

** For the Netherlands – accounting issues.

The picture of national structures of the public research sector that emerges in Table 6-1 is one of enormous variance. Obviously it would not be very consistent to produce any normative rules against which one can measure how each country is fitting one unique best pattern. Initial conditions are different as well as the political and institutional structures, therefore diversity and heterogeneity among national models within the EU and beyond is perfectly understandable. However, as previously stated, a modern public research system should include a large RU system and a much smaller GRL sector. As a first approximation, a 70%-30% distribution could be roughly taken as a fairly sensible allocation principle. According to this principle, a few countries are clearly above this average of 70% share for their RU sector. Among the most prominent cases are Denmark, Sweden, Ireland, Poland, Austria, Portugal and Belgium within the EU, along with Switzerland, Norway and Turkey. In countries like Switzerland, Denmark or Poland, the GRL sector is, in quantitative terms, almost non-existent. It is also worth to note that EU average is at 64%. The countries that are systematically ranked very high in the various global innovation rankings such as Denmark, Sweden or Switzerland are those countries with the 'right' balance between RUs and GRLs[11].

France count numerous GRLs (26), including a few giants such as CEA (Commissariat à l'Energie Atomique), INSERM (Institut National de la Santé et de la Recherche Médicale) and CNRS. German GRLs include the Leibniz and Helmholtz networks of research centres, federal departments research centres, as well as the Fraunhofer (FhG) and the Max Planck (MPG) societies. FhG and MPG have clear 'special missions' (transfer of knowledge to industry in the first case, elite academic institution in the second case) which give them clear objectives, goals and metrics to measure performance. Both institutions are viewed as effective in undertaking these special missions (EFI, 2010).

France and Germany are the two European countries where the GRL aspect of the public research sector is rather high, followed by Italy and Spain; certainly too high according to the policy guidance as suggested above[12].

One question arising from Table 6-1 concerns the strategic and directionality capacities of countries that are characterised by a GRL sector, which is quantitatively negligible. What does it mean in regards to the capacity of these countries to conduct strategic R&I programmes? By design, in these countries, academic freedom is the general norm, and logically, the capacity of government to conduct strategic research is weakening. A recent policy discussion illustrates this point in Switzerland – a country that exhibits the highest share of public funding allocated to the RUs' sector: the executive manager of a platform ('the food centre'), established at the Ecole Polytechnique Fédérale de Lausanne (EPFL) to support research on the food transition, resigned while complaining about the fact that it was very hard to mobilise EPFL scientists to achieve food transition research objectives, and that he had no means to 're-direct' academic research towards the strategic topics of his centre. He concluded that, in a certain sense, 'academic freedom has perverse effects' – thereby conducting academic scientists to stay away from some research fields of strategic importance for the country[13].

11 The somewhat surprising numbers of the US case are due to two facts: firstly, the GRL sector is, indeed, very large; secondly, a significant part of the RU sector (including some of the best universities) is privately funded. Thus, the interpretation of the dominance of the GRL sector to explain R&I performance in the US case should be done in a very cautionary way.

12 It is also fair to say that countries characterised by a strong political and administrative culture of state centralisation and interventionism – such as France – have a natural tendency to develop a very robust and powerful GRL sector, which is then difficult to change.

13 Interview in the Swiss newspaper *Le Temps*, 08-01-2024.

The point is not to ask the countries with a very small GRL sector to change their model. It might, however, be more useful to consider how strategic research and directionalities can be better introduced in a system where RUs get the largest part of public resources. This point will be discussed below in section 5.

4. Directional adjustment costs

4.1 Freedom to experiment and autonomy as key ingredients of successful R&I

In the first place, it is always important to recall that bottom-up principles and freedom to experiment are fundamental ingredients for R&I success. This means that policies cannot simply decree the 'right' direction, and that trying to obtain it through the manipulation of incentives has a cost.

In science and fundamental research, academics are free to make their own production decisions. This is a fundamental principle. Empirical evidence shows that research grants awarded for projects (in predetermined areas) have a lower productivity than research grants awarded for people who are free to determine their research field, goal and method. In a path-breaking empirical study, Azoulay et al (2011) compare two groups of researchers. The scientists in the first group are supported by the Howard Hugues Medical Institute (HHMI), which gives the researchers great freedom to experiment and set their research agenda. The scientists in the second group are funded by the National Institutes for Health (NIH) and are subject to predefined deliverables; their degree of freedom and autonomy is therefore lower than for scientists belonging to the first group. They find that the scientists supported by HHMI produce high-impact articles at a higher rate than what is produced in the other group of similarly accomplished NIH-funded scientist. Here, it becomes clear that any R&I policy aiming at influencing directions comes with costs. Such costs have different origins.

4.2 Science inelasticity

Funding matters, and the allocation of more funding to specific fields can change the course of science. Gaulé and Murray (2011) take malaria research as a case study, and analyse the effect on an exogenous funding shock, which occurred due to NIH decisions to double of funding between 1999 and 2001, after a long period of steady but moderate growth. They find that the funding shock led to the entry of new people in the field of malaria research, and that scientists who entered during, or just after, the funding shock are significantly more productive than those who entered just before it.

Obviously, funding matters and can help to re-direct public research. But recent theoretical and empirical research shows also that science is inelastic, at least in the short run. This was initially highlighted by Paul Romer (2000), who showed clear implications on the complementarity between subsidising R&D and promoting the training of scientists and engineers to avoid any friction on the market for scientists. A few empirical papers go on to show that switching costs are high – in some cases so high that they are detrimental to any directional changes.

Myers (2019) is probably the first scholar to address the issue of switching costs through a systematic empirical analysis. He provides evidence based on an empirical study of targeted calls issued by the NIH. More precisely, he exploits the fact that the NIH quite regularly creates funds for one-time competitions, which request proposals on a predetermined topic (a specific disease or population, and/or methodologies). This funding mechanism is called 'Requests For Applications' (RFA). Designing and issuing multiple RFAs clearly show that the NIH believes it can steer researchers to certain topics and directions. Myers attempts to estimate how costly it is to operate this sort of migration of researchers towards determined topics. He finds that 'it is possible to induce scientists to shift their research focus, but incentivizing these redirections requires a substantial amount of funds'. Directional adjustments costs are high, which can explain that grants allocated to proposals responding to targeted calls are larger than grants allocated to proposals responding to non-directed call competitions.

Employing a different approach, Cook and Foray (2007) also address the elasticity of science. They present a study of an extreme case of a thematic grant scheme: the research agency of the Department of Education in the US decided to push strongly quantitative research and experiments based on randomised clinical trials (RCTs). The goal of the agency was that RCT-based approaches in education should increase from being <5 % of causal educational studies before 2002 to being 75 % just three years later. However, directional adjustment costs were so high within the field of educational research, where most researchers developed sociological analysis and case studies, that very few proposals were developed. The research agency was, thus, obliged to call for expertise from outside the field – contract research firms and researchers from public health.

4.3 The temptation of piloting science at a macro-level

If science is inelastic in the short term, policies can perhaps anticipate societal needs and plan structural changes in resource allocation among fields – providing more support to the fields which are critical for societal goals. Nathan Rosenberg (2009) documented and somewhat criticised the incredible increase of the NIH biomedical research expenditures that started around 1990, which led to the 2001 figure where federal R&D expenditures in US universities for life science counted for 58 % of the total of federal R&D expenditures in universities.

Drawing on such figures, scholars warn against the temptation of 'driving' science by piloting the system with frequent controlled variations in resource allocation among science domains: *The management of public science requires steady and balanced research budgets. First, research is an experimental, cumulative and interactive process, and it is very costly to adjust the level of effort over time. These large adjustment costs make multi-year funding horizons crucial. Second, there are strong complementarities among scientific fields, and these are hard to predict in advance* (Shankerman, 2009, p.125).

Paula Stephan (2012a) used the case of the 'NIH doubling' to warn against the idea that money is the answer to any problem – such as the problem of re-directing science towards socially desirable areas or objectives: *The doubling of the NIH budget from 1998 to 2003 triggered universities to hire more people and build more buildings, while scientists increased the number of grant's they submitted and the size of their labs. Now this biomedical machine needs increasing amounts of money to sustain itself, with calls for more funding* (p.31). And it seems likely that diminishing returns have set in (ibid.). Again, it is not easy and perhaps not without risk to make decisions about piloting and directing science towards specific areas – such as biomedical research in this case.

Lessons from all these works can be summarised as follows: in the short run, the efficiency of huge re-allocation of funding towards a specific scientific domain is limited, because only a subset of researchers have the right human capital to advance the knowledge frontier in the considered area. Moreover, the supply of adequate human capital both in terms of quality and quantity is very much inelastic in the short run. Human capital is not the only barrier: good research ideas may also be scarce. In a world of scarce ideas, increasing funding invariably leads to diminishing returns.

For these reasons, it is important to preserve a large measure of balance across fields, resisting any faddish focus on single scientific areas. This does not provide policy makers with detailed investment guidance – but it does provide caution and a longer range perspective than they may otherwise take.

5. Managing directionality in public research

We turn now to the specific issue of managing directionality in public research, taking into account the discussion thus far about the two different institutions that are ruled by different social contracts, and the existence of directional adjustment costs.

5.1 The Azoulay framework

Azoulay et al (2018) propose a framework to analyse how R&I can be 're-directed' according to strategic or societal goals. They use a two-dimensional table that deals with the source of idea generation (investigator initiation *vs.* mission-inspired solicitation) and the locus of control for project execution (investigator freedom *vs.* empowered programme staff). The two quadrants in the right column – where the source of idea generation is a thematic-inspired solicitation – are relevant for policies involving directionalities. In all these cases, a public agency or a foundation identifies a thematic priority's area, and issues a call for proposals within this area. The other dimension – locus of control – allows a clear distinction between the two logics of operation under the same directionality principle.

Table 6-2 Research management strategies

Idea generation Project execution	Investigator, scientist	Thematic-inspired solicitation
Investigator freedom	Competitive grant system	Directionality mode 1
Empowered programme staff	Venture capital	Directionality mode 2 (ARPA)

Source Azoulay et al. (2018) – modified

5.2 Mode 1: easy to implement, low cost… and low effect?

The first mode in Table 6-2 ('mode 1') is, in a sense, easy to implement: the agency predefines a priority area for R&I, issues a call and let researchers to explore freely this research area. Directional adjustment costs are thereby minimised because of large freedom and little oversight. It is easy to implement, but the capacity to drive a specific transformation or to achieve a specific (technological) solution is weak. This mode fits better the general objective of advancing any kind of knowledge within the considered specific area.

A good example is provided by Brodnik (2023), who presents the Vinnova's Challenge Driven Innovation Programme (CDI), in which directionality and flexibility are combined: *The program defines the overarching challenges that projects need to address, thereby providing long term orientation. At the same time the CDI leaves it up to the projects to define which solutions are required or which actors need to be involved thereby providing short term flexibility* (p.65).

Another point can be made under mode 1 on managing directionality in public research. Mancuso and Broström (2023) provide evidence on the so-called application effect. They address the issue of re-directing public research and provide evidence based on an empirical study of targeted calls issued by the Swedish Foundation for Strategic Research. The evidence they produce has implications on how to structure and manage a call. Indeed, they find that both winners and non-winners of the targeted call (e.g. the entire group of applicants) shift their research agenda towards the topics of the call, and that there is no difference between winners and non-winners in the type of shift that is produced. There is therefore what they call an *application effect* (instead of a *funding effect*), which clearly applies to mode 1 of managing directionality, and therefore needs to be considered by funding agencies.

Finally, mode 1 raises two potential issues.

Firstly, a specific risk arising from this mode is duplication and inefficiency when multiple agencies identify similar priority areas and don't coordinate their calls. Let's assume a country has three funding agencies – one more oriented towards academic research, another focusing on transfer of technologies, and a third that is a body of the ministry of energy. They are all interested in supporting R&I in renewable energy. Given poor coordination between them and little oversight about research activities, the risk of duplication is significant. Such situations happen in many countries.

Secondly, because of a low level of programme management, monitoring and oversight, this type of programme is not the best mechanism to deliver concrete solutions.

To summarise: mode 1 is a way of minimising DAC, is rather effective in advancing knowledge within a certain priority area, but is not the best way to generate concrete solutions or applications and entails high risk of duplication.

5.2 Mode 2: ARPA

The second mode ('mode 2') emphasises command and control mechanisms, which may imply high directional costs. It is much more demanding on the agency side, because empowered and proactive programme managers will be deeply involved in the design and the execution of any programme that is targeted towards very specific and precisely defined goals. In this sense, this mode better fits the goals of developing, for instance, a specific technology, or solving a specific problem.

Insights from the US experiences show that such top-down and centralised mechanisms – if properly designed – can be very effective in boosting some technological domains and achieving specific innovation targets. This is the story of the US ARPA model and its featuring principles, such as general organisational flexibility, bottom-up programme design, discretion in project selection, and active project management – all these features relying on highly talented, independent and empowered programme staff. As analysed in Azoulay et al. (2018), the ARPA model showed that:

- it is possible to *efficiently organise R&I around technology-related missions or a set of overarching goals*;
- it proved to be particularly optimal for *technological areas where technology exists, is relatively unexplored, and has great potential for improvement*;
- it is also useful to solve *friction on markets for ideas and technologies* in sectors where the path from idea to impact is extraordinary difficult (such as in energy, due to many obstacles such as large amount of capital for demonstration and scale up, strong infrastructure inertia, etc.).

A typical ARPA process involves the following stages:

- the ARPA board selects a broad thematic area and hires a high-standing potential programme manager from academia, industry or elsewhere in government for a period of three to five years;
- the programme manager has about one to two years to identify the specific target, design the programme and build a network of partners;
- they then pitch the programme to ARPA leadership and, if successful, launch several projects, monitor execution and make decisions about funding increases, or cut within the remaining period.

The deployment of the ARPA mechanism across sectors – first in defence (DARPA), then in energy (ARPA-E) and health (ARPA-H) (perhaps soon, as recommended by Rodrik [2022]), and lastly in production and digital technologies (ARPA-W) – shows the popularity of this instrument in the US. Some ARPA-like experiences are arising in Europe – for instance, in the UK – as well as at the EU level[14]. In Switzerland, the Swiss Science Council (2023) has recommended the design and implementation of an ARPA mechanism within innovation funding agency InnoSuisse. In a recent paper published by the RTD Chief economist and staff (Cavicchi et al., 2023), the argument for reinforcing effective directionality goes in the same direction.

There is, therefore, a buzz around ARPA, and this is certainly well-deserved. However, policy makers need to comprehensively understand two points:

- First, a true ARPA schema (located in the bottom-right quadrant of Table 6-2) obviously entails high DAC – the cost for a scientist to adjust their research agenda to fit the mission – generated by a significant decrease of freedom to experiment and decentralised initiatives. This is clearly a sharper issue here than in the first logic (top-right quadrant of Table 6-2).
- Second, empowered staff and programme managers of high standing and reputation is a boundary condition that might be difficult to fulfil in Europe. The US culture of *va et vient* between the public and the private sector for high-calibre scientists and managers is a strength. Some wage flexibility within the public administration is also key to propose attractive packages to top managers or scientists coming from private companies or top universities for a temporary three to five-year position in the public sector to manage an ARPA programme.

Observations of national policies within the EU generally conclude that there are a lot of initiatives which can be associated to the first mode – but almost none according to the second one. Although some country's specific programmes could be viewed as between the two logics (such as in the Netherlands or the UK), the picture is clear: countries have numerous instruments to advance knowledge in some important mission areas under a mode 1 logic, and they don't have many programmes to operate under within that of mode 2.

5.3 Why (and how) can RUs respond spontaneously to directionality?

Returning to our conceptual framework highlighting the two models – RUs and GRLs – the viability of governance solutions become obvious, and it is possible to minimise DAC while developing a public research system highly responsive to societal goals and challenges. A short illustration is presented below.

Let's start with the RUs. In observing the evolution of educational programmes and teaching topics in any European university, one can only stress that these universities have experienced remarkable evolutions in their teaching domains and research fields – while not being obliged to do so by any kind of top-down planning decisions of the concerned national ministries. These universities are simply capable of responding positively to societal needs, as they are expressed by their students!

14 The Joint European Disruptive Initiative (JEDI) presents itself as the European ARPA.

Looking at the Ecole Polytechnique Fédérale de Lausanne (EPFL) – but most universities in the EU are experiencing the same process[15] – thousands of students are hoping to attend Bachelors and Masters programmes in critical areas such as sustainability, environment or artificial intelligence and data sciences. EPFL has enough resources and leadership to be able to respond to such needs through the creation of new programmes in these areas. For these programmes to be taught, the university therefore needs to hire new professors in the concerned expertise areas, whereby these scientists will conduct their research and produce scientific knowledge within these areas. Thus, no top-down planning (or 'directionality mode 1' in the Azoulay framework) is needed for universities to concentrate resources and focus education and research in areas of strategic importance for society. It is, rather, enough for a university to listen to its students and respond positively to their demand through a bottom-up, decentralised process which fully respect academic freedom and does not generate high directional adjustment costs.

The only boundary condition is the level of resources, leadership and autonomy the university can enjoy to be able to transform its educational offer – and subsequently, its research agenda – to adapt the supply of teaching and knowledge to students' values, aspiration and needs, with the students being always the best 'messengers of society' for a university. Concretely, EPFL has created a dozen new programmes during the last ten years in the areas of sustainability and artificial intelligence, and has recruited more than 50 new professors to meet the new teaching needs[16].

Conditional to a sufficient level of resources, autonomy and leadership, an RU is well positioned to concentrate assets and activities in areas of high societal relevance. A question arising from this claim, however, is whether most of the research programmes labelled as 'directionality mode 1' are necessary. Perhaps the resources spent for these programmes would be used more efficiently if they were transferred directly to RUs, to increase their capacities to respond to their students' needs, and to build the relevant teaching and research programmes. They just need to know their students, listen to them, and respond to their new values and aspirations. When an RU is doing that, it becomes naturally and logically a key asset to help society overcome the Grand Challenges.

With a strong and powerful RU sector, many programmes located in the top-right quadrant of table 6-2 become redundant. The strategic goal of concentrating resources on thematic areas while preserving academic freedom can be almost entirely fulfilled by RUs at lower cost[17] and higher social returns because of the double-positive externality.

The same cannot be said regarding the capacities of RUs to manage and execute spontaneously ARPA-like programmes as per mode 2. These programmes, which are targeting very specific and concrete goals within a short period of time, are not easily executed in a spontaneous way within the RU system. High levels of coordination, oversight and monitoring, and high DAC require specific management and governance mechanisms, and hence specific agencies and instruments. By design, the GRL sector should always be a key resource in any country willing to deploy an ARPA-like policy.

15 EPFL is part of the Eurotech Alliance – including DTU, TUM, TU/e, Technion and Ecole Polytechnique Paris – which are all powerful higher education and R&I institutions. Of course, this is just an example of the many European universities that exemplify the model presented here.

16 Source: General Secretariat at EPFL.

17 There is no administrative cost to manage a mode 1 programme, and DACs are minimised given the newly recruited scientists match the fields of high societal relevance.

5.4 Research universities and the 'triple spillover' in the context of Grand Challenges

When Grand Challenges matter, powerful and autonomous RUs are well prepared to concentrate resources and focus research in areas of critical concern, and can thereby generate spillovers in terms of knowledge and human capital in the relevant areas of societal priorities. Empowering RUs to make them capable of responding to student demands by creating new programmes and recruiting new professors to teach in these programmes and conduct research in the corresponding areas is a priority.

In fact, when Grand Challenges matter, RUs generate a third type of spillover through international student flows. A vibrant campus of any European RU is a powerful mechanism for raising awareness and communicating a new narrative – for instance on climate change, sustainability, etc. – to students arriving from countries outside of Europe. By way of utopic example, a student coming from outside of Europe to make a chemical engineering degree may return in her home country four years later to launch a start-up in *green* biochemistry. However, the spillover mechanism is not about imposing some kind of green propaganda or teaching the doxa. It is just as much about student's socialisation within a great campus – through the coffee-shops, the student associations and the social events – as it is via the offer of relevant educational programmes[18].

RUs are, therefore, a precious asset for countries that are today under pressure to address various Grand Challenges. Because of this pressure, countries should allocate more resources to their RUs, which clearly need to have enough capacities, leadership and strategic autonomy to be able to re-direct teaching and research agendas in a decentralised and bottom-up fashion, and to maximise the triple-positive externality in the considered areas of societal relevance.

Regarding the GRL sector, a more administrative logic should apply. According to principles of planning and control, GRLs serve specific or 'special' missions which are determined by the government or its agencies. The problem here is one of how the tension between job autonomy (as distinct from academic freedom) and discipline is managed, how well the predetermined research objectives are met, and thus, how the key principles of public accountability and discipline apply.

18 Empirical evidence on the third spillover effect is missing, although a research project is currently in progress, titled 'Are student flows a source of knowledge spillovers for green technologies?' (Marino, M.).

6. Conclusion

This critical review was developed as a reminder of the fact that coining a new word such as 'directionality' in the area of innovation and research is not enough to see it working in practice. The opposite is the truth: science and innovation is very difficult to drive, and there are some risks involved in trying to do it. The importance of the emerging science and innovation policy research domain therefore becomes clear.

Overarchingly, this chapter discussed the issue of 'directionality' in relation to the public research system. It was also demonstrated that RUs are better suited to i) concentrating resources on strategic areas which matter for society (purely by responding in terms of teaching and hiring to student's needs and demands), and ii) producing a triple-spillover (education, research and rising awareness) in relation to these strategic areas. Conversely, a relatively small, transparent, and accountable GRL sector was held to be effective in responding to urgent technological policy needs, as well as to inform the fast paces demands of data-driven policy making.

Because of the great properties of the RU sector, the way countries are managing strategic research needs to be critically evaluated. According to the Azoulay framework as modelled through table 6-2, one mode of managing strategic research is easy to implement and minimises directional adjustment costs, but is likely to have a weak impact on the mission identified. In countries where the RU sector is operating well in terms of resources, leadership and autonomy, such programmes are in many cases superfluous. The other *modus operandi* – often identified with the ARPA US policy – is much harder to operationalise, and entails high directional adjustment costs. However, its potential impact is likely to be much higher when the foci of research objectives are about fast and rather precise technological achievements. Nevertheless, it is not easily managed in a system where academic freedom and decentralised decisions are the rules.

A set of recommendations for European countries could therefore be:

- to develop, improve and empower the RU sector;
- to keep the GRL sector as a small fraction of the public research funding, and reform it under strong principles of public accountability and discipline;
- to implement an ARPA agency when and where it is needed to improve the strategic arm of the government.

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CHAPTER 7

GREEN START-UPS

Hanna Hottenrott, Technical University of Munich (TUM)
and Leibniz Centre for European Economic Research (ZEW)

Abstract

New companies that lower the environmental damage associated with producing and consuming goods and services or that directly contribute to higher sustainability standards are crucial in the transition to a more environmentally-friendly economy. Green start-ups are, however, confronted with multiple challenges including the triple externality problem. By investing in greener solutions and by adopting more sustainable business practices, founders carry much of the costs and risks associated with the entrepreneurial activity. The social returns to their efforts, however, likely exceed the benefits that founders earn. This is also reflected in the findings on who founds green start-ups, where they locate, how they perform and how they are financed. This review presents key insights from the still small - but growing - stream of research on green start-ups. Given the characteristics of founders and their green start-ups, it also discusses implications for the public support of green start-ups and policy more generally.

1. Introduction

Given the increasing visibility of the consequences of climate change, governments have declared climate emergencies and society increasingly demands more decisive action toward environmental protection. The transition to a low-carbon economy and a more sustainable approach to economic activity has emerged as the primary solution to address the global environmental crisis. Hence more than 140 countries, encompassing approximately 90 % of global CO2 emissions, have already taken the step of announcing or contemplating net zero emissions targets by the year 2050. However, the attainment of these ambitious climate goals cannot be accomplished solely by scaling up existing technologies, such as renewable energy or current material recycling methods. Moreover, environmental disaster goes beyond climate change and includes pollution of the oceans and drinking water, as well as various pollutants in the air and soil. The real game-changer therefore lies in innovation: the generation and diffusion of ground-breaking ideas, products, processes and methodologies beyond individual sectors or applications. Thus, a crucial aspect of the green transition involves individuals and organisations embracing environmentally friendly practices, and pursuing radical and continuous innovation to develop sustainable solutions (Criscuolo and Menon, 2015).

Recent numbers show that companies affected by climate change are indeed more likely to introduce eco-innovations (Horbach and Rammer, 2022). This indicates that societal demand and policy initiatives are providing incentives for companies to react and innovate in environmentally relevant areas. While attention until very recently has been devoted almost exclusively to understanding the motivations, incentives and environmental efforts of established organisations (Brunnermeier and Cohen, 2003; Hottenrott and Rexhäuser, 2015; Aghion et al., 2016; Hottenrott et al., 2016; Horbach and Rammer, 2020), the spotlight is now turning to start-ups (Demierel et al., 2019; Kuckertz et al., 2019; Goldstein et al., 2020; Chapman and Hottenrott, 2022).

Green start-ups have the potential to play a crucial role in facilitating the transition to a low-carbon future. Identifying green start-ups is, however, a challenge as well as a matter of definition. In general, green start-ups can be defined as newly established companies that offer products or services with environmental benefits. While this definition is already quite comprehensive, it does not sufficiently incorporate business practices and processes within the companies that are more sustainable than current standards (Trapp and Kanbach, 2021). Thus, expanding the definition of what makes a start-up green to include all new companies that significantly reduce the negative impact of any business activity on the climate and the environment more generally seems plausible (Saari and Joensuu-Salo, 2020; Chapman and Hottenrott, 2022). Some studies propose a more narrow definition related to emission reduction or certain 'clean tech' applications (see e.g. Bjornali and Ellingsen, 2014; Leendertse et al., 2020; Goldstein et al., 2020). Since environmentally friendly products and process innovations also typically impact emissions directly and indirectly, the broader definition aligns well with the narrower one, even though some of the environmental benefits may not be directly related to emissions. When trying to detect and study green companies, the empirical literature has mainly relied on measuring green innovation using either survey data (such as from the Community Innovation Surveys) or information from patents. In the latter case, businesses that file patent applications that are classified as green, according to international classification schemes (such as the WIPO Green Inventory, the OECD EnvTech and the ECLA Y02 class) are regarded as green while others are 'grey' or even 'brown'. One challenge with this approach in the case of start-ups is that they are typically not part of the sampling population of larger-scale surveys, such as the CIS; also, nascent companies typically do not yet hold patent portfolios that are comprehensive enough for a detailed analysis, they have not yet filed patent applications or they do not patent at all. Especially in the case of fledgling companies in some service-oriented or digital sectors, an analysis of patenting may be less meaningful than in high-tech sectors for measuring the green orientation of companies. Using text-based indicators derived from companies' websites may provide a useful additional indicator for the detection of young, green businesses.

For a better assessment of the role of green start-ups in the transformation to a more sustainable economy, it is crucial to understand how and where they emerge, how they develop and how their impact can be evaluated. Understanding these factors will enable the design of ecosystems and policy frameworks that are conducive to the birth and development of young green companies.

The goal of this chapter is, therefore, to provide a focused overview of research on green start-ups with regard to three main questions:

- What makes start-ups green and what are the central challenges they face?
- Who creates green start-ups and how do they perform?
- How can innovation and entrepreneurship policy support green start-ups?

Relevant articles for this review were collected until January 2024 and include peer-reviewed journal articles, discussion papers and policy reports. Articles have been screened for quality and compatibility before being included in the overview with a focus on more recent studies. The review, therefore, does not claim completeness or geographic coverage. The term 'start-up' used here implies that founders pursue the goal to grow the business in terms of sales and employees if possible. This definition is applied to new independent ventures as well as corporate spin-offs. However, the focus of this essay is clearly on the former. Some of the entrepreneurs may have substantial experience from their previous business formation activity or their previous employment. The terms entrepreneur and founder are used interchangeably.

2. The role of green start-ups in the green transition

Young green companies likely play an essential role as they develop and introduce new products and services or implement more sustainable ways of offering existing ones. Similar to innovation in general, new green, innovative companies benefit from a lower path dependency compared to established businesses. This allows them to adopt more radical approaches without facing the dilemma of giving up profits in 'dirtier' products and services (Bendig et al., 2022). Moreover, in young organisations, the resistance to change within the company tends to be significantly lower, allowing decision-makers to pursue more radical approaches (Harris and Ogbonna, 1998; Young, 2000).

Besides their direct role in green innovation, green start-ups can promote the adoption of environmental technologies by established companies with less sustainable business models by providing a 'proof of concept' and by creating pressure to innovate (Hall et al., 2010; Cojoianu et al., 2021; Bendig et al., 2022). If successful, they may also set new environmental standards, which are subsequently demanded by customers. These factors contribute to the special role that new companies play in the development and diffusion of green innovations, and explain the high expectations of policymakers and environmentalists.

Yet, despite the recent increase in the emergence of green start-ups (Fichter et al., 2023), it is still only a small fraction of new businesses that can be classified as green (Goldstein et al., 2020; Chapman and Hottenrott, 2022), pointing to some factors that hold entrepreneurs back from starting new companies offering greener products or pursuing more environmentally friendly business models.

From what we know based on economic research, there are at least two important factors that may hold back the rise of a new green business wave. The first relates to the double externality problem (Popp et al., 2009) that has long been discussed in the context of green innovation and which may apply, especially to young companies: being confronted with externalities related to environmental research and development (R&D), i.e. not all the returns of such R&D will be appropriated by the investing company, implying that the private return on investment is likely to be smaller than the societal one (Hottenrott and Rexhäuser, 2015). Thus, there is a positive externality from the innovation the environmental innovation to society. At the same time, green start-ups generate positive externalities related to the reduced adverse environmental impact, which the founders or owners are typically not compensated for via the prices of their products and services. Greater greenness at the expense of higher costs of production or service provision through abatement and careful resource use may result in benefits for the end-user and the environment. Yet it is not self-evident that the benefiters have a higher willingness to pay. Besides these challenges that relate to the 'green side', founders are also likely to face the typical problems related to the liability of newness that results in financing challenges and the need to build a brand and reputation, as well as the challenges of building a functioning organisation (Stinchcombe, 1965). This constitutes a second externality. Importantly, in the case of green start-ups there exists a third positive externality. It results from the pressure to innovate that their activities have on established companies. This way start-ups contribute to the overall creation of innovation in the economy as well as the diffusion of green technologies beyond their own organisation. Yet this diffusion may also result in larger corporations adopting green innovations fast(er) and with economies of scale and scope, hence overtaking the green start-ups' products and services. Hence, in the context of green start-ups, it is a 'triple externality problem' that affects incentives of founders. Anticipating such developments, it lowers entrepreneurs' incentives to invest time, money and effort in the formation of green start-ups as much of the returns to their efforts will be entrepreneurs will be appropriated by others. It may also lower the willingness of investors to invest in the scaling of such ventures.

Thus, while on the one hand we can expect that new companies have a comparative advantage in developing novel and greener approaches as they are less path-dependent and less entrenched in existing solutions, they are also confronted with financing constraints, a limited track record in supplier and customer relationships, and business model uncertainty (Hottenrott et al., 2018). Moreover, market and regulatory uncertainty also play important roles in the incentives to found green start-ups – as well as from an investor's perspective to invest in one. Finally, while competition may drive green innovation in a race for the conscious consumers, it may also imply market exits for younger companies that fail to successfully compete against companies that, because of their size and market reach, leverage the innovation or technology more efficiently.

Despite these challenges, we do see an increasing number of green start-ups in Europe (Fichter et al., 2023) as well as rising investment volumes in green technology (Inderst et al., 2012; Fichter et al., 2023). In addition, a larger share of (new) jobs can be classified as green (Janser, 2018). Cohen and Winn (2007) indeed argue that the more pressing environmental concerns will be, the larger the opportunities for entrepreneurs to earn returns, while at the same time serving the green purpose. They argue that there is not necessarily a trade-off between private profitability of a business and its environmental orientation or benefit. Instead, new opportunities arise from the challenge to overcome existing solutions. As existing practices may become obsolete or increasingly irresponsible, entrepreneurs may spot these opportunities and replace harmful practices with more sustainable ones and thereby reap the benefits.

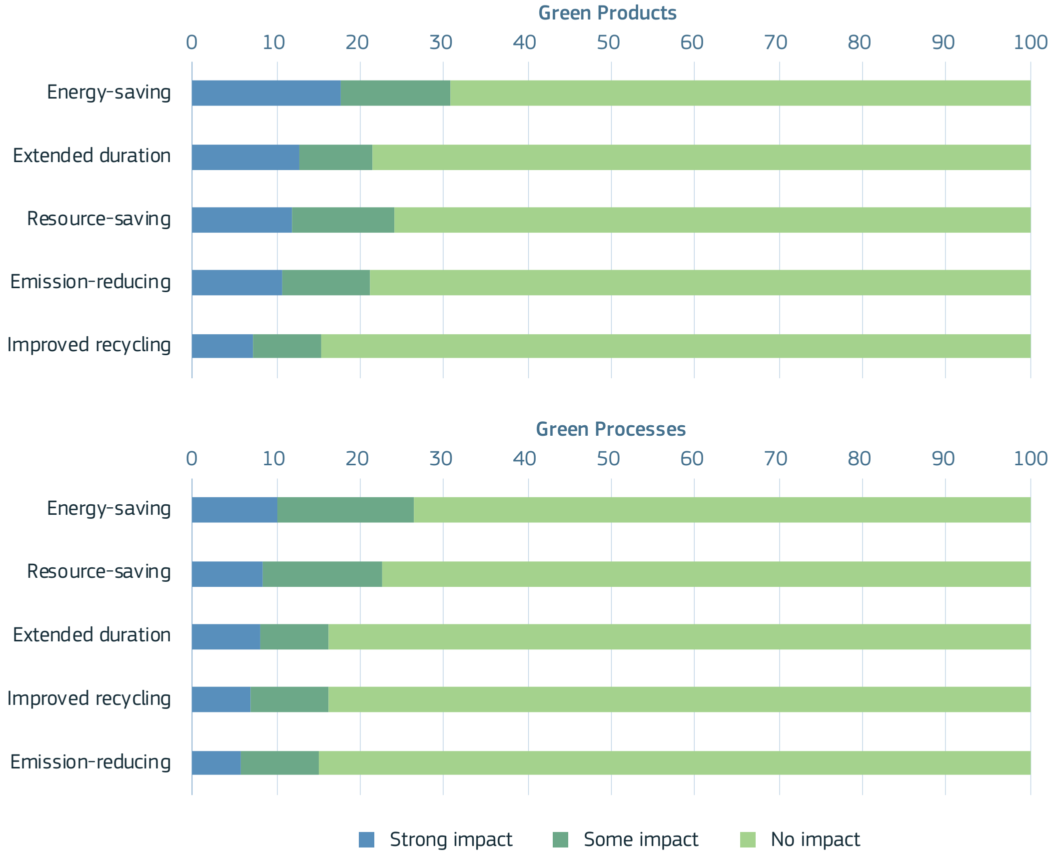
This shows that understanding the factors that drive green start-up formations is crucial due to the potential societal benefits they create. However, the intrinsic motivations of founders and the external drivers that facilitate green start-ups seem complex, and the factors that play a role are likely different from other entrepreneurial ventures. In addition, identifying the benefits of start-ups' green engagement (Ambec and Lanoie, 2008) that go beyond the immediate effects on the environment, i.e. in terms of classical business performance, is relevant for understanding the persistence of the rise in green start-ups and their sustainability in the longer term. Exploring potential hampering factors in the birth and development, as well as strategies that support green start-ups in overcoming barriers, appears, moreover, crucial for the design of environmental policies (Cojoianu et al., 2021) and start-up support programmes (Hottenrott and Richstein, 2020; Zhao and Ziedonis, 2020).

3. What makes start-ups green and who founds them?

New companies can be characterised as green-based on multiple dimensions. One way to categorise greenness is to differentiate between 1) products and their environmental impact when consumers use them, and 2) green processes and business practices that the start-ups engage in. For both the measurement is relative to current standards of sustainability and how high the environmental impact of the product or process is on either the consumer's or the company's side.

Data from more than 5 000 start-ups founded between 2011 and 2017 in Germany were analysed in Chapman and Hottenrott (2022) along these two dimensions. The information had been collected as part of the IAB-ZEW Start-up Panel, which was based on structured, computer-aided telephone interviews. The responses to a set of questions related to the greenness of their businesses shows that there is considerable variation between a) the extent to which start-ups provide green products or b) engage in green business activities. Figure 1 summarises the responses to the 10 survey items along the dimension of greenness and whether they are related to products (left) or internal processes (right). The most frequently reported dimension of greenness is related to energy-saving properties, both on the side of consumers and within the company. Other resource-saving properties are also relatively common. However, within a company's own processes they play a larger role than reducing emissions, improving recycling or extending the duration of process innovations. When looking at start-up products, on the other hand, the resource-saving properties of new products seem relatively more important than improved recycling.

Figure 7-1 Share of start-ups reporting strong or some environmental impact from their products on the side of consumers (up) and from internal process innovations (down)



Science, research and innovation performance of the EU 2024

Source: see Chapman and Hottenrott (2022) for details on the survey and question design.

The figure above shows the share of businesses that report a strong impact in darker green, report some impact in lighter green, and show no impact in grey.

'Going green' in the context of established organisations has typically been explained by the cost-saving potential of resource-saving innovations (Rammer and Rexhäuser 2014), customer expectations or being driven by regulation (Hottenrott and Rexhäuser, 2015; Ambec and Lanoie, 2008; Porter and van der Linde, 1995). This is a pattern that can also be observed in the context of start-ups. The important role of consumers is reflected in the relative importance of products that are energy-saving, have a longer product life expectancy, or contribute to the saving of some resources other than energy. In line with the Porter hypothesis, which predicts that companies have incentives to go green if it is economically attractive, the data also shows that energy and resource-saving green-process innovations within the businesses is more frequent than those green activities for which the private returns are less clear (Ambec et al., 2013). The right-hand side of Figure 1 illustrates this with those green processes that likely have higher social than private returns as they are less frequent, i.e. those that reduce emissions or improve recycling. This pattern illustrates the private versus social returns to green innovation: where private returns are higher, the triple externality problem is less pressing and such activities are hence much more frequent. Overall, the survey, which reflects a representative sample of new businesses in Germany, illustrates that in all categories the share of businesses reporting green attributes hardly exceeds 30%, implying that green start-ups are the minority of new businesses and the vast majority are not green in any of these dimensions.

The question is, therefore, what characterises those founders who create green businesses? It is generally assumed that the objective decision-making processes of their founders drive the environmental engagement of companies, including start-ups. This approach involves founders objectively evaluating the value and obstacles associated with environmental engagement and making a decision based on this assessment. However, starting a new company involves a substantial amount of risk, especially when it is active in business segments that are not long established, and the more fundamental or radical the greener solution is compared to existing products and services. In these cases the uncertainty in terms of costs, consumer expectations and sales, as well as technology development and regulation, may be high. As outlined before, creating a green company may come with additional challenges (Pacheco et al., 2010), resulting in reduced incentives to start a business or severe hurdles for business expansion and hence environmental impact.

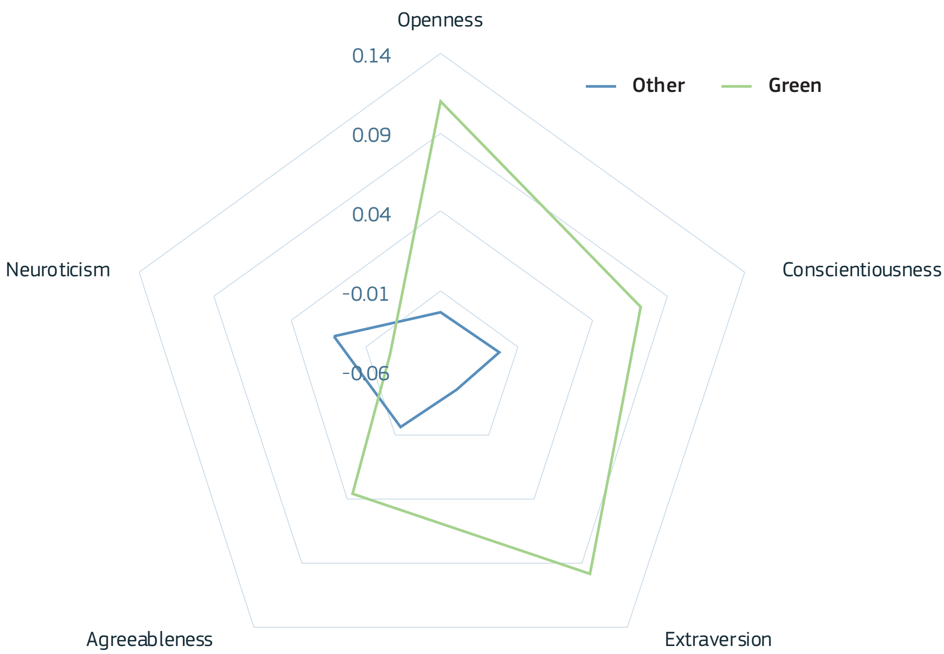
In new organisations, however, the business model itself may centre on environmental concerns, thereby addressing stakeholder expectation up front. These firms are 'born green' rather than 'turned green' (Demirel et al., 2019). Born-green start-ups are therefore likely to be different from previous generations of new innovative companies, with environmental goals driving their product design, operations and the market they serve (Criscuolo and Menon, 2015; Esty and Winston, 2009).

This implies that the emergence of a green start-up may be initially driven by its environmental motivation – either in terms of products or in terms of business processes and the design of its operations. Thus, the detection of a business opportunity that is greener than the established means of production, service provision or existing products may be central to the emergence of green start-ups. It seems likely, therefore, that green start-ups are founded based on different core values, which may impact market positioning and success as measured by conventional indicators. Moreover, in some markets, green start-ups co-exist and compete against established companies, thus stressing the role of consumer preferences and the degree of green innovation between established and younger companies.

When investigating founder characteristics, including both cognitive skills and personality traits appears plausible. Research in the fields of psychology and entrepreneurial personality indeed stresses the significant role that founder personality plays in predisposing them and their start-ups towards environmental engagement (Hirsh, 2010; Milfont and Sibley, 2012; Busic-Sontic et al., 2017). Specific combinations of personality traits can incline founders towards favouring the integration of green products and innovations in their start-ups, while other traits may lead to a less favourable disposition. One way of capturing an individual's baseline personality is looking at the well-established concept of the 'Big 5' personality traits: openness to experience, conscientiousness, extraversion, agreeableness and neuroticism (Brandstätter, 2011; Kerr et al., 2018). Thus, certain traits, such as openness to experience, conscientiousness and extraversion, may increase the likelihood that someone founds a green start-up due to differences in how these traits affect a person's perception of opportunities and threats related to the green opportunity. Scoring higher on these traits may also predispose someone to detect a green business opportunity (Chapman and Hottenrott, 2022).

In a study that analyses data for more than 5 000 independent, new businesses founded between 2011 and 2017, Chapman and Hottenrott (2022) show stark differences in these personality traits between founders of green versus other businesses while accounting for various other founder and firm characteristics. Figure 2 shows that all traits – except neuroticism – are much more pronounced in founders that started a business that is green in any of the dimensions discussed above (i.e. these firms perform above the sample mean for all items).

Figure 7-2 Personality traits of green start-up founders



Source: Predicted item scores from Chapman and Hottenrott (2022)

The striking differences in founder personality traits show that the decision to engage in environmental business activities is not solely driven by objective factors such as expected financial returns, but is also influenced by inherent founder characteristics. Consequently, even in cases where the benefits are recognised and barriers are minimised, founders with certain combinations of traits may still not steer their start-ups towards embracing greener products and innovations. On the other hand, it suggests that barriers to green activities may be perceived as differently binding depending on the individual founder characteristics. Personality traits may therefore contribute to how severe an entrepreneur perceives certain hurdles and constraints. The uncertainty may therefore be more or less discouraging, depending on the relevance that a person devotes to the factors that define the degree of uncertainty. Thus, the risks and returns to green business activity may be partially subjective, so we can conclude that within the same regulatory and business environment some people may pursue green business opportunities while others do not. While there are certainly some factors that can be assessed objectively, others may require a substantial amount of the founder's own judgement and taste. In the domain of green technology, such subjective assessment can be explained by several factors, such as the uncertainty and complexity of underlying technologies, the ambiguity in the assessment criteria depending on the time horizon and the lack of established evaluation frameworks for new technologies, and uncertainty in market demand and regulatory environment (Demirel and Parris, 2015; Petkova et al., 2014).

In summary, these insights suggest that founder personality traits are an important factor – outside the control of regulation and innovation policy – as those possessing different (combinations of) personality traits may respond differently to incentives, barriers or benefits, and thus different policy interventions or incentives may be needed across personality types. While in young, small businesses the influence of the founders is typically undisputed, it remains unclear whether these insights persist as start-ups develop and become more mature organisations. Some research, however, indicates that, including in established companies, the founder's impact is sustained through their effect on corporate culture, which is also a determinant of eco-innovation (Kiefer et al., 2019).

Besides baseline personality there are likely further motives that play a role. Research has long shown that preferences and experiences shape economic behaviour (Horbach and Jacob, 2018). Altruistic motives may also play a role in shaping a founder's mission to develop a business that positively or less negatively impacts the environment. This aspect further illustrated the soft boundaries between green entrepreneurship and social entrepreneurship (Saari and Joensuu-Salo, 2020; Neumann, 2022; Hörisch et al., 2017). Benefits for the environment or the reduction of adverse impacts could also be considered a social impact if they reduce harm in vulnerable regions or groups of people, plants or animals.

Moreover, it may not only be the personality of the founders that matters. Wealthier individuals may feel the desire to give something back to society and hence start companies where the profit motivation is secondary compared to the social mission. In other cases, it may be the founders who have the green idea and seek socially and environmentally oriented investors to support their business financially. Again, the mission to serve the environment with the business may be at least as important as the profitability of the company in such cases (Alt et al., 2023).

In some instances, however, green activities may be pursued for marketing and branding reasons rather than for the green purpose as such. While independent of the motive, the outcome of these activities is still green, showing that it's not only internal factors such as personality or preferences that play a role, but also outside factors such as market demands and norms that affect entrepreneurial incentives. Reacting to changing consumer needs and expectations can be a rational and profitable strategy, resulting in green start-ups that are not necessarily mission-driven or inspired by the founders' entrepreneurial preferences.

In this context it seems important to differentiate branding and 'green washing' from those entrepreneurial activities that have an actual positive environmental impact. Green washing would be considered in cases where the products are labelled as 'green' while, in fact, there is no such benefit for either the consumer or the business operation. In reaction to changing consumer demands, most companies have started to use eco-labels or marketing tools that stress the 'green' aspects of their products, even though the overall ecological footprint may not have changed over time. For start-ups without a product or service history, this comparison is harder to make. One extreme example of green washing in the domain of product packaging applied by several producers, including start-ups, was the introduction of bottles that appeared to be made from recycled paper. However, the paper packaging was only the outside shell of a conventional plastic bottle. The statement that the outside packaging was made from 100 % (recycled) paper was clearly misleading and consumer attention led to relatively quick detection.

Such attempts of green washing or even simply exaggerating the environmental benefits may therefore not be an ideal strategy to establish a new product or service. Ioannou et al. (2023) estimate that established companies that are perceived to be green washing experience a significant drop in their customer satisfaction scores. The impact of green washing on the performance of green start-ups is less well understood. It seems likely, however, that in a phase of trust and reputation-building, customers will punish green washing even harder, which can lead to a quick demise of the new business.

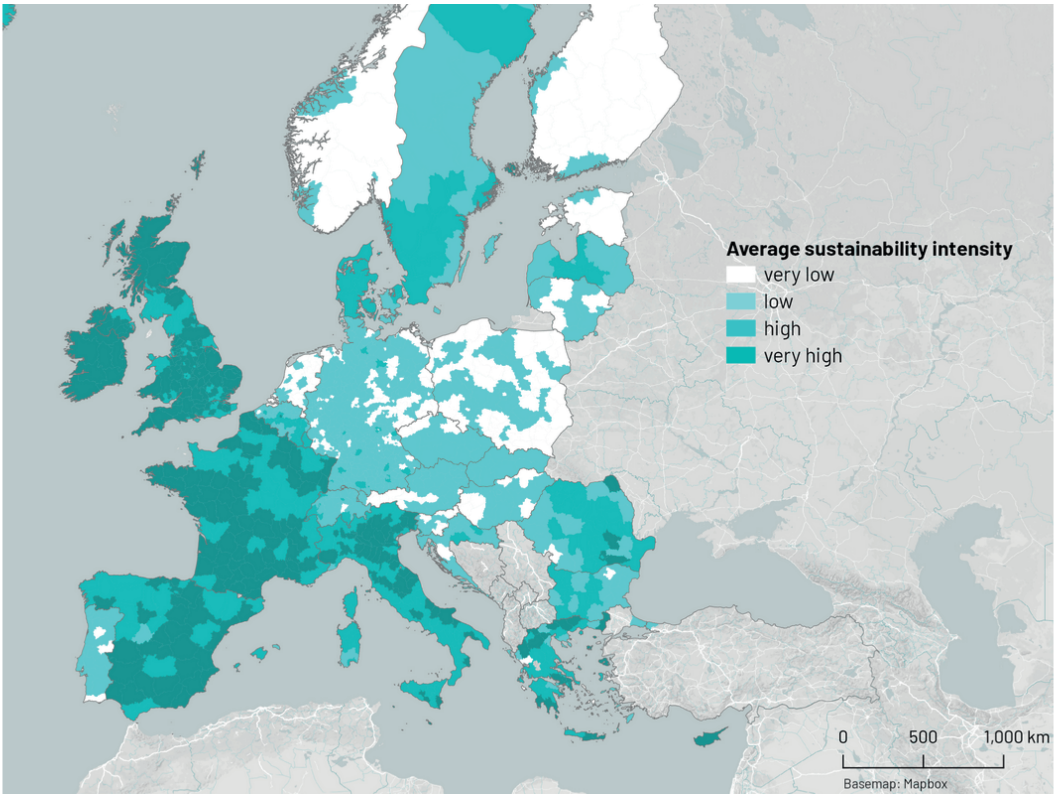
4. The geography of sustainable businesses

In some cases, laws and regulations can be considered strong external drivers of eco-innovations and more sustainable business practices (Hottenrott and Rexhäuser, 2015; Meng et al., 2020; Horbach and Rammer, 2020). In certain technology fields, by requiring thresholds for energy-use, recyclability or durability, entrepreneurs may be steered towards finding solutions for new products and services that fulfil the requirements. In the case of older, established companies, we know that regulation can indeed be an effective way of reducing negative environmental impacts directly (Aghion et al., 2016; Calel and Dechezleprêtre, 2016). For new companies, the evidence is less clear-cut. The results presented above suggest that consumer demand, climate change affectedness, and founders' own preferences play strong roles. In some areas such as energy or consumer products, regulation can indeed shift the relative attractiveness of investments substantially. In other areas, regulation – or more precisely regulatory uncertainty – could also render entrepreneurial action even more risky and increase the uncertainty about any return on investment, such that founders rather refrain from devoting money and other resources to such start-ups.

The regulatory environment typically depends on the location of a company and – hence – variation in green innovation can be a flection of differences in laws and regulation and set or reduce incentives. When looking at the geography of sustainable companies, we also see a strong regional variation in sustainability intensity, even across European regions. Figure 3 shows the average regional sustainability intensity as measured by the occurrence of terms related to green business practices on company websites relative to the entire website texts. Using website texts instead of patents for identifying green companies has its ups and downs. The main advantage is that it allows capturing green activities that are not inventions in the sense of intellectual property rights. As discussed before, most green activities may stem from improving existing products by making them more environmentally friendly or by providing greener solutions to established business practices. In some technology-based sectors, there can be a significant overlap between firms that are green in this sense and those that hold patents that can be classified as green (Goldstein et al., 2020). In other cases, however, such as in service or digital sectors, green activities can be essentially non-patentable (Kinne et al., 2024). Thus looking at websites enables capturing green companies even if they do not patent in green technologies, e.g. solar panel installation companies, or those that buy rather than make the green technology for the provision of a sustainable product or service, e.g. packaging companies that license the technology from the inventor. Comparing Figure 3, which is based on website-measured sustainability, to a map as presented in Figure 4, which reflects green patents, shows similarities as well as differences in the geographic scope of green activities. Website-based green activities are relatively stronger in Belgium, Ireland, Spain and regions in the southeast of Europe, areas that would have been under-measured in their relative importance using patents. Yet the map shows that regions with a high green patenting intensity also show a high sustainability score in the web-based data and vice versa, especially in Germany, Poland, the Netherlands and other regions in central Europe with high patenting intensity, where the average sustainability intensity is lower than what we would have expected based on patents. However, it needs to be acknowledged that the two measures are difficult to compare directly. The different geographic patterns, however, show that some of sustainable business activity is not captured using patents as an indicator of green innovation.

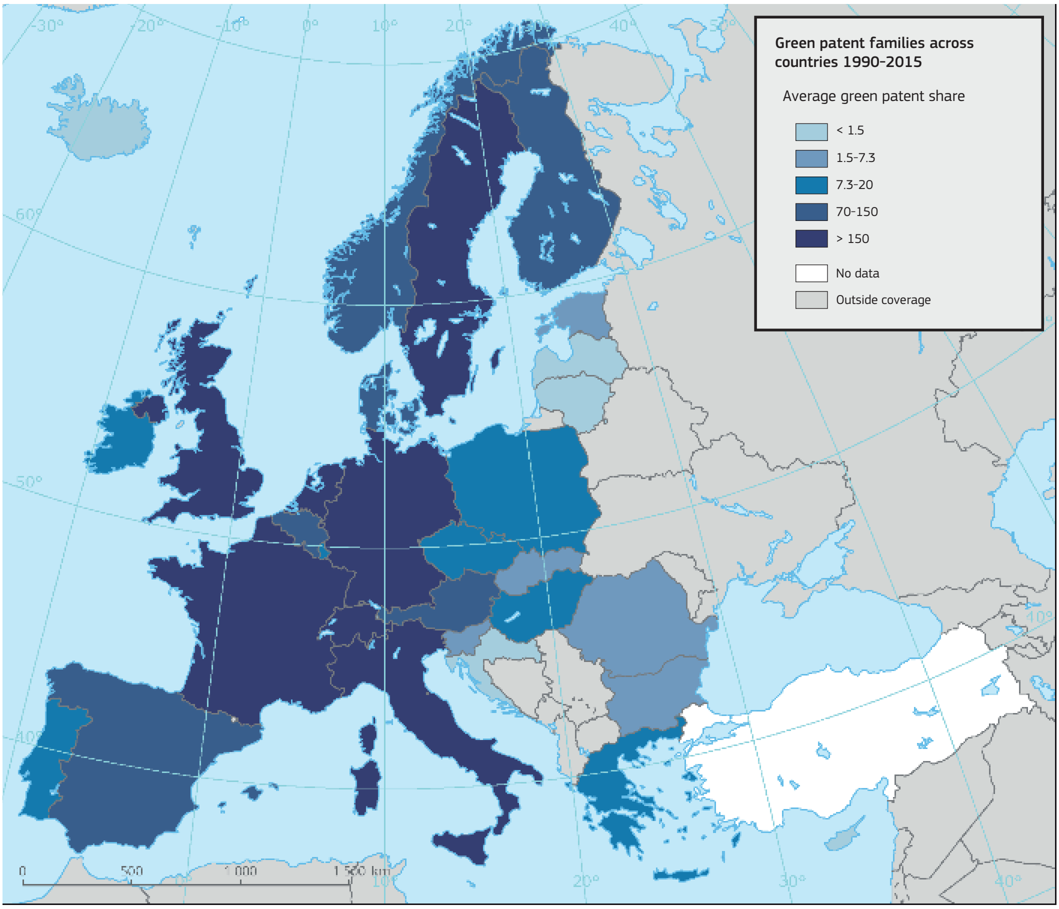
Moreover, a more fine-grained geographical analysis reveals substantial heterogeneity within regions. For example, Italy scores high to very high in both measures: the map presented in Figure 5 (at left) shows that much of the green activity in the Turin area happens outside of the city centre. To the contrary, in the area of Frankfurt and neighbouring counties (Figure 5, at right), we see a hotspot of high sustainability intensities in the downtown area, as well some districts further outside that show a high relative intensity.

Figure 7-3 Companies' sustainability scores across Europe



Source: Istari.ai, September 2023.
Note: measured based on company websites

Figure 7-4 Green patent families across Europe (1990-2015 averages)



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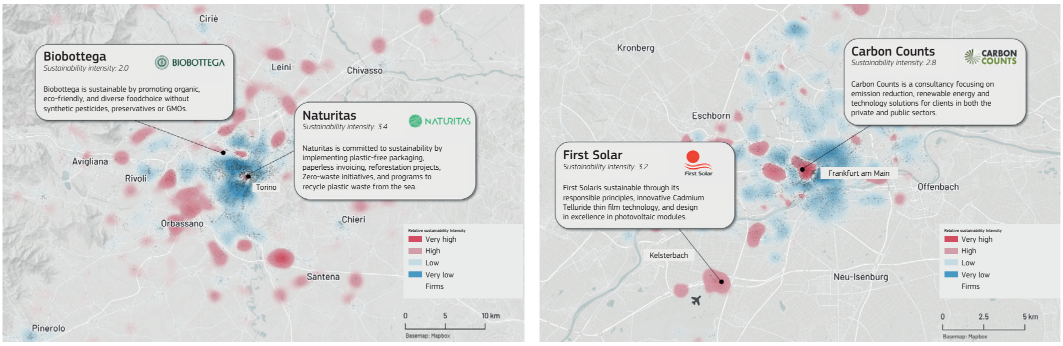
Source: European Environment Agency.
Note: measured based on company websites

Figure 7-5 Local sustainability scores of companies in the area of Turin, Italy (left) and Frankfurt, Germany (right)



Source: Istari.ai, September 2023.
Note: Measured based on company websites

The literature on environmentally friendly innovations provides useful insights on the role of local knowledge spillovers for the emergence of green businesses – or rather the introduction of green practices in the business sector more generally (Florida, 1996; Oltra and Saint-Jean, 2005; Rennings and Rammer, 2009; Zeppini and van den Bergh, 2011). Most recently, Horbach (2023) shows that the higher the existing stock of environmentally related patents in a region, the higher the probability that a start-up introduces eco-innovations. In line with this finding, Colombelli et al., (2021) illustrate that the birthplaces of green start-ups in Italy show higher levels of knowledge variety in terms of green and 'dirty' technology, which points to the relevance of diverse and heterogeneous knowledge sources for the development of green innovations. Thus, pure 'green clusters' may not be what we would expect based on these insights. Similarly, Kim et al. (2023) show that green-tech absorptive capacity and green-tech innovative capacity in a region both correlate with a higher number of new green-tech enterprises. The co-location of green hotspots and agglomerations of low-sustainable businesses in the two example regions as illustrated above underscore this argument. Research on the locations of blockchain companies in the US shows that blockchain-based companies are more likely to have sustainable applications if there are located on a local eco-system that allows them to have close ties with other sustainable companies (Kinne et al., 2024). This result indicates that green ideas may spill over from non-green to green companies, but also the other way around. If that was the case more generally, the impact of green start-ups may be even more important given their role as a multiplier in the diffusion of green innovations and their function as a driver of regional sustainability.

5. How do green start-ups perform?

Few studies have investigated the long-term performance of green(er) companies and very limited evidence exists for start-ups. Bjornali and Ellingsen (2014) reviewed the literature on the factors that affect the performance and growth of clean technology start-up firms, a definition of green start-ups that is slightly narrower than in other research. In their review they show that in the 13 articles that they have identified that most focus on external drivers of performance such as policy instrument and none of the studies has a design that would allow a causal link between greenness and performance. In fact, many of the studies ignore individual and firm-specific factors, e.g. characteristics of the clean-tech entrepreneurs and their teams, as well as their networks, that likely drive both greenness and performance.

A likely explanation for the scarcity of performance studies is that it constitutes a central challenge to distinguish correlation from causality. That means, a positive (or negative) correlation between green technology adoptions (or innovation) and company performance does not necessarily imply that the performance is caused by eco-innovation. For established companies we know that more profitable businesses have more slack to finance risky and ambitious projects, including non-environmental R&D and green innovations. Better performing companies may also be able to recruit different types of managers and certain kinds of employees, including those who are more forward-looking and care more about the environment. Identifying the causal impact of green technology or environmental business practices is therefore not straightforward and requires taking into account the timing of activities and addressing the endogeneity problem with econometric techniques.

Bjornali and Ellingsen (2014) also challenge the view that performance should be measured mainly in terms of the environmental and innovative performance of clean-tech start-ups. Instead, it should be measured using standard indicators, allowing conclusions regarding the 'triple bottom line', that is to measure performance using the traditional financial bottom line of a company, i.e. the financial profit, as well as by the company's social responsibility and the company's environmental responsibility. While the first measure is also related to innovativeness and firm growth, which are two standard performance indicators, the last two are rather qualitative in nature and may (or may not) correlate with the first. Some studies emerged after this review had been completed. Meyskens and Carsrud (2013), for example, study the partnership portfolio of 50 green-technology businesses and find that partnership diversity is positively related to venture development, i.e. whether a business plan will be turned into a start-up. This suggests that ecosystems that provide expertise and opportunities for partnering are better breeding grounds for green start-ups. Looking at facilitators within rather outside of companies, Hottenrott et al. (2016) studied the productivity implications of emission-reducing technology in SMEs and found that green innovation may come with a loss of productivity if not combined with organisational innovations that compensate for higher abatement to compliance costs. These insights also stress the need for analysing the performance effects of green innovation in combination with other factors, such as founder's skills, experience and managerial strategies.

While Hottenrott et al.'s (2016) study does not focus on new companies, Leendertse et al. (2020) investigate the performance of sustainable start-ups and document a trade-off between business performance and potential climate impact in the sense that lower business performance comes with higher potential climate performance. Their insights are based on detailed data from 197 international start-ups that participated in the Climate-KIC accelerator programme in the Netherlands, Germany, Austria, Switzerland and the Nordic countries (Denmark, Norway, Sweden and Finland) and were founded between 2012 and 2016. Their key finding corresponds to the idea that green activities are more attractive – and hence more frequently adopted – in areas where resource-saving also has some economic benefits and the gap between private and social returns is lower. In line with this, the authors also show that this trade-off is context-specific since start-ups can partly escape this pattern by focusing on novel and hardware technologies. In contrast to this, Neumann (2023) investigates the performance of green start-ups using Global Entrepreneurship Monitor data on more than 9 500 entrepreneurs from 51 countries, and shows that start-ups with a higher environmental orientation are of higher quality regarding their innovativeness, growth expectations and exports. These results hold at different entrepreneurial stages and across countries.

Goldstein et al. (2020) investigated short-to-medium term (5-10 years) outcomes, such as patenting activity, and business success (as measured by acquisition or initial public offering), survival and venture capital (VC)-raised start-ups that received funding by the US Advanced Research Projects Agency – Energy (ARPA-E) – in 2010. They find that ARPA-E's awardees produced significantly more patents than similar companies. However, while ARPA-E awardees performed better than rejected applicants in terms of their ability to attract VC investment post-award, the likelihood of surviving, of being acquired or going public, they had no advantage over the average similar clean tech company in these dimensions. Unfortunately, the study does not allow any conclusions to be drawn regarding the performance relative to non-clean tech ventures from the same cohort. The findings are nevertheless very useful for understanding barriers to green companies in gaining market traction.

What these existing studies have in common is the lack of a suitable comparison group for the performance assessment. Ideally, we would be able to compare the development of start-ups from the same cohort over time while distinguishing between green and other start-ups. Initial results based on data on start-ups from Germany that participated in the IAB/ZEW Start-up Panel show that there are hardly any performance differences between green (as measured based on the items presented in Figure 1) and other start-ups once the analysis accounts for founder, company and location characteristics. In this analysis sample, 34% of start-ups were classified as green based on above-average item scores (compare Figure 1). More precisely, firms in both groups perform similarly in terms of likelihoods of sales growth, profitability, exporting or failure. If anything, green companies do show slightly higher employee growth and a higher likelihood of exporting, but the latter difference is small and only weakly significant.

Table 7.1 Differences in performance for green start-ups (Average treatment effects after matching)

Outcome	Sample mean	ATE	Std. Err.	z	P > |z|
Sales growth	3.813	0.539	2.763	0.20	0.845
Employment growth	0.268	0.075	0.038	1.99	0.047
Profits (yes/no)	0.662	0.008	0.014	0.58	0.562
Exports (yes/no)	0.181	0.023	0.014	1.84	0.065
Failure	0.088	-0.001	0.009	-0.07	0.945

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Notes: n = 9.730 (unbalanced panel with firm-year observations). Covariates used in matching: years of industry experience, R&D expenditures, entrepreneurial experience, number of employees, gender distribution in founding team, founding motives, founders' academic education, average founder age, founder team size, industry affiliation, location characteristics, legal form, company age, risk tolerance and Big5 personality traits.

While it is not immediately evident that consumer preferences play a role in green start-up performance – as indicated by no differences in sales growth – the higher employee growth shows that being green may come with advantages in hiring. The (albeit weak) evidence for export orientation may suggest that the markets of green start-ups are less domestically orientated than that of other newly founded businesses.

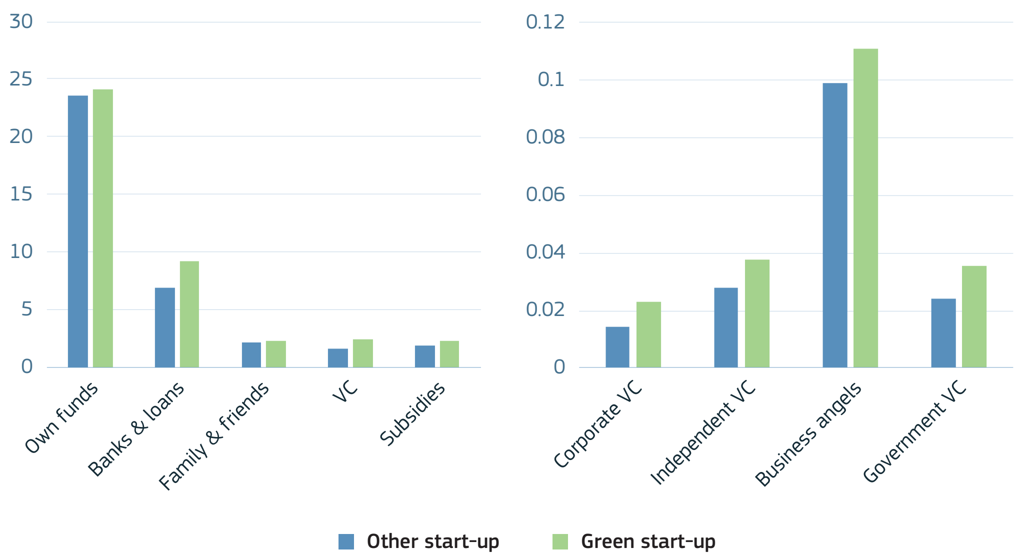
The finding that there are no significant performance differences between green start-ups and other new businesses when accounting for factors that drive green orientation in the first place can be considered good news. Importantly, there does not seem to be a performance penalty for being 'born green'. Thus, if we assume that there are at least some environmental benefits from the existence of these companies and the market introduction of their products, the triple bottom line is likely to be overall positive. The key question that remains unanswered is whether this insight is generalizable across different countries and degrees of greenness. Unfortunately, there is still too little research on the longer-term performance effects of green start-ups and their accumulated impact on emissions or pollution more generally.

Access to financing is generally considered a crucial driver of innovation and firm growth. However, analyses on the access for start-up and growth financing for green versus other start-ups are scarce. Descriptive analysis for start-ups that are part of the IAB-ZEW Start-Up Panel shows that there are indeed some differences in the financing structures between green and other start-ups, defined by whether they offer products that are green in any of the dimensions presented in Figure 1(a). While the patterns are comparable across groups, green companies have similar shares of own financing but higher shares of financing from banks. As one may expect given the recent focus of some policy programmes, they have a higher share of financing from public support programmes. In addition, the share of financing from venture capital investors is, on average, somewhat higher (Figure 6a). When looking more closely into the types of VC providers, we see that the nature of VC differs between green and other start-ups. The analysis based on the definition of green start-ups, as used by Chapman and

Hottenrott (2022) and the classification of investors by Berger and Hottenrott (2021), shows that business angels play a prominent role in the financing of green start-ups; government VC is also more often the source of financing in green start-ups when compared to other new companies (Figure 6b). This descriptive comparison does not account for any structural differences that could also explain differences in the use of financing. When controlling for various other drivers of access to certain types of financing in regression analyses, it turns out that the financing structures are generally not statistically significantly different for green versus other start-ups.

The analysis can, however, not distinguish between successful and unsuccessful attempts of raising financing from the difference sources. It also does not differentiate between the different dimensions of greenness and the degree to which the companies offer products that are more environmentally friendly. The crucial question that remains unanswered is therefore whether green start-ups face hurdles in the success rates of getting access to their desired source of financing and how a potential access penalty relates to the degree of greenness.

Figure 7-6 **Financing mix of green versus other start-ups**



Source: IAB-ZEW Start-Up Panel, September 2023 (pooled reference years 2011 to 2019), n = 7.003.

6. How can innovation and entrepreneurship policy support green start-ups?

One important factor that is typically stressed in the context of promoting start-ups from a policy perspective is the provision of seed funding through grants and subsidised loans (Hottenrott and Richstein, 2020; Zhao and Ziedonis, 2020; Berger and Hottenrott, 2021) or through the reduction of organisational or bureaucratic barriers to entry (Colombelli et al., 2020). It is unfortunately, by and large, unknown whether the share of green start-ups in Europe that received some form of public support differs to that of non-green new ventures. From an economic welfare point of view there are good arguments in favour of stronger policy support and specific, targeted programmes such as ARPA-E in the US, but also in favour of more general start-up support schemes. While there is an increasing number of policy initiatives at national levels to promote green start-ups in Europe as well, one challenge in designing such programmes is the definition of what counts as green. Most programmes therefore focus on green-tech, which comprises many relevant sectors but overlooks others. As discussed above, there are broader and narrower definitions. Applying a narrow definition favours start-ups in undeniably green sectors such as renewable energy or recycling. Such a definition, however, may neglect important areas where green innovation is crucial, such as in consumer products, logistics and transportation or construction.

Government support, however, likely plays a crucial role for green start-ups as it does for other entrepreneurship. Regulatory incentives (Berrone et al., 2013) and financial support can both drive and steer entrepreneurial actions. The analysis of green start-ups in Germany indeed illustrates the role played by start-up support programmes and government VC. Green public procurement may also play a role in drawing attention to public and private sector needs (Krieger and Zipperer, 2022). Green public procurement aims at procuring specific goods with lower detrimental effects on the environment throughout a product's life cycle when compared to other goods that serve the same primary function (European Parliament, 2008). In the procurement process, technical specifications can be defined during the different phases, which allows procurers to adjust to technological developments (Appolloni et al., 2019). Technical specifications may include environmental standards or performance requirements such as on a product's energy usage, the carbon footprint of a production process or the use of hazardous substances (European Commission, 2016). Finally, contract performance clauses regulate the monitoring possibilities of public authorities to examine the compliance of the selected awardees with regard to their guaranteed environmental performance. Results presented by Krieger and Zipperer (2022) indeed show that winning public procurement awards with additional environmental selection criteria increases the probability of a company to introduce new and more environmentally friendly products by 20 percentage points, on average. This can be interpreted as a direct impact from the procurement contract while there is no evidence that the company becomes more sustainable overall, which would be reflected in the implementation of more environmentally friendly processes. Given its direct impact, green public procurement is high on the policy agenda. It remains, however, unclear whether new firms react to such incentives in similar ways or whether green public procurement can even trigger new green start-ups. Füner and Krieger (2023) provide some first insights that this might indeed be the case and that procurement opportunities set incentives for green entrepreneurship.

Environmental regulation is moreover a direct lever for altering technology paths. It may be used to create incentives and markets for environmentally beneficial technologies (Gerlagh, 2008; Dechezleprêtre et al., 2011). Industrialised countries have more advanced environmental and climate regulations and some of these regulations have had an impact beyond the regulatory terrain. For example, vehicle emission regulations in the US led to technology sourcing from Japan and Germany (Lanjouw and Mody, 1996). Analyses by Dechezleprêtre et al. (2011) suggest that regulation in China may have spurred technology flows into the country that had some beneficial impact. In sum, however, the effectiveness of regulation in setting incentives for new firm creation is still unclear, especially in light of international competition and different regulatory regimes. Recent numbers, however, suggest that even the expectations about future regulation can incentivise entry as the surge in energy start-ups shows (Gottschalk and Hottenrott, 2024).

Considering environmental policies more generally, as one of the most comprehensive studies, Cojoianu et al. (2020) investigate how different types of environmental policies affect new firm formation in green (low carbon), brown (fossil fuel) and grey (unrelated to natural resources) technologies across 24 OECD countries. Their results show that that regional environmental knowledge is a key contributor to the creation of green start-ups. They also find evidence for positive externalities that these firms create because 'grey industries' also benefit from the improved availability of start-up financing in regions where new environmental knowledge is created. Another key result is that more stringent environmental policy regimes negatively impact the creation of new ventures overall, though the effect is stronger for new fossil fuel-based companies. However, while some policies appear to discourage entry, there seems to be a positive correlation between policy stringency and the availability of financing across sectors. In particular, feed-in-tariffs and emission standards are significantly and positively related to new regional green venture capital financing, across different investment stages and green sub-markets.

7. Implications and conclusion

Recognising the challenges and need for action to reduce the negative impacts of climate change is of central importance. Policies that promote incentives and provide support to overcome technological and market hurdles play a fundamental role. Achieving this goal has been high on the policy agenda for many years now (European Commission, 2005, 2011, 2012) and there is some evidence that green start-ups are becoming relevant agents in the transformation process.

The insight that the green transformation requires radical and fundamental innovations puts the spotlight on green start-ups that develop and introduce more innovations with environmental benefits and adopt more sustainable business practices. The evidence, however, also indicates that in order to increase the number and performance of green start-ups for a transition to a low carbon economy, the existing focus on influencing objective decision-making processes of founders alone might be insufficient. Instead, policymakers may need to account for the innate business climate that enables founders to successfully pursue their ideas. The multiple externalities related to green entrepreneurship require special attention to hurdles that prevent green ideas from being implemented. In addition, policymakers may be able to take advantage of helpful predispositions (e.g. high levels of openness and extraversion) by targeting support but may need to provide additional intervention and support to overcome the effects of the negative predispositions of other traits (e.g. high levels of neuroticism). Second, in an environment increasingly pushing organisations and start-ups to be green, founders and entrepreneurs need to be cognizant of the environmental implications of their personality traits, and potentially take steps to overcome the unhelpful environmental dispositions of traits like neuroticism.

The definition of green start-ups used throughout this chapter considers companies to be green if they offer environmentally friendly products or services that either directly benefit the environment or reduce negative impacts as compared to established products and services. This definition also comprises innovation on processes, company organisation and logistics, or other management practices (including human resources, finances, and sales). This relative broad definition allows the inclusion of start-ups into the definition without having to focus on specific technologies such as clean energy, materials or recycling, which may overlook more subtle green innovation in all other sectors.

In light of the need to transition entire economies toward more sustainable practices and outcomes, it seems important to incentivise green entrepreneurship across all sectors, including services and low-tech industries where the green potential may mainly lie in greener processes.

While the role of start-ups in the green transition is likely to be of fundamental importance, previous research, however, has mainly focused on green innovation in larger established corporations. There is also a substantial lack of studies that investigate 1) the causal impact of policy instruments and programmes on the formation of new green start-ups, 2) how being green is related to start-up performance, and 3) whether there are differences depending on the dimension or degree of 'greenness'. From a policy perspective, the missing insights on green start-ups are problematic as it remains unclear how they contribute to the invention and diffusion of different technologies, business practices or the spread of informal environmental standards. While there is a consensus on the role of start-ups in innovation more generally (Aghion and Howitt, 1992; Wennekers and Thurik, 1999; Carree and Thurik, 2003; Audretsch et al., 2006), we know little about whether and how this extends to green innovation in the form of new products, services and business practices.

In the upcoming decades, green start-ups could potentially be of even greater importance as a driver of sustainable regional development and regional employment dynamics (Fritsch and Schindele, 2011; Dejardin and Fritsch, 2011). Therefore, understanding the dynamics of the creation of green start-ups, their locations and international mobility is crucial for economic policy. Such ambitious initiatives call for larger-scale systematic studies of new green business creation across Europe and beyond.

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CHAPTER 8

TECHNOLOGY SOVEREIGNTY OF THE EU: NEEDS, CONCEPTS, PITFALLS AND WAYS FORWARD

Jakob EDLER

Fraunhofer Institute for Systems and Innovation Research ISI, Karlsruhe & Manchester Institute of Innovation Research, University of Manchester

Abstract

Technology sovereignty has become a major concern in science, technology and innovation policy debates in the last years. An intensive discussion has unfolded as to how countries and the EU should safeguard their abilities to produce and use the technologies needed, based on their own values and independent from unwanted foreign interference. The EU is lagging in a number of technologies, and is reliant on foreign input of knowledge, technological components and raw material. At the same time, it has been a long-held principle to work towards ever more openness, in particular for science, technology and innovation. Against this background, the chapter aims to shed some light on the specific challenges and opportunities related to technology sovereignty faced at EU level, delving into the conceptual underpinning of the concept and its link with open strategic autonomy and economic security, and current approaches adopted to determine the EU's sovereignty position. The chapter concludes with a number of considerations towards an effective and efficient technology sovereignty strategy at EU level.

1. Introduction

Technology sovereignty has become a major concern in science, technology and innovation (STI) policy debates in recent years. In small and big countries alike and, in particular, at European level, the idea has taken hold that responsible STI – and indeed industrial – policy needs to take into consideration how vulnerable systems are in terms of the ability to make available technologies regarded as critical. Of course, it has always been the duty of governments to ensure availability of core technologies, as technological innovation and capabilities are regarded as major determinants of economic competitiveness and welfare more generally. However, both the COVID-19 pandemic and, more importantly, a number of geopolitical developments in the last 10 years have triggered a new awareness and brought technology sovereignty to the top of policy agendas.

The COVID-19 reaction of Member States and the EU has shown two aspects. First, many countries were not able to secure all necessary medical equipment themselves and experienced shortages in times of acute crises. Second, as a reaction, in the first weeks of the acute crisis we saw a rather nationally orientated crisis reaction with limited flow of equipment and medical products across borders. Even if those developments were reversed quickly, they triggered a renewed awareness as to the vulnerability of support chains even within Europe (Darnis, 2020).

Furthermore, a few major geopolitical developments challenged the notion of international division of labour. First, the trust in the reliability of open exchange in the highly integrated world of the north-western hemisphere has been damaged. The Presidency of Donald Trump and his America First campaign have challenged the trans-Atlantic relationship. The potential for future disruptions may grow through strong political initiatives such as the Inflation Reduction Act, which may lead to the relocation of technological capabilities to the US, broadening the corridor of dependencies should a more protectionist administration return to power in 2024. In addition, Brexit has reminded us about the vulnerability of the internal market. Both developments have been particularly challenging, as these countries have been enormously reliable technological partners and are host to leading edge science in many fields. Second, and more important still, the relationship with China has been characterised by decreasing levels of trust and a development towards system competition and strategies of de-coupling or de-risking. As China is in the process of becoming a scientific superpower, and consequently a future technological superpower, and at the same time is still a major market for technology from western democracies, the question as to how the exchange of technologies with China will and should develop is at the top of geopolitical and STI agendas (Kroll and Frietsch, 2022). De-coupling and de-risking strategies, particularly with China, are now being intensively discussed and in parts implemented (Schüller and Schüler-Zhou, 2020; European Union Chamber of Commerce in China and Merics, 2020). Finally, the war in Ukraine and the conflict in the Middle East have put further pressure on the free exchange of technologies and scientific collaboration that had become the norm after the fall of the Berlin Wall. The global political debate around these conflicts has further demonstrated that the world is about to become a much more multipolar system, with a few strong, progressively self-confident actors (Münkler 2023). It is increasingly unclear what this global reorientation will mean for international technological cooperation and trade. We may find ourselves in a world of new trade and cooperation walls around different geopolitical camps in the future. What we know already, though, is that the world has become more unpredictable, and that concerns over technology sovereignty are here to stay.

Against this background, an intensive debate has unfolded as to how countries and the EU should safeguard their abilities to produce and use the technologies needed, based on their own values and independent from unwanted foreign interference. This is, normatively and conceptually, different from the traditional discourse on technological competitiveness. The EU as a whole is lagging behind in a number of technologies and reliant on foreign input of knowledge, technological components or raw material. At the same time, it has been a long-held principle to work towards ever more openness, in particular for science, technology and innovation. It was the European Commission not long ago that focused its entire STI strategy on three dimensions of openness (Soete and Burgelman, 2023), stressing and embracing the value of international cooperation, division of labour and exchange. This new focus of STI policy on sovereignty, of course, produces a number of tensions with long-held principles of free exchange and collaboration in STI, international division of labour and international trade as major drivers of welfare. Governments increasingly face a need to navigate this tension between technology sovereignty and openness in STI carefully. In particular, for the EU and at EU level, the challenges are tangible. With its internal market and high level of techno-scientific integration, Europe holds, in principle, a strong position. The EU is characterised by immense complementarities in terms of technological competencies between its Members States, which can be mobilised to ensure leading-edge production of new technologies in many areas.

Those developments now pose a series of challenges and pressing questions: What is the most effective strategy to safeguard technology sovereignty on the one hand, and to maximise the benefits from open exchange in STI on the other? What is the best way to navigate the different kinds of tensions between sovereignty and openness playing out in different dimensions of science, technology, innovation and the production of technologies? How should access to technologies from outside Europe and production of technologies within Europe be balanced? How can it be ensured that the question for technology sovereignty does not lead to a race to ever more protectionism and self-reliance? It is the aim of this chapter to shed some light on the specific technology sovereignty challenges of the EU and at EU level and on the conditions of the continent to face the challenges ahead, and on that basis to critically comment on current strategies at EU level.

The chapter is structured as follows. The next section will summarise and qualify the conceptual underpinning of technology sovereignty. Its focus is on the discourse in Europe and the tensions of the concept with other current concepts such as the Open Strategic Autonomy and economic security, and the possible pitfalls of technology sovereignty approaches at EU level. Section three will then discuss the status quo, both in terms of the approaches suggested to actually determine the sovereignty position, and the actual empirical findings as to where Europe stands. Section four will discuss the specific conditions in Europe and at European level, both those that support and those that challenge a strong sovereignty policy. The final section will critically assess European strategies and suggest a number of core principles for a future policy approach that navigates the multiple tensions.

2. Conceptual underpinning and tensions at EU level

2.1 Taking technology sovereignty seriously

For a concept like technology sovereignty to be meaningful, there must be a clear distinctive added value. This added value needs to stem from a clear differentiation to earlier approaches, as well as to neighbouring concepts that are being discussed and put forward at European level. While a certain level of ambiguity around policy-relevant concepts can be highly functional, e.g. in terms of leaving space for idiosyncrasies and negotiations (Edler and James, 2015), there needs to be a sufficient level of joint understanding as to the additional opportunities and challenges of any new concept. Thus, if for technology sovereignty this conceptual additionality is not given at European level, the debate and implementation of technology sovereignty strategies might be ineffective, confusing or even counterproductive. Thus, we need to take a short look at the definition and at the delineation to earlier concepts, such as technological competitiveness and key enabling technologies (KETs), before technology sovereignty is discussed in the context of broader autonomy and security concerns at European level.

There is no single, widely shared definition of technology sovereignty across Europe. However, the definitions put forward in the European debate, in particular when European technology sovereignty is analysed, have at their core the ability – and competences – of a system to have reliable access to a technology it deems critical for its own system, without any structural, uncontrollable dependency from third countries (Di Girolamo et al., 2023; Kroll et al., 2023; Edler et al., 2020; Da Ponte et al., 2023; March and Schieferdecker, 2023). Where definitions and approaches differ is the extent to which the access to a technology now and in the future encompasses the need for actual production capabilities within the system. In some broader approaches, it is about the ability of the system to actually produce the technology itself, and in doing so gain economic benefit and independence, as well as retaining the opportunity to influence the future development of a technology (e.g. European Parliamentary Research Service, 2021; Archibugi and Mariella, 2021).[1]

Another, more narrow viewpoint is less focused on the production capabilities. In this perspective, there is a stronger acknowledgement of the division of labour globally and the effectiveness through taking advantage of comparative advantages in different systems. Here, the focus is much more on making sure that the system has access to the technologies and is not structurally dependent on other systems in ways that can barely be managed. In this perspective, it is of critical importance to identify redundancies and complementarities with international partners and establish trusted relationships with them (e.g. Edler et al., 2023; Kroll et al., 2023; Di Girolamo et al., 2023).

A further differentiation one needs to keep in mind is the focus on technology. It is important to understand that the concept of technology sovereignty focuses exclusively on technologies; it has to do with the access

1 The European Parliamentary Research services define European technological sovereignty as 'the ability for Europe to develop, provide, protect, and retain critical technologies required for the welfare of European citizens and prosperity of businesses, and the ability to act and decide independently in a globalised environment'. European Parliamentary Research Service, 2021, p. 3.

to and use of technologies. It is distinct from products, in which technologies are embedded, and it is far less broad than innovation or economic sovereignty (Beckert et al., 2021; Edler et al., 2023; Kroll et al., 2023) or even strategic autonomy (Rühlig, 2023). Innovation and economic sovereignty are broader and encompass the conditions with which a technology is mobilised for innovation and economic added value, thus considering broader ecosystems rather than the availability of or access to technological competencies and capacities as such.

In European debates, the various perspectives – the narrow one focusing exclusively on the technology and the broader one including the production and entire ecosystems required – are used in a rather unsystematic way. This, however, runs the risk that the *specific* challenges for technology sovereignty are not taken seriously enough, and analyses of technology sovereignty end up being traditional analyses of technological competitiveness (see for a discussion e.g. Crespi et al., (2021)).

A short look at the history of KETs shows the differences between technology sovereignty considerations and technological competitiveness approaches, which has a number of important implications. The strategies around KETs, starting in the late 2000s, have also been about choosing technologies that are critical across the board of sectors and determine the future competitiveness of Europe (European Commission, 2009, 2012, 2018; Herlitschka, 2023). The ambition was and is to be able to produce technologies that are regarded as dominating the high-tech competition of the future and, thus, to make sure Europe can realise the main value added for those technologies. The technology sovereignty debate has a different, broader claim. It is about enabling Europe to be agent of its own technological destiny and with it its own value and societal choices. Importantly, it is also functionally broader. It is geared towards access not only to ensure economic benefit and competitiveness, but also to ensure the state can deliver on its core functions and societies can accelerate the transformations they seek using the technologies needed, in line with the ethical standards defined in Europe. Consequently, a Commission working paper stresses the strategic value of technology sovereignty not so much as linked to competitiveness, but to the issue of safety and security, health and green transition (European Commission, 2021a). This is in line with a definition of Edler et al. (2020) who distinguish the functional dimensions in the three dimensions of economic welfare, main duties of the state and transformational aspirations of societies.

Of course, KETs and technology sovereignty agendas overlap, but there is a danger in mixing the two. In the current analyses concerning European technology sovereignty, what is very often measured and assessed is the European scientific and technological capabilities and competencies – or even leadership (Bauer and Erixon, 2020a) – as well as its trade patterns. Clearly, a system that is able to develop scientific knowledge feeding into new technologies and turn those into products can be regarded as sovereign when it comes to that technology. However, what is actually meant, and measured, here is a rather traditional concept of technological competitiveness or leadership. It would be, in theory, perfectly reasonable to assume that a system, let us say the EU, has full, reliable access to a critical technology which is produced in a number of reliable countries outside Europe that have a comparative advantage for that technology. If access is assured and if there are redundancies to ensure resilience, the system would not need to strive to produce that technology itself and still be sovereign in the use of that technology. For smaller countries, which often lack certain capabilities altogether, this is the norm rather than the exception.[2] Within the EU, with its division of labour and high level of market integration and mutual trust, such a narrow understanding of technology sovereignty is perfectly reasonable. This aspect of reliable access to technology without one-sided dependency needs to be taken seriously if the concept of technology sovereignty is not just another label for technological competitiveness. Furthermore, what distinguishes technology sovereignty from technological competitiveness in the KETs agenda is the fact that one has to look at all the critical components of that technology, down to raw materials, and ensure access or develop alternative inputs or solutions altogether ((Airaghi et al., 1999; European Commission, 2021a; Edler et al., 2023; European Commission, 2023b). In the past, trusting in the free flow of inputs across borders, this dimension has often been neglected.

What follows from that with regard to the conceptualisation of technology sovereignty? Three requirements need to be established. First, as with KETs, there need to be clear criteria against which one assesses what technologies are seen as critical and through what processes the decisions are taken. The criteria for the choice are broader and more complicated than in the traditional approach. In extension of the traditional technological competitiveness approach of the past, technology sovereignty also needs to be more explicitly concerned with the secure provision of current and future technologies to meet critical societal challenges (crises and transformations), as well as for delivering the core duties of the state, such as internal and external security or health provision. In this approach, even if a technology would not deliver on economic welfare, it may still be critical for societal and political reasons and, thus, subject to sovereignty policies. In this approach, the logic of the market economy alone cannot deliver.

A second requirement is the analysis of the capabilities of Europe to produce this technology *or* to secure access to it. Again, in extension to the traditional technological competitiveness approach, analyses now need to take into account how, for example through international cooperation and open trade with trusted partners, access can be assured, both to technologies and to inputs into technologies (Di Girolamo et al., 2023). In this analysis, even in a technology in which Europe is highly competitive it may not be sovereign if critical components are not provided within Europe, putting their provision from abroad in danger.

Finally, even if a technology could be sourced from abroad on a reliable basis, Europe would not be sovereign if the features of those technologies were not in line with its value system. This aspect has been much less prominent in the traditional competitiveness discourse around KETs. Technology sovereignty not only means that Europe has access and can use a technology, it also means it can be used according to the basic values and norms of the continent. Thus, when analysing the partners that provide technologies, Europe cannot develop on its own; the in-built values of those technologies need to be part of the analysis, and thus part of a technology sovereignty strategy.

Having established a few major core requirements for a meaningful use of a technology sovereignty approach, we can now discuss its relationship to important neighbouring concepts, not only to clarify the differences, but also to understand how the various concepts can reinforce each other.

2 For a similar line of argumentation see Kroll et al. (2023), who put the concept of technology sovereignty into the context of Open Strategic Autonomy and economic security. See below for a further discussion of this approach..

2.2 Technology sovereignty, openness and open strategic autonomy

It is a conceptual challenge that the concept of technology sovereignty is embedded in long-standing efforts of the European Commission to 'open up'. The rather defensive, inward-looking character of technology sovereignty appears to contradict the three dimensions of openness (innovation, science, world) as declared by Commissioner Moedas (European Commission, 2016; Soete and Burgelman, 2023). As a consequence of the developments discussed above, the openness discourse has flattened in recent years. One strategy through which Europe increasingly seeks to reconcile this openness and its advantages with the basic idea of asserting more sovereignty is the concept of Open Strategic Autonomy. This concept emerged after the financial crisis of 2008. It was first formally mentioned at European level in a Council declaration in 2013, but has broadened in recent years through the external shocks of Brexit, the irritations with the Trump Administration and the Russian war in Ukraine. As a result, it still is somewhat ambiguous (Damen, 2022). It refers to 'the capacity of the EU to act autonomously – that is, without being dependent on other countries – in strategically important policy areas' (Ibid.). Here, 'open' refers to the need and willingness of Europe to engage in multilateral cooperation wherever possible and appropriate (Amaral-Garcia et al., 2023, p.1). In fact, in a core document of the European Commission, the focus was very much on openness, claiming that European leadership and open cooperation would best serve its global interests (European Commission, 2021b; see also European Commission, 2023b; Cagnin et al., 2021).

It is thus a conceptual and a policy challenge to define the appropriate levels of and strategies for openness in a quest for technology sovereignty. Given the European economic and geopolitical position, openness can be seen as a means to achieve strategic autonomy (Bardt et al., 2022, p.48). Through openness, international cooperation and engagement, Europe not only benefits via trade, division of labour and international complementarities, but also influences international rules, regulations and standards, and increases its negotiation power (Franke and Torreblanca, 2021).[3] This means, there is, in principle, a virtuous circle of openness on the one hand, and economic as well as political power and autonomy on the other. The stronger the EU is technologically and economically, the more powerful it is in international negotiations and trade relations; and the more open it is to those international cooperations and relations, the more economically powerful and autonomous it can become.

It is against this basic idea of open strategic autonomy that one has to conceptualise technology sovereignty and define sovereignty strategies. One needs to consider that any related activities that limit openness, justified as they may be for all kinds of reasons discussed in this chapter, will have repercussions on this potential virtuous circle. How the added internal strengths envisaged through technology sovereignty strategies that rely on European capabilities influence the potential welfare and power losses produced by reduced international engagement and exposure is hard to predict. However, this welfare calculation

3 Franke and Torreblanca Klicken oder tippen Sie hier, um Text einzugeben.go one step further and stress that the technological power of Europe is a determinant of its geopolitical power in general. Technology sovereignty is thus a direct indispensable basis for a strong geopolitical role of the Union.

needs to be taken into consideration in an overall assessment of the benefit of a risk-reducing technology sovereignty strategy.

It is, therefore, important to further differentiate the meaning of openness. As a recent ESIR report (European Commission, 2023b) has noted, openness has a different meaning for science, for economic competitiveness, for fighting global challenges and for securing Europe's security (Ibid., p.6-7). Therefore, the role of technology sovereignty in relation to those dimensions as outlined in the ESIR report needs to be looked at separately – and this leads to particular challenges for Europe. It will remain of great importance to secure scientific collaboration. Scientific knowledge production is now characterised by a highly differentiated global division of labour. Restrictions here, as a consequence of consideration of technology sovereignty or economic security (see below), will inevitably reduce the productivity of the science system to the detriment of everyone. Of course, this price would have to be paid in areas in which scientific knowledge production has direct security implications (dual use) or is used by others in ways not compatible with Europe's value system. But the balance needs to be struck very carefully and on a case-by-case basis to not undermine the knowledge base for the transformative progress sought. The same holds true in areas of obvious contributions to tackle global challenges together. Reduction in scientific cooperation will reduce effectiveness and speed in tackling these challenges. Furthermore, as stressed above, Europe's economic model relies heavily on the openness of trade, and any restriction on trade because of technology sovereignty concerns will reduce the effectiveness of international trade, one way or another.

A further tension in the relationship between technology sovereignty and open strategic autonomy arises from the breadth of the open strategic autonomy concept. A recent JRC background paper to the CONCORDI conference 2023 signifies the conceptual, methodological and political challenge of technology sovereignty (Amaral-Garcia et al., 2023). Here, technology sovereignty is conceptualised as an *essential* element for Open Strategic Autonomy (OSA) as well as the twin transition. However, OSA itself is defined as a strategy that not only supports twin transitions, but also does so while supporting regional and societal cohesion. In a positive reading, one can hope to leverage 'the unique strengths and capabilities of different regions' to create 'synergistic ecosystem that drives growth and innovation' (Amaral-Garcia et al., 2023, p.24). This of course is another way of stressing the complementarities within Europe to broaden its technology sovereignty. Notwithstanding the normative value of regional and social cohesion, as well as the added value of complementary assets across different regions, this framing of 'not leaving anyone behind' adds yet another layer of complexity to the design and effectiveness of technology sovereignty policies in Europe – and may actually dilute strategic efforts.

2.3 Technology sovereignty and European economic security

More recently, the European Commission and the High Representative for Foreign Affairs have further developed the relationship of technology with concerns for open strategic autonomy by developing a European strategy for economic security, for which they define technology sovereignty as indispensable (European Commission, 2023a). This draft puts further stress on the relationship between sovereignty and autonomy on the one hand, and openness on the other. The economic security strategy concept is far reaching.

It strives to ensure Europe's independent economic development by enhancing its technological and production capabilities. It is thus an extension of the broad technology sovereignty definition outlined above. Moreover, this is to be done on the basis of identifying and reducing various kinds of risks, while keeping in mind 'the inherent tensions that exist between bolstering our economic security, and ensuring that the European Union continues to benefit from an open economy' (Ibid., p.2). The list of strategic risks is comprehensive and goes far beyond dual use and ethical considerations. It includes risks concerning supply chains, physical and cyber infrastructure, technological leakage (in relation to those technologies that are critical for economic security), as well as weaponization in terms of economic dependencies or coercion. Furthermore, the concept, at least implicitly, divides the international partners into those that share 'our concerns and interests on economic security' (Ibid.) and those that do not. For technology sovereignty this would mean that the concerns against which technology sovereignty needs to be defined have broadened, and with it the claim as to what technologies are 'critical' (Ibid., pp.9 and 14) and for which sovereignty must be secured strategically. Any technology sovereignty strategy would be even less selective on that basis. It also means that the openness to develop technology together, to exchange through technology trade or technological collaboration, may be further reduced, for example through tighter export controls and more security consideration for outward investments.

2.4 Potential pitfalls of technology sovereignty approaches

Any conceptual consideration of technology sovereignty must take into account the potential downsides of this approach. To start with, technology sovereignty policy interferes in market dynamics for reasons beyond traditional market and system failure, as it inserts a number of additional drivers for state interference and radiates a defensive spirit of closing down. This may severely reduce the overall efficiency of the national economy for two reasons. First, it may distort markets, as the responsibility of securing the conditions for production of technologies shifts away from businesses and towards the state, potentially overburdening governance capacities of the state and advantaging lobbying efforts over market performance. Second, the idea of technology sovereignty most certainly reduces the international division of labour and trade with interim products and technologies. As the competition around selected technologies intensifies and openness reduces, the global market may even split up in separated areas of technological influence, with diverging standards and norms and reduced interoperability and complementarities across the emerging blocks.

A convergence of technological efforts across countries may also be seen, with potentially counterproductive effects on diversity and variety. Historically, countries have had the tendency to converge to a narrow set of technologies in their strategies for key enabling or critical technologies. As Lee et al. (2023) have shown, the recent national debates and strategies for technology sovereignty build upon strategies on KETs or 'critical' technologies that all advanced countries and the EU have had for decades. A longitudinal analysis of eight countries (US, Japan, Germany, UK, Australia, Canada, France, South Korea) and the EU (Ibid., 2023) finds astonishing similarities of lists of technologies across the comparative countries. In the more recent, intensified debate on technology sovereignty this pattern is very likely to be continued. This then may intensify the competition across the selected technologies, which may lead to an acceleration of technology development. However, this convergence runs the risk of a reduced variety in the global production and application of technologies in those areas that are not in the immediate focus of technology sovereignty policies. In addition, it may further increase the sense of urgency and vulnerability and foster reactions of closing down nationally, thus contributing to a vicious circle. This, in turn, would confirm the major criticism by Soete and Burgelman (2023), according to which technology sovereignty is a severe threat to and limitation of the three dimensional openness of Commissioner Moedas.

Another downside of the technology sovereignty momentum may arise from the poor conceptualisation or the ambiguous discourse around it. In the past, as Lee et al. (2023) show, the selection and support of KETs were based on economic growth and competitiveness, while only a few countries had systematic linkages to societal benefits and broader innovation goals in the past. Thus, traditionally, the debates on what technologies and sectors to foster were closely linked to considerations of industrial policy, sectoral strengths and priorities in each country. If technology sovereignty is applied according to its broader, functional concept of criticality, the debate on what is to be supported is by definition broader. In combination with the ambiguous discourse on technology sovereignty and the broadening of claims due to open strategic autonomy and economic security, this may invite broad and fierce lobbying for subsidies and preferential conditions across a range of industrial sectors and, indeed, research organisations.

All these potential downsides of technology sovereignty debates need to be taken on board, not only as footnotes in strategies, but as criteria against which any technology sovereignty strategy is being implemented.

3. State of play: measuring European technology sovereignty

Any empirical analysis of technology sovereignty must start with the question: which technologies are critical, and why? This has two elements, which are often confused. First, which technology is indispensable for core activities in the system and/or core duties of the European Member States or the European Union as such; and how are choices made? Second, how competitive and vulnerable is a country or Europe in terms of providing for this technology and its development in the future? While various contributions have different methodological and sometimes conceptual approaches, those two questions are, one way or another, part of any meaningful analysis of technology sovereignty at national or European level.

In this regard, a range of powerful new conceptual and methodological advances are being developed, which enable going beyond the concepts of technological competitiveness or leadership and to be true to very idea of technology sovereignty. In particular, very sophisticated approaches have been developed to define sovereignty positions of technologies at national and European level, and first steps are being made in order to understand the existing and potential partnering approaches to broaden resilience for technology sovereignty.

In one of the more sophisticated approaches, Di Girolamo et al. (2023) analyse the position of Europe in terms of 'complex technologies'. Rather than applying an ex-ante functional framework for the choice of technologies to be analysed, the authors define the level of complexity of the technologies. Knowledge complexity is used as a tool to assess a country's knowledge base that 'encompasses both value and quality of innovation outputs' (Ibid., p.7). A high knowledge complexity index (KCI) means that the technologies produced are hard to replicate by others. Second, they use the concept of technology relatedness, meaning the level of capacity a country (or Europe, or a firm) has to absorb a technology from elsewhere based on the prior level of related knowledge held by the country, Europe, firm, etc. (Ibid.). The study finds that Europe has lost ground versus other major economies in the last 30 years, and has a weak position in those technologies that have a high knowledge intensity, in particular computer technologies, digital communication optics and semiconductors, while it is relatively strong in technologies with a lower complexity and in technologies relating to the green transition.

Di Girolamo et al. (2023) also show that Europe has a structural disadvantage to close the knowledge gaps with other innovators, pointing to the risk of remaining dependent on partners to drive its own transformation. This can severely limit Europe's technology sovereignty, as, for example, digital technologies (where the US and China are clearly leading and have structural advantages) are critical for energy transition efforts (Ibid., p 17). This analysis thus shows that it is not (only) the economic welfare argument that is of concern, but also the broader argument of losing the independent agency to use the best available technology for the transformations needed.

A second effort on the European level worth noting is Kroll et al. (2023). Similar to Di Girolamo et al. (2023), this study also introduces conceptual and methodological innovations based on technology sovereignty logics. It introduces the distinction between autonomy at the technological level (the 'innovation' domain) and the ecosystems level (the economic domain), trying to approach this delicate relationship in two steps. They first distinguish between autonomy as the freedom from external reliance and sovereignty as being independent from external partners. The former is a measure of international division of labour, while the latter is a measure of the trust that this openness holds. They then distinguish between innovation autonomy as a measure of reliance on external partners for the production of knowledge, and economic autonomy as the measure of reliance on getting components or technologies from abroad. The higher the reliance, the lower the autonomy. This approach is a helpful one to navigate the relationship between technology sovereignty and economic autonomy. For a comprehensive strategy that seeks to ensure economic autonomy, one would have to differentiate between the autonomy with which Europe can create knowledge (innovation autonomy) and the autonomy with which it can source and develop technological products (economic autonomy), analysing the sovereignty risk in each of the domains separately. Such an analysis supports strategic decisions as to the need for specific technology sovereignty policies for any given economic domain. Only if a domain is heavily relying on a technology for which both the autonomy is low and dependency is high would a technology sovereignty policy be needed. At the same time, if sovereignty in the core technologies of an economic domain is not sufficient, further conditions beyond technology production must be met. Importantly, their approach also allows differentiating different kinds of dependencies, and incorporating a risk analysis for trade partner countries.

A further recent approach to analyse technology sovereignty at European level focuses on one specific technology, 5G mobile communication, without offering a general, broadly applicable selection framework for that choice. Da Ponte et al. (2023) develop a technology sovereignty index (TCI), focusing on assets and competencies (human capital, science and technology efforts, innovation capacities, capitalisation of research and development), conditioners (external and outsourced resources) and technology sovereignty drivers (resilience in terms of human capital, production, logistics and raw material dependencies). They operationalise the index through a broad range of indicators and demonstrate that those indicators can be meaningfully filled with available data. In terms of material results, the sovereignty index is much lower than that of China and the US, by and large confirming the previous two studies. The methodological and conceptual added value is the differentiation into a set of indicators, which allows a pressure point analysis and setting policy priorities. Furthermore, this approach can be used to show heterogeneity across European countries, as the data in principle is available on a country level.

Recently, Reiss et al. (2023) performed the first[4] comprehensive technology sovereignty analysis for a specific economic sector, i.e. the pharmaceutical sector. They conceptualised technology sovereignty following the definition of Edler et al. (2023). Their added value, though, is the fact that they analysed both the level of competitiveness in a selected technology and the level of international integration and dependency, and measured international integration in three dimensions: knowledge, technology and trade. In their approach, a high level of international integration is a prerequisite to benefit from knowledge and technologies that is generated abroad (co-publications and co-patents), as well as mutual interdependence in trade (Reiß et al., 2023). However, integration is only a positive asset if the country shows a strong position in terms of technological competitiveness, in which case integration ensures mutual benefits and dependencies. A high level of integration

4 As of December 2023, and to the knowledge of this author.

combined with poor domestic technological performance and competences, however, is associated with a high level of dependency. Equally, if a country is highly competitive, but poorly integrated, this position may not be future-proof as it risks falling behind future international developments and thus becoming vulnerable in the years to come.

A recent analysis of the US Critical Technology Assessment Network is worth noting here as it highlights both the sense of the US' self-reliance when it comes to technology sovereignty, as well as a specific methodological approach (National Network for Critical Technology Assessment, 2023). The authors indicate why a range of technologies are critical and need specific support, not so much to prevent dependencies, but to ensure future technological leadership. Both the sense of self-reliance and the understanding of technology sovereignty are based on the understanding that the US has, in principle, the basic critical assets to actually deliver sovereignty across a broad range of technologies with their own domestic competencies. Based on expert views and AI-supported database analyses, the report determines the relative importance of a technology for the economy and for tackling selected challenges (the need analysis), and domestic as well as international capabilities and competences. This multi-perspective analysis covers all relevant department and agencies of the government.

This network also highlights the challenges of a time-critical assessment of international production capabilities and the change in relative competitiveness. They advance methodologies, but not so much in analyses of dependencies, rather in the sense of competitor analyses and analysis of US capabilities.

They also apply a rather crude but effective selection process when it comes to technologies: in consultation with the interagency working group they identify and annually review and update a list of not more than 5 US societal, national and geostrategic challenges that may be addressed by technology. They then pick not more than 10 key technology focus areas and evaluate the relationship between US societal, national and geostrategic challenges and the key technology focus areas (National Network for Critical Technology Assessment, 2023, p.1).

As for the selection of technologies, the European Aerospace and Defence Industry Association suggests a stepwise filtering approach, whereby only those technologies that are absolutely essential for making a specific defence and security function are seen as critical and deserving a sovereignty policy (AeroSpace and Defence Industries Association of Europe, 2020). Importantly, they include the underlying value chains and seek to understand the 'appropriate level and form of European control over the value chain'. On that basis, they identify gaps and dependencies that 'may undermine our sovereignty'. The detailed and deep consideration of value chains, as well as the understanding of 'control' needed over the value chain, are critical elements that exceed many existing approaches. Given the absolute criticality of specific technologies in terms of military performativity, this in-depth value chain analysis appears to be a feature more generally of the defence sector (see also Gholz, 2023): '*However, to achieve an appropriate level of technological sovereignty in strategic sectors, Europe should avoid dependencies that would enable a non-European actor to unilaterally impose constraints on European technologies, or to hinder European suppliers from mastering and executing all of the key steps of the technology development and industrial cycle*' (AeroSpace and Defence Industries Association of Europe, 2020).

4. European assets and liabilities for a technology sovereignty strategy

Within the EU and at European level there are a number of specific conditions which could result in a relative advantage of the region vis-à-vis other countries and partners globally. At the same time, a EU-level concept has to deal with a variety of challenges stemming from its heterogeneity, both in terms of socioeconomic levels of performance and different national profiles, as to the selection of technologies and potential partners to secure technology sovereignty. As, by definition, technology sovereignty policy means to make choices that are more consequential than traditional innovation and technology policy, different national profiles might pose even more challenges than those currently experienced.

4.1 Favourable conditions for active technology sovereignty policy

What are the EU's structural assets that may give it an advantage over competitors and partners globally? Firstly, the awareness regarding the importance for systematic considerations as to technology sovereignty is now considerably high; all political actors at the Commission and in the Council have understood the criticality of the issue. Against the background of the pandemic and geopolitical frictions, technology sovereignty strategies at European level and within Europe are high on the political agenda. Furthermore, in comparison to the initiatives regarding the key enabling technologies of the past, there are now more stakeholders involved: it is not only specific industrial sectors or scientific organisations lobbying for more support for their key technologies. Now it is a debate that is functionally broader, where stakeholders involved in all kinds of important sectoral policies, including defence and security, and transformational policies have a stake. This can and should broaden and enhance the awareness for the importance of investment in sufficient assets and capabilities. The support for science and technology policy as a basis for self-defined developments across Europe appears to fall in line with a change of Zeitgeist in Europe more generally. As Schmitz and Seidl (2023) have shown empirically, what they call the 'neo-liberal consensus' within Europe as to open trade and removing trade barriers is under pressure through 'socially oriented politisation' and through 'geopoliticisation', despite a considerable and persistent share of free trade advocates. Instead, the Open Strategic Autonomy discourse has gained momentum: the free trade and competitiveness focus has shifted towards endorsing active trade policies, recognising systems competition and defence considerations[5], as well as transformation.

Secondly, Europe already benefits from the internal market. This is a considerable strength already, albeit with much room for improvement. As for technology sovereignty, two aspects stand out. One is complementarities across Member States, which can be pooled and thus secure a broader coverage of technologies to be provided within Europe (Schmitz and Seidl, 2023). The new world order will mean

5 The survey by the authors was made before the second Russian aggression in Ukraine in 2022, thus the importance of defence considerations across Europe has most likely further increased..

not only to trade with trusted partners, but to develop integrated technology sovereignty strategies with partners outside Europe with complementary assets. This strategic option is in-built in the fabric of Europe. To be sure, European countries are also competitors. But when it comes to resilient and reliable value chains to secure future technologies, the balance between competition and cooperation within Europe is unique. In particular, as technology sovereignty is more than just the front end of a scientific and technological development, the integrated internal market is a core asset, even if, as argued below, it has serious room for improvement.

Thirdly, there is a further positive effect of the internal market. As the Commission itself has stressed in the context of its broader approach for economic security, a strong internal market enhances the position of Europe when it comes to opening up international supply chains and influencing international trade and production. (European Commission, 2023a; see also Bardt et al., 2022). What has been labelled the 'Brussels Effect' in the past, the normative effect of the export power of Europe on global markets may also play to the advantage of Europe. However, the very merit of the internal market is not fulfilled as yet, which leads us to the specific challenges and dysfunctionalities for the EU when it comes to technology sovereignty.

4.2 Specific challenges

While the internal market is one of the greatest assets for the EU in the global technology competition, it is still far from complete in order to deliver all the advantages it could in terms of technology sovereignty.[6] The internal market still suffers a great deal from fragmentation when it comes to specific regulations (Da Ponte et al., 2023). For example, the scaling of digital business models is much more complicated in Europe compared to the huge internal market of the US or China. If new technologies are being exploited much quicker and more profitable in other areas, the competencies and capacities to develop those technologies will also concentrate in those markets. Thus technology sovereignty will suffer in specific sectors, as will technologies that rely on data and the exploitation of data in large markets, with the potential spillover to other neighbouring sectors and business models. Furthermore, there is still considerable market concentration of business activities across Europe, producing a range of internal dependencies (European Commission, 2021a, pp. 28-29).

This is particularly true given the changes in Europe's relative weight. The 'Brussels effect' and the power of the European technology export markets will diminish. The relative share of Europe will reduce from its current 15% of global GDP in 2022 to 9% in 2050.[7] The regulatory and lead market advantages in some markets will potentially become smaller and will need more elaborate and proactive strategic efforts, particularly in terms of participation in international standardisation and norm activities. This may very well turn into a vicious circle of less relative weight economically, and less regulatory and lead market power.

A further challenge for a European approach to technology sovereignty is the need for EU-wide legitimacy in the face of persistent heterogeneity in terms of levels of economic

6 See Herlitschka (2023) for the example of the semi-conductor industry..

7 See https://www.statista.com/statistics/253512/share-of-the-eu-in-the-inflation-adjusted-global-gross-domestic-product/ and https://www.pwc.com/gx/en/research-insights/economy/the-world-in-2050.html

and technological performance, technological and industrial profiles, and international trade relations. A shared polity like the EU, under conditions of multi-dimensional heterogeneity, needs a technology sovereignty strategy that is very explicit, transparent and regarded as legitimate throughout. As Chrétien and Drouard (2022) point out, the EU has been delegated sovereignty from Member States, but is itself not sovereign. As with any major strategic approach, technology sovereignty also needs to find sufficient support in Member States. However, a consensus on the very nature of and need for technology sovereignty has yet to develop (Ibid.). Heterogeneity exists in the Member States in terms of their positions and ambitions as regards technology sovereignty, in terms of their international exposure and dependence, and in terms of their perception of the need to emancipate Europe from the US. Furthermore, explicit and consequent technology sovereignty strategies involve, by definition, a stronger role for the Member State to define and select critical technologies for which specific measures to secure sovereignty are to be developed. While, as stated above, there are indications of a shift towards a more proactive Member State again, the understanding of the basic role of the Member State (and in particular the basic direction of Member State action) differs enormously across European Member States, increasingly so given the right-wing shift in a number of countries.

Thus, tough choices need to be well justified and posteriorities explained (Crespi et al., 2021). This has further practical and political reasons: the complexity in terms of technological capabilities and gaps across Europe is strong, and the European-wide discourse on choices and instruments highly complex. In addition, and maybe more importantly, there are two political problems. First, technology choices have to do with power and economic gains and, as with any policy with distributive effects, will lead to political controversy between constituencies, stakeholder groups and countries. A second point has to do with the level at which tough choices are made and are being accepted. This in fact resembles an argument made by neo-realist and neo-conservative scholars (Lieven, 2020) who concede that only a strong legitimacy based on national identity and elections could successfully implement transformative policies that ask for a change of behaviour. As an analogy, we could expect that the preferential treatment of a selected number of technologies, supporting certain sectors more than others, could be easier to accept at national level. If Europe turns much more interventionist than it used to be in terms of technological and sectoral choices, this issue of heterogeneity, of winners and losers across the EU, will become more relevant. Thus, at EU level the choices for technologies and related technology sovereignty strategies need to be made in light of different positions, and of the overall importance of a technology for the Union as such. That is why the focus cannot only be on competitiveness issues, but also on issues of value-based duties of the Member State and societal preferences in terms of directionality and in-built values. In addition, any strategic intelligence to support decisions on technology sovereignty must be sound and transparent, and political choices well communicated.

Against this background, the EU's technology sovereignty approach meets different ideational contexts and policy traditions in the 27 Member States. There is still no evidence that the meaning of technology sovereignty and related policies, let alone the depth of related intervention, is commonplace across the EU institutions and EU Member States (European Parliamentary Research Service, 2021). In fact, Bauer and Erixon (2020b) show the basic differences in the German and French approaches and concede various further country positions in their paper. A survey done in eight European countries in

2021 (Friedrich-Ebert-Stiftung and Fondation Jean Jaurès, 2021) reveals the diversity of attitude when it comes to sovereignty in Europe, and the relative meaning of European vs national sovereignty. In general, the share of the population associating sovereignty as positive is much smaller in the Mediterranean countries (including France) than in Germany, Sweden or Romania. There is a clear north-south divide, with considerably more people in the south associating power and nationalism rather than independence with sovereignty. As for European sovereignty, while the majority of all countries surveyed supports a strengthening of European sovereignty, the population in France, Italy, Spain and Sweden is divided and far more sceptical than in Germany or eastern or central European countries. Furthermore, there are obvious material differences in terms of the fears based on the loss of technology sovereignty. For example, new AI-based production technologies influence the core industry of a country like Germany, and thus there is a strong feeling in the country that the domestic system must be able to generate those new technologies to determine its direction. In other countries, the access to those technologies may be seen as sufficient. Finally, there are indications of a notable difference between small and larger Member States when it comes to aligning with European approaches (MIT Sloan Management Review). For example, while in Austria the discussions on technology sovereignty strategy take the EU approach as a starting point (Austrian Council for Research and Technology Development, 2021), the German Futures Strategy, limited as it still is in terms of an explicit technology sovereignty strategy, does not appear, as of December 2023, to develop a coordinated approach.

In short, diversity, a seed for complementary assets and creativity in Europe, can turn into uncertainty and ambiguity as to what actually is to be expected from technology sovereignty policies (Schmitz and Seidl, 2023). Moreover, even if the necessity of joint forces for technology sovereignty in Europe is acknowledged, and even if the instruments are recognised and available, there are voices from the industry that (based on experiences on KETs) doubt the readiness and willingness of Member States to combine forces in order to do so meaningfully (Herlischka, 2023). The quality with which national and European-level approaches align when it comes to technology sovereignty will remain the critical issue for years to come.

5. Conclusions

In Europe, across a range of political areas, from economic policy to security policy, there is a high resolve to strengthen Europe's ability to act more independently. In this context, technology sovereignty has become a top priority, framed to be critical for a number of European goals in times of geo-political upheaval, not as an end in itself, but rather as a mean to enable Europe to control its technological destiny, encompassing not just economic benefits but also fulfilling state duties and societal transformation goals. However, the resolve to be technologically sovereign is not yet met by a clear strategic understanding as to how this should come about.

As argued in this report, any concrete strategy to develop technology sovereignty must have a clear understanding of what this concept entails, how it differs from older approaches, from neighboring, complementary ones, and to what end it is applied. Achieving technology sovereignty in the EU requires a nuanced strategy that goes beyond traditional competitiveness considerations or the focus on individual key enabling technologies. It is about ensuring the EU has reliable and independent access to critical technologies and its components, including raw materials, balancing the need for being able to master the production of certain technology within Europe on the one hand with the benefits - and risks - of the global division of labor on the other hand. Technology sovereignty thus carries with it a defensive, at times even aggressive, connotation. Any system striving for more self-reliance risks reducing its openness and cooperation with other systems. Consequently, greater sovereignty risks leading to increased isolation from those outside the circle of trust, thereby creating a downward spiral of protectionism, where each step towards self-sufficiency further limits engagement with the broader global community. For a continent like Europe, interdependent with other parts of the world, this risk needs to be managed carefully.

Therefore, rather than simply seeing technology sovereignty activities as reactive and defensive - or as precautionary at best -, it should be understood as functional for Europe's global standing (Ringhof and Torreblanca 2022). Technology sovereignty in this perspective does not only mean being sovereign, but being a technological leader, creating technologies that are globally indispensable, shaping and benefiting from early markets in order to strengthen the European position. This would be a consequence of a particular strength, the European internal market - which indeed is "much more than a market" (Letta 2024) - and could result in an extension of the "Brussels Effect", whereby Europe could proactively influence global technological norms and standards, in line with European values and priorities, and in partnership with technologically strong value partners.

However, a technology sovereignty approach defined at EU level, in conjunction with open strategic autonomy and economic security, would still face the material challenge to define which technology to choose and how to support it. Even if the basic concept of technology sovereignty finds enough support in the political space, the implementation of a strategy tailored towards European level considerations and technological positions remains a huge challenge.

In this regard, the EU faces hurdles also due to the incompleteness of its internal market and regulatory fragmentation. The heterogeneity across Member States in terms of economic, technological, and industrial capabilities - alongside different international exposures and ambitions for technology sovereignty- complicates consensus-building. This diversity, while a source of creativity, can lead to uncertainty regarding the direction and expectations from technology sovereignty initiatives.

There are a range of operational and strategic steps to be taken. First, Europe needs an appropriate strategic intelligence to underpin a robust technology sovereignty strategy. Here, Europe is making commendable efforts, including not only traditional metrics like patents, trade, and publications, but also embracing a mix of indicators and qualitative assessments that consider value chain complexities, thereby going beyond the inner core of technological development. In this respect, one can only support the demand of a recent ESIR report to set up a sophisticated technology monitoring and more awareness when it comes to dependencies of raw materials and how they can be mitigated (European Commission, 2023b; p. 11-12). Second, STI policies will need to be increasingly strategic, with a focus on complex technologies and its components. This includes the need to form explicit international partnerships aimed at collaborative technology sovereignty. It also includes embedding in a holistic, coordinated policy approach, with strategic STI policies coordinated with trade policies, industrial as well as foreign policy (European Parliamentary Research Service 2021)

However, even if those two conditions were met, there is still a profound dilemma at EU level. Given the size and capacities of individual European countries and the advantages of the internal market, technology strategies are only meaningful and promising at EU level. At the same time, as technology sovereignty policies are about strategic choice, priorities and posteriorities, the interventionist policies needed are contested and need a high level of legitimacy. This, unfortunately, is a particular challenge for the time being at EU level. If governments strive for sovereignty, they need a high level of legitimacy to implement all measures needed, which may privilege one group over the other. If that legitimacy is limited, sovereignty policies will be under pressure. At the same time, if sovereignty policies are proclaimed, but fail to deliver, the repercussions for the legitimacy of the EU may be immense. In this respect, it remains questionable at best to link technology sovereignty, as was recently done, with consideration of cohesion. If technology sovereignty as a policy approach is stretched to respond to the sovereignty imperative *and* cohesion consideration at the same time, chances are high that it fails to deliver on one of the two accounts, or maybe even on both accounts. This would inevitably limit the credibility and legitimacy of technology sovereignty approaches. Cohesion goals, important as they are, should thus be pursued through other means.

While skepticism remains regarding the readiness and willingness of Member States to harness their strengths collectively towards European technology sovereignty, there is no alternative to do so. The path forward requires navigating these complexities and the legitimacy challenge with strategic intelligence, transparent decision-making, and effective communication to align diverse Member State interests with the broader EU technology sovereignty agenda. And surely, established European instruments to support technology development, chiefly the European Framework Programme, will have to play a major part in this critical journey Europe is undertaking.

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CHAPTER 9

REGIONAL DIVERSIFICATION IN GREEN TECHNOLOGIES

Dario Diodato[(1)], **Lorenzo Napolitano**[(1)], **Emanuele Pugliese**[(2)]

[(1)] *Joint Research Centre - European Commission*
[(2)] *UNU-Merit*

Abstract

A key intuition behind the European Green Deal is that the transition to climate neutrality should be growth enhancing. This will require massive changes in habits and laws, and, above all, an extraordinary effort in transforming technology, the most important determinant of pollution levels and economic growth. This chapter provides an overview of the current state and future outlook of green technologies across the European continent, through the lenses of the emerging paradigm of economic complexity. The analysis shows a heterogeneous landscape in Europe, in which specialization and diversification vary considerably, calling for different investment strategies at EU, national, and regional levels. The chapter highlights the importance of regional cohesion, and call for policies informed by the principle of accumulating capabilities: each region can look at its own set of skills and potential to direct investments towards technologies that are feasible, but also allow the region to accumulate new know-how and fuel growth.

1. Introduction

A key idea behind the European Green Deal is that the transition to climate neutrality should be growth enhancing. No one expects this to be an easy task: it will require massive changes in habits and laws, and, above all, it will require an extraordinary effort to transform our technology – the most important determinant of pollution levels and economic growth.

This chapter thus aims to give an overview of the current state of and future outlook for green technologies across Europe. It does so through the lens of the emerging paradigm of economic complexity, whose theoretical understanding of technology and empirical data-driven predictions are, in our view, very well positioned to contribute to this difficult discussion.

Chapter 2 of this report shows that the EU is still a technological powerhouse in green innovation. However, while this is true on the whole, there are some technological sub-classes in which Europe is not a global leader. Our analysis complements that of chapter 2 by studying key green technologies to identify potential gaps in this area in Europe. We use regional patent data to identify not only the differing abilities of regions in these key technologies but also the potential that regions have. That is the core empirical contribution of economic complexity: it can identify regions that are not currently actively developing a given technology (and, therefore, may not yet have acquired all the necessary capabilities) but have mastered related know-how and thus have the potential to develop the technology in the future. As we clarify in the following sections, we define know-how related to a target technology as the presence in a region of a set of technologies that are good predictors of its future development in that region.

We show that the landscape in Europe is heterogeneous, with regions with little or no green patenting and potential coexisting with regions with higher potential but few green patents and regions with high levels of green patenting and potential. We also observe that, while some regions are always high or low performing, for some, this varies depending on the technology.

This chapter does not exist in isolation. The body of literature investigating the link between economic complexity and sustainability has grown in recent years. Contributions have explored many directions of enquiry, ranging from measurement of the relationship between production and sustainability (e.g. Mealy and Teytelboym, 2022) to proposing indices of national or regional innovative performance (e.g. Pugliese and Tuebke, 2019) or development of methods to predict green innovation based on the composition of regional patent portfolios (Sbardella et al., 2022).[1] Irrespective of the question they tackle, researchers in the field share the view that, at regional scale, innovation (like economic development) is compatible with a process of accumulation of capabilities that makes possible increasingly complex outcomes. In this view, diversification and progress go hand in hand. It is, therefore, possible to extract valuable information about the future evolution of economic systems by measuring whether and to what extent their parts diversify over time.

In this chapter, we follow the literature that has been attempting to predict green innovation. With patent data, we observe how countries move from non-green to green technologies – and then apply that observation to European regions to assess which are better placed to develop green technologies in the future. To this end, we build

1 For a recent review of the literature applying economic complexity techniques to sustainability-related issues, see Caldarola et al. (2024).

on the methodology proposed by Pugliese et al. (2019) for identifying non-green technologies that are good predictors of the future appearance of a specific set of green technologies and use this information to compute a technology-specific regional-potential metric.

The chapter is organised as follows: section 2 introduces the reader to economic complexity. While we refer the reader to other more technical documents for an in-depth understanding, this section gives an idea of both the theoretical underpinning and the empirical methods of economic complexity. Section 3 identifies the EU's weaknesses in green technologies through a global comparison of 48 green technological categories. Section 4 presents the main results, mapping the green technology ability and potential of European regions. Section 5 discusses a possible key for reading the findings for policy purposes. Finally, section 6 concludes the chapter with some reflections.

2. Technology and complexity

Economic complexity is a set of methods with a strong data-driven component. With foundations in big-data analysis and machine learning, some see it as an entirely atheoretical method. However, economic complexity has deep theoretical roots, arising from an original understanding of what technology is. Technology, in fact, can be thought of as a combination three things (Balland et al., 2022):

- tools, like industrial machines – that is knowledge embodied as physical objects;
- codes, like blueprints or patents – that is knowledge codified into abstract symbols and stored in papers or computers;
- know-how – that is knowledge residing solely in the human brain.

Our ability to operate technology typically requires all three forms of knowledge, which complement each other. Imagine you come into possession of the blueprint for an electric engine: in order to make it operational you would need not only the material and tools to build it but also the know-how to do it successfully. Numerous empirical studies show that there is considerable tacit know-how involved in the operationalisation of a patented invention and that the subsequent transfer of technology is often achieved through personal relationships (Lee, 2012).

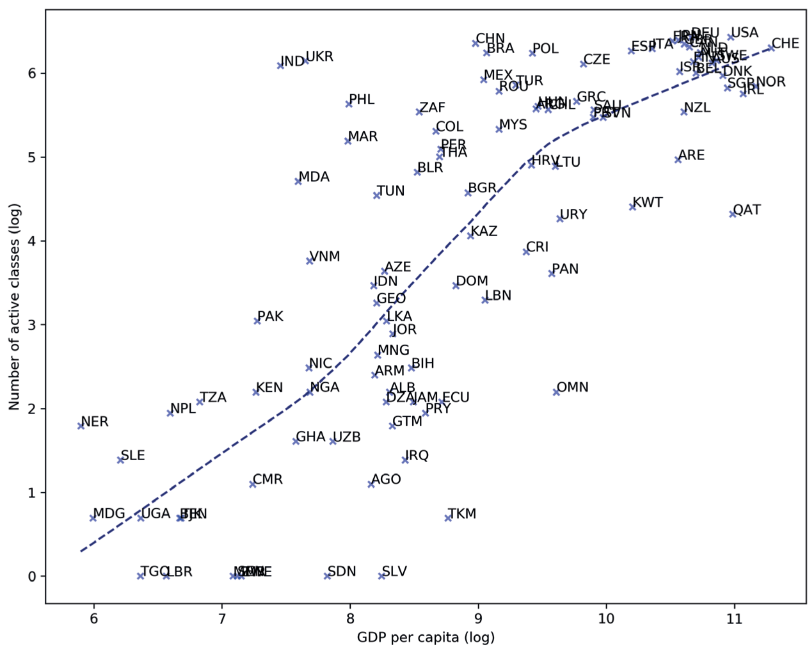
This observation highlights the fact that, among the three constituents of technology mentioned above, know-how is the real bottleneck: it cannot be easily bought, transported, transmitted or accumulated. Here is where the economic complexity approach conveys its important theoretical insight: given the limited capacity humans have to accumulate knowledge, technology can only accumulate at societal level through the distribution of know-how across different brains. But this implies that a society that has accumulated a lot of knowledge is a diversified society, with individuals who specialise in storing different bits of knowledge (Hausmann, 2013).

This theoretical insight resonates with a known empirical regularity about development: production in rich countries is more diversified than in developing economies. While it is subject to some nuances[2], this stylised fact appears to hold with respect to technological diversification (see figure 9-1).

2 There is evidence that, at a relatively high level of development, a country's production tends to reconcentrate. However, the reconcentration is only partial and, therefore, it still holds that, on average, production in rich countries is more diversified than in developing economies (Imbs and Wacziarg, 2003; Cadot et al., 2011).

Figure 9-1 gives a static depiction of the complexity theory of technology: developed countries have a lot of know-how, but since different parts of know-how are distributed across many brains, developed countries are more diversified on average. On the other hand, figure 1 also reflects the dynamics of knowledge creation in a complex world: invention often emerges from the combination of existing technologies (Fleming and Sorenson, 2001). Thus, a country that has a lot of know-how (that has access to many diverse types of know-how) has a higher chance of combining its bits of knowledge into new technology.

Figure 9-1 Technological diversification and GDP per capita



Note: The horizontal axis depicts the 2016 World Bank estimate of GDP per capita by country (in logs), while the vertical axis depicts the number of four-digit cooperative patent classification (CPC) patent classes in which the country was active in that year. Both axes are in logarithmic scale.

To maximise the transformative and growth-inducing effects of the European green deal, the EU should thus aim at mastering as many green technologies as possible. But how to achieve this? While economic complexity is not a magic wand that can formulate prescriptive policies, it can, nonetheless, offer guidance regarding the direction of policy intervention. The theory of economic complexity, in fact, suggests that, when technology is made by a combination of bits of know-how, it is possible that a country (or region) already has many of the necessary bits. The economic complexity methods known as 'relatedness' and 'product space' are designed specifically for that purpose: to allow us to infer which products or technologies are related to the know-how present in a given region.

In practical terms, this is achieved in three empirical steps.

1. Measuring the breadth of know-how of a country or region. By virtue of the complementarity between codes and know-how, patents can be used as a proxy for tacit know-how. Patents are also classified by technology, which gives an indication of which type of know-how is held in the territory. Figure 1 is an example of the measurement of know-how diversity via patents.

2. Measuring the similarity between technologies. To what extent do two technologies use the same bits of know-how? While it is very hard to give a direct answer, economic complexity proposes a method for indirect measurement: two technologies are similar if they are often produced in the same places. For instance, if most regions that produce innovations in four-stroke piston engines also produce a significant number of patents for two-stroke piston engines, we can deduce that the two technologies have many know-how elements in common.

3. Measuring the proximity of a place to a technology. Now that we have a map of which technologies require which types of know-how (from step 2), we can use the information on the existing know-how in a region or country (from step 1) to assess which technologies it is feasible for that region or country to develop.

From these three steps, we can assess whether a region has the know-how to make development of a given technology feasible, even if we do not currently see significant patenting activity. Throughout this chapter, we will call this measure the **potential** of the region in the technology.

3. Selection of green technologies

The prominent role of diversification in economic complexity theory suggests that the EU's focus should be on green technologies in which it is relatively weak. While the theory of (Ricardian) comparative advantages has at times been interpreted as indicating that one should focus, instead, on areas in which one is relatively strong, according to economic complexity, growth comes from the accumulation of diverse know-how. The challenge, therefore, is to fill technological gaps[3].

Since not all technologies are equally important, in this report we look only at green technologies that satisfy the following four criteria:

- the technology is sizable (worldwide patenting output above the median);
- the technology is growing (10-year worldwide patenting growth rate above zero);
- the EU's share is low (below that of the US or China);
- the EU is not closing the gap (the EU's growth is below that of the US or China).

To perform this assessment, we analyse green technologies in accordance with the CPC green patent classification[4]. Using an 8-digit system, this classification distinguishes between 48 green technologies. While it is possible to use economic complexity methods at higher or lower levels of aggregation, we believe the following level of coarse-graining is an excellent compromise: green technologies are

3 This is a multifaceted topic; see section 5 for a more in-depth policy discussion.

4 We consider the Y02 and Y04 patent classes.

considered in sufficient diversity to advance our understanding but not in so fine-grained a way as to introduce unwanted noise[5].

Applying the criteria above to the 48 green technologies, we select the following four.

- Filters (Y02A50/00): technologies for adaptation to climate change in human health protection, e.g. against extreme weather. They include catalytic converters to control or reduce vehicle emissions and technologies to guard against vector-borne diseases.
- Aeronautics (Y02T50/00): aeronautics or air transport. This includes drag reduction, wing-lift efficiency, weight reduction and efficient propulsion technologies for aircraft.
- Energy-efficient computing (Y02D10/00): climate change mitigation technologies in ICT – energy-efficient computing, e.g. low-power processors, power management or thermal management.
- Energy efficient communications (Y02D30/00): climate change mitigation technologies in ICT – reducing energy consumption in communication networks.

By using less strict criteria, a larger set of technologies could be analysed. However, we believe that limiting the number of technologies helps to keep the analysis focused. While future work could look at other innovative activities, in the next section, we analyse the possibilities for diversification in these four technologies.

4. Main results

To assess the potential of different regions in the EU with respect to these four technologies, in which the EU is lagging, we use the three-step methodology outlined in section 2. In the context of green technologies, the steps are as follows:

- measurement of the capacities of EU regions in all technologies (not solely green technologies);
- measurement of the relatedness between non-green and green technologies (using global data);
- computing of a measure of potential: does the region have non-green technologies that are related to the green technology of interest?

This approach is very suitable for evaluating potential in regions where there is no output. As discussed in section 2, economic complexity has both a theoretical and an empirical basis. The driving principle behind the method can be found in both. The theoretical basis suggests the use of information on a region's existing know-how (together with a map of similar technologies as regards required know-how) to assess whether a technology has potential in that region. However, from an empirical perspective, we are often not in a position to judge whether two technologies require similar know-how. That is why similarity between technologies is assessed via methods resembling machine learning techniques.

5 We also note here that the methodology is flexible and can accommodate a variety of technological definitions. In chapter 2 of this report, for instance, the methods of economic complexity are employed to study 15 key strategic technologies, including (but not limited to) green technologies at a different level of aggregation.

When we buy a pillow online, we may be prompted to buy a pillowcase as well. Such recommendations are not based on knowledge of the relationship between the two objects but on other people's purchasing habits: if many users have bought pillows and pillowcases together, an online platform may infer a connection and make a recommendation. In a similar way, if many countries are innovating in a given pair of technologies, one may infer a technological similarity between them.

This was the original intuition of Hidalgo et al. (2007). Since then, extensive evidence has been accumulated showing that the appearance of products and technologies can be predicted (Hidalgo et al., 2018). We internally validate the exercise in this analysis by verifying that our measure of green-technology potential can correctly predict the appearance of a green technology in the following 10 years.

While patenting output in the four green technologies is low, it is not zero in all regions in Europe. It is, therefore, useful to see in which regions patenting activities in these areas have already taken place. For every region, our analysis highlights both the patenting activities and the potential for patenting in these green technologies – a potential that we assess via the economic complexity methodology.

We summarise our core results in the maps in figures from 9-2 to 9-5. The maps depict the actual patenting activities through changes in hue: oranges for regions with few patents, purples for medium-level patenting and blues for the regions most active in the technology. Potential is highlighted by saturation. For instance, regions with most patenting will have the following colours: light blue for low potential, mid-toned blue for medium potential, darker blue for high potential. The full colour scheme can be seen in the top-right corner of each map.

If one looks at the colour pattern of all of the maps together, one feature stands out: there is an almost complete absence of light pink and light blue. This implies that, when significant patenting activity in a technology occurs in a region, our measure of potential correctly assigns a high value to that region[6]. The opposite is not true: the prevalence of yellow and orange suggests that there are many regions with high potential and low levels of patenting activity, indicating the absence of specific capabilities but the presence of related know-how. These regions could be a good starting point for policy purposes. In section 5, we discuss in more depth possible interpretations of these patterns for policies at regional level. Hereafter, we describe the findings in a more neutral manner[7].

A second common feature of the maps is that some core regions – partially along Europe's blue banana but especially in southern Germany and southern France and the Île-de-France – perform highly in almost all technologies, while others – specifically in eastern Member States and, to a lesser extent, the Iberian Peninsula – are often characterised by a lack of both patenting and potential.

In spite of this, a third feature that stands out is the variety across the maps, with some regions having high capabilities or high potential in some technologies, while performing poorly in others.

Figure 9-2 summarises our findings concerning regional[8] innovation in green technology Y02A50/00 (a class that includes catalytic

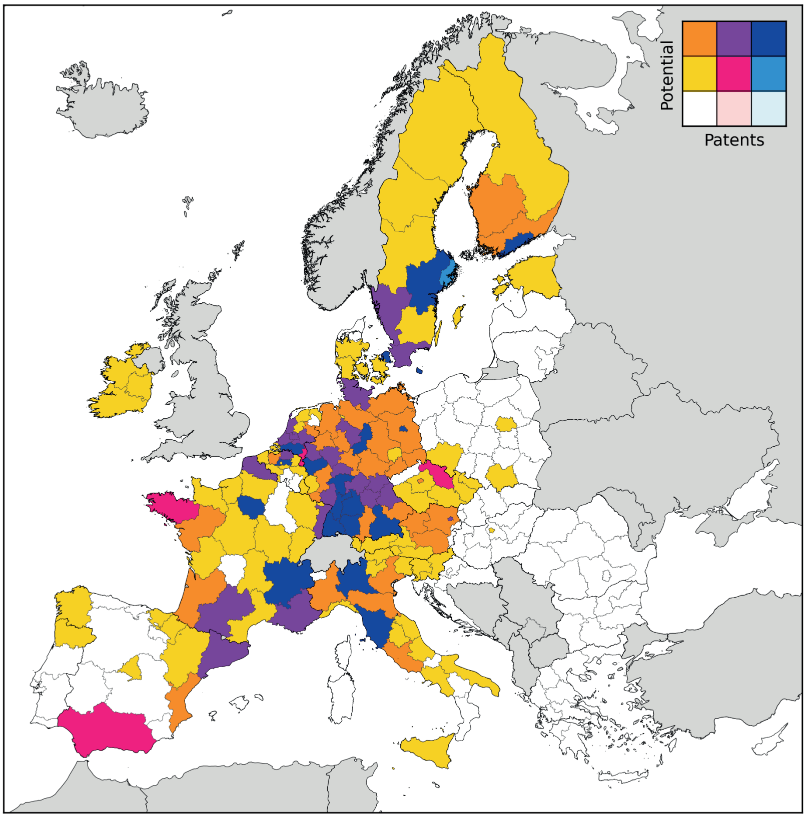
6 Note that our measure of potential does not use information on patenting in green technology. This suggests that potential is an early sign of future patenting. We see this as a corroboration of our approach: the potential metric we propose is likely capturing a relevant signal.

7 Some would say the analysis in this section is 'positive', while that in the following section is 'normative'.

8 NUTS 2 regions as defined by the 2021 nomenclature of territorial units for statistics.

converters for vehicle emission control or reduction, which, for simplicity, we label as 'filters'). The map shows a heterogeneous landscape across the EU, with low levels of patenting and potential (white) in many regions. Such regions are concentrated mostly in eastern Member States and the Iberian Peninsula. The remaining Member States are mostly coloured, which implies that their regions have at least medium patenting potential in filters, irrespective of the volume of patents they currently produce. Most of the coloured regions are either yellow or orange, meaning they have medium or high potential and low current levels of patenting. Regions of this kind are present in all Member States active in green technology. The map also shows a relatively large number of violet and dark blue regions, i.e. regions that combine high potential with medium or high patenting activity. Purple regions are concentrated mostly in France, Germany and Sweden, while blue regions also appear in Belgium, Denmark, Finland, Italy and the Netherlands. A rare occurrence in figure 9-2 are pink regions, i.e. regions with medium potential and medium patenting activity; we see a few in Czechia, France and Spain. Less frequent still are medium-toned blue regions, i.e. regions with medium potential and high patenting activity; we see only one such region, in Sweden.

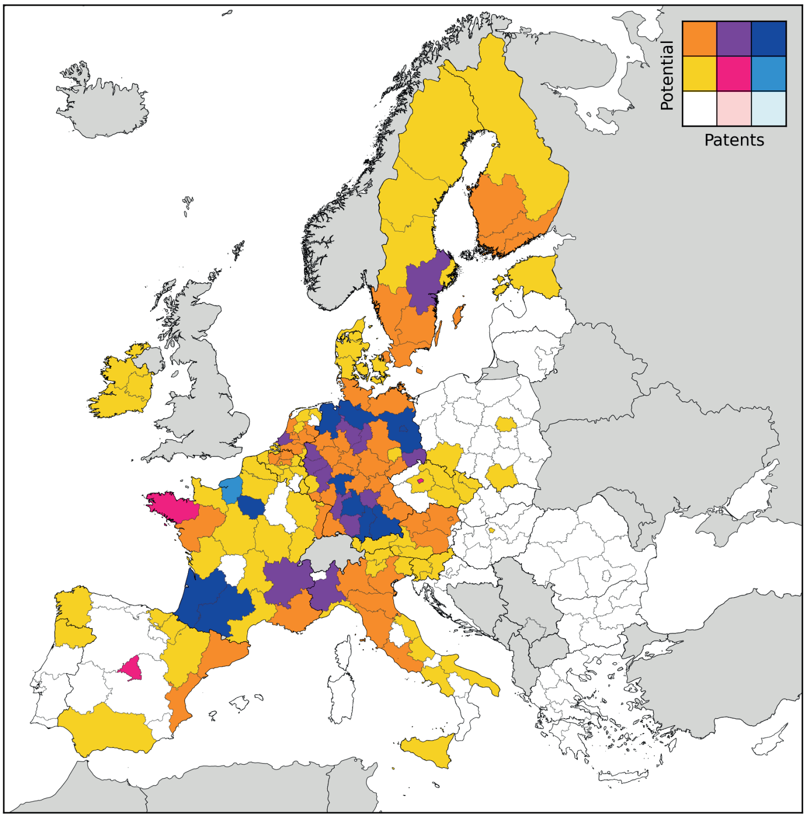
Figure 9-2 Map for green technology 'filters'



Note: The map depicts the level of patenting activity in and the potential for green technology Y02A50/00 – technologies for adaptation to climate change in human health protection, e.g. against extreme weather ('filters'). Each NUTS 2 region is assigned a colour based on two variables: number of patents determines the hue (low: oranges, medium: purples, high: blues); potential of the technology determines the saturation (low: white, light pink, light blue; medium: yellow, pink, medium blue; high: orange, purple, blue).

Figure 9-3 depicts activity in green technology Y02T50/00 (aeronautics). The prevalence of yellow and orange tones indicates that there are many regions with potential in this technology. With minor differences compared with filters, a lack of patenting and potential in aeronautics is again observed in the Iberian Peninsula and across the east of the EU. Additionally, highly performing regions in France and Germany maintain a relatively strong position. However, compared to filters, there are important differences. For instance, the good performance (highlighted in blue) of regions in south-western France and northern Germany is noteworthy – likely driven, in part, by the presence of Airbus. Beyond France and Germany, a few purple regions (strong potential, medium-level patenting) are observed in Italy, the Netherlands and Sweden, while pink (medium-level potential and patenting) can be found in Madrid, Brittany and Prague. Again, there is only one region in light blue (medium-level potential and high patenting), namely Upper Normandy.

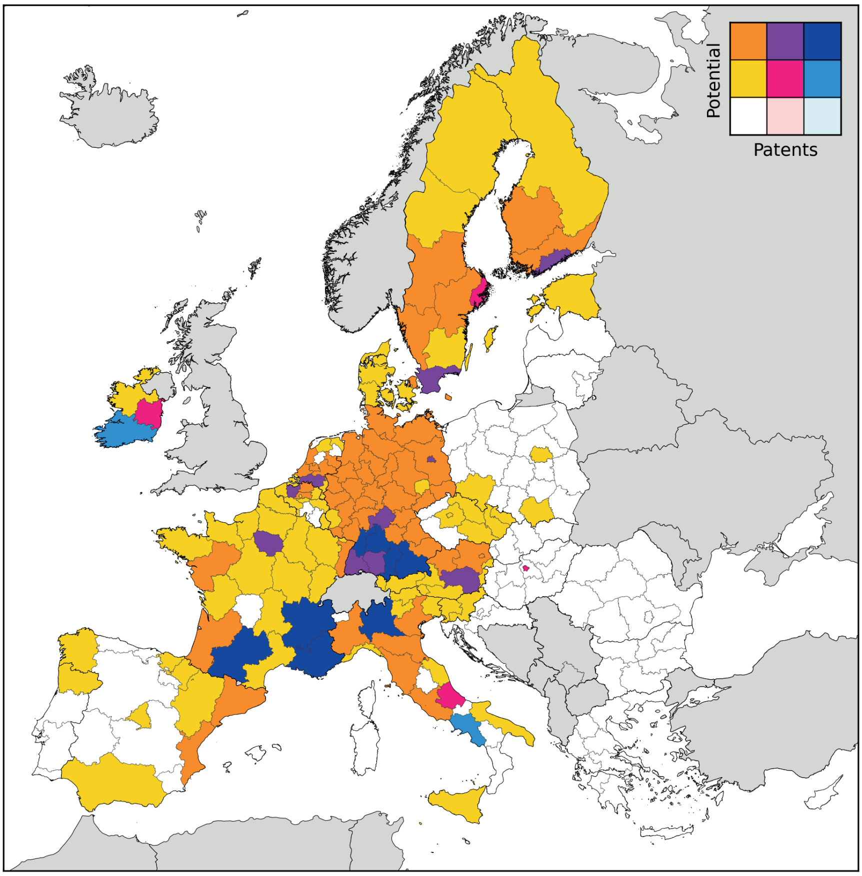
Figure 9-3 Map for green technology 'aeronautics'



Note: The map depicts the level of patenting activity in and the potential for green technology Y02T50/00 – aeronautics or air transport ('aeronautics'). Each NUTS 2 region is assigned a colour based on two variables: number of patents determines the hue (low: oranges, medium: purples, high: blues); potential in the technology determines the saturation (low: white, light pink, light blue; medium: yellow, pink, medium blue; high: orange, purple, blue).

For the green technology, energy-efficient computing (figure 9-4), we can identify the usual broad patterns. Nonetheless, there are some important differences. Northern Germany is not as strong as in the other three technologies analysed. There are only a few high performing (blue) regions, mainly clustered around the Alps in France, Germany and Italy (the only exception being the region of Midi-Pyrénées in France). We observe promising potential in purple regions in Austria, Belgium, Finland, France, Germany, the Netherlands and Sweden and medium potential with significant patenting activity (pink and light blue regions) in Hungary, Ireland, Italy and Sweden.

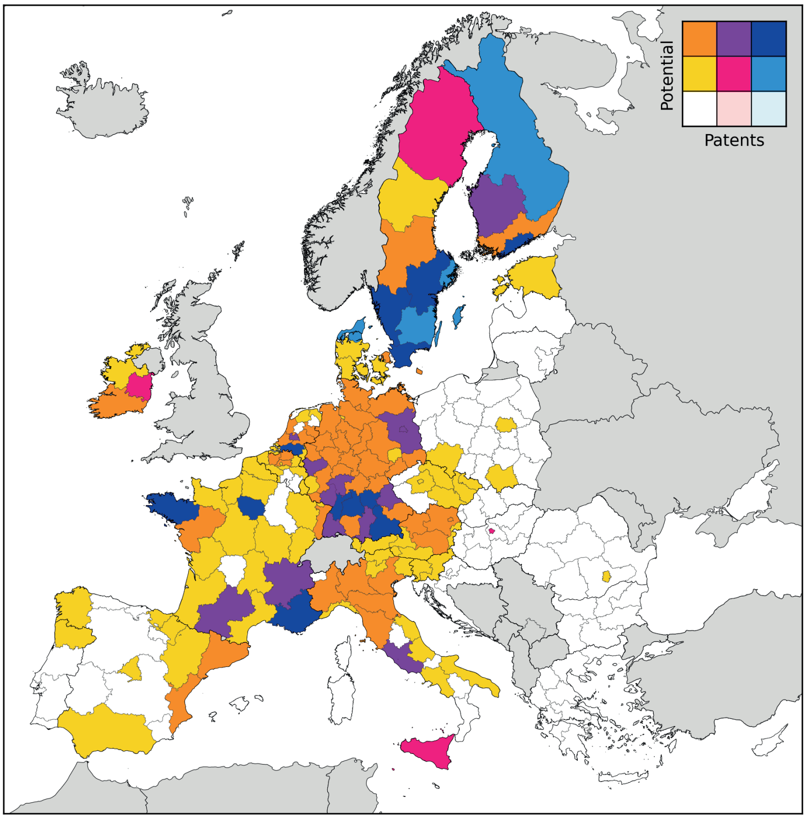
Figure 9-4 Map for green technology 'energy-efficient computing'



Note: The map depicts the level of patenting activity in and the potential for green technology Y02D10/00 – climate change mitigation technologies in ICT: energy-efficient computing ('energy-efficient computing'). Each NUTS 2 region is assigned a colour based on two variables: number of patents determines the hue (low: oranges, medium: purples, high: blues); potential in the technology determines the saturation (low: white, light pink, light blue; medium: yellow, pink, medium blue; high: orange, purple, blue).

Lastly, figure 9-5 highlights regional performance in energy-efficient communications. Beyond the patterns that are common across the maps, the most striking feature is the strong performance of Finland, Sweden and (to a lesser extent) Denmark. Regional hubs in this technology also exist in Belgium and, as usual, France and Germany. Other areas of interest are the region of Lazio, which is purple, and the mid-performing regions of Budapest, Eastern and Midland Ireland and Sicily.

Figure 9-5 Map for green technology 'energy-efficient communications'



Note: The map depicts the level of patenting activity in and the potential for green technology Y02D30/00 – climate change mitigation technologies in ICT: reducing energy consumption in communication networks ('energy-efficient communications'). Each NUTS 2 region is assigned a colour based on two variables: number of patents determines the hue (low: oranges, medium: purples, high: blues); potential in the technology determines the saturation (low: white, light pink, light blue; medium: yellow, pink, medium blue; high: orange, purple, blue).

5. Policy

In this chapter, we have aimed to highlight that (green) technological diversification is important for growth. For this reason, we have focused our analysis on four technologies where the EU, by some measures, has been performing poorly.

The idea of focusing on 'weak' technologies is justified by the economic complexity theory of growth, but to avoid misinterpretation we feel it is necessary to better explain the concept with a few remarks.

Firstly, focusing on weak technologies does not mean neglecting one's comparative advantage. The guiding principle, in this context, is that of accumulating capabilities. Thus, policies may focus on technologies that are closely related to currently available know-how but are not yet fully developed. This is similar in spirit to the entrepreneurial discovery process in smart specialisation, where the aim is to focus on one's own competences and capabilities in order to expand into new domains. Regions that are coloured yellow and orange in section 4 are prime candidates for this type of policy. Such policies may also be suitable for purple and pink regions, which already have some patenting activity to show for. Blue regions, on the other hand, have significant patenting in the technology, though that does not necessarily mean that public investment in those regions would go against the principles of economic complexity. This relates to our second remark.

Specialisation and diversification are often a matter of scale. We have observed that wealthier countries are more technologically diversified, but that does not imply that this translates to lower levels, for instance to cities or regions. Some technologies may need agglomeration economies and, while at national level diversification may be desirable, at subnational level it may make sense to concentrate on just a few areas. This is perhaps the case when a country is relatively weak in a technology but has a region that exhibits some capabilities in that technology. The concept also translates to a larger scale, for instance EU level: when assessing how to address low levels of performance in a technology, the decision on whether to invest more in regions with high potential or in regions with high capability might take into account the degree of concentration in the technology.

Thirdly, the guiding principle of accumulation of capabilities can also inform policies from a regional cohesion perspective. In other words, while the maps show some variety, a number of regions (and countries in some cases) have little patenting activity and little potential. A separate analysis could find out which green technologies are most closely related to currently available know-how in these regions, giving them an opportunity to contribute to the green transition, while accumulating capabilities (and growing) in the process.

6. Conclusions

In this chapter, we have applied the worldview and methods of economic complexity to the issue of the achievement of a growth-inducing green transition. The theory of economic complexity states that growth happens through the accumulation of a diverse set of capabilities, indicating that the EU should attempt to master a variety of green technologies rather than focusing on what it does best. But how can this be achieved?

Economic complexity gives an indication of how the EU can accumulate such capabilities. Technological diversification of countries and regions rarely happens in big leaps. Rather, it is a gradual process, with countries and regions gravitating towards new technologies that are, to some extent, similar to those that they have already mastered.

This chapter has thus performed an empirical assessment of the diversification possibilities of European regions – that is, their potential in a specific green technology, based on current capabilities. We have identified four green technological classes that appear important from observation of worldwide patenting activity and in which the EU seems to be lagging behind China and the US. For these four technologies, we have looked at existing capacity and potential across the EU, identifying which regions are always strong, which often underperform, and which have capabilities geared towards a specific technology but not towards others.

We believe this analysis can provide a rich framework for designing policies at different scales. At EU and national levels, officials who are interested in a specific technology can use the framework to help identify investment opportunities. Regions that are already strong are potentially good candidates if the technology of interest exhibits strong local externalities and clustering behaviour. On the other hand, when these externalities are not present to any great extent, policy interventions could target regions with high potential.

For regional policymakers, the framework can provide guidance as to which technologies are worth focusing on. The guiding principle, we argue, should be that of accumulation of capabilities: each region should look at its own skill set, as well as its potential, and only invest in technologies that are feasible to develop and that will allow the region to accumulate new know-how that fuels growth.

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CHAPTER 10

SUSTAINABLE AND INCLUSIVE PRODUCTIVITY GROWTH? DIAGNOSIS AND POSSIBLE POLICY ACTION

Won Hee Cho, Chiara Criscuolo, Isabelle Desnoyers-James, Martin Reinhard, Rudy Verlhac

Organisation for Economic Co-operation and Development

Abstract

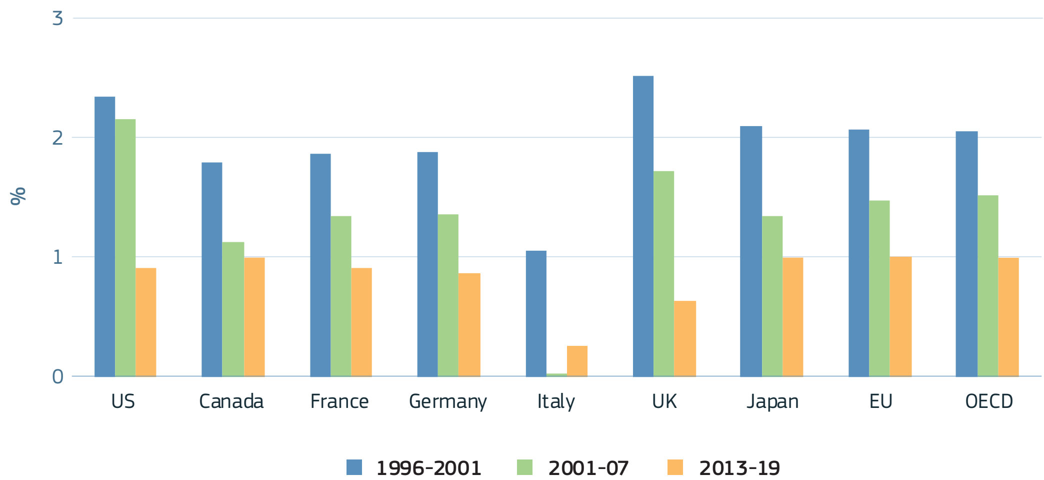
This chapter investigates the considerable slowdown in productivity growth observed globally, with a particular focus on the European Union. It explores the causes and consequences of this deceleration, highlighting the growing productivity gaps between leading "frontier" firms and less productive "laggards", as well as the challenges posed by digitalisation and the green transition. The analysis points out that digitalisation has favoured the emergence of "superstar" firms, increased market concentration, and reduced business dynamism. It suggests that these persistent trends may potentially dampen innovation and growth. The chapter also emphasizes the positive relationship between productivity growth, employment, and wages, and underscores the importance of inclusive growth strategies for strengthening these relationships. It argues for comprehensive policy actions to boost digital adoption, encourage innovation, and ensure that the benefits of productivity growth are widely shared.

1. Introduction

Productivity growth is vital for enhancing living standards and bolstering overall economic prosperity. The widespread productivity slowdown, i.e. the deceleration in the rate of productivity growth, is therefore a prevailing concern among both policymakers and academics.

Figure 10-1 illustrates the widespread nature of the productivity slowdown in both EU and OECD countries. Focusing on the evolution of productivity growth over time, data reveal a notable trend in the EU, where annual productivity growth averaged 2% during the period 1996-2001 but declined to 1.5% over the period 2001-2007 and further dropped to 1% during the period spanning 2013-2019[1]. These figures underscore the persistent and concerning deceleration in productivity growth over the years.

Figure 10-1 Gross Domestic Product (GDP) per hour worked: annual average growth



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Source: Calculations based on the OECD productivity database.
Note: Each bar represents the average annual growth of labour productivity, measured as GDP per hour worked for each period. The data for OECD excludes Estonia and South Korea due to differences in the periods covered.

1 The Figure excludes the period 2008-2013 corresponding to the great financial crisis and the Eurozone crisis, and subsequent recovery years, which were marked by particularly low productivity growth.

OECD research has further documented simultaneous and interconnected trends reflecting a decline in business dynamism. This decline is underscored by diminishing entry rates, reduced job reallocation rates and a shrinking share of young firms in total employment. These indicators collectively suggest a potential attenuation in the role of creative destruction, a vital driver of both employment and productivity growth. Moreover, prior and ongoing OECD analyses shed light on the evolution of proxies of competition at the sectoral level, with increases in mark-ups, concentration and entrenchment (Bajgar et al., 2019; Bajgar, Criscuolo and Timmis, 2021). These trends are also coupled with an increase in the gap between productivity-frontier firms and the rest of the business population (Andrews, Criscuolo and Gal, 2016; Berlingieri et al., 2020), with potential consequences for innovation (Akcigit and Ates, 2020) and inclusiveness (Criscuolo et al., 2022).

Academic research and OECD analyses have put forward different potential explanations for the observed phenomena. Notably, the uneven and incomplete nature of digital transformation and the increasing importance of intangible assets have played a key role in widening the productivity gap between the leading performers at the frontier and the rest, with the least productive firms (laggards) further falling behind (Berlingieri et al., 2020; Corrado et al., 2021).

Over the last few years, heightened uncertainty and what are generally referred to as polycrises, with events such as the COVID-19 pandemic, the Russian invasion of Ukraine with the subsequent increase in energy costs, heightened geopolitical tensions, global warming and recent shifts in economic conditions, have collectively moulded a new state of the economy, potentially presenting considerable challenges for productivity growth. A silver lining to these headwinds was thought to come from the sudden widespread adoption of digital technologies and telework during the pandemic (see also Criscuolo et al. (2021) and Calvino, Criscuolo and Ughi (forthcoming)) and the implementation of ambitious rescue and recovery packages. And the question is still open on whether the ongoing resurgence of new industrial policies and reliance on mission-oriented industrial strategies, for example in the context of COVID-19 resilience packages, could have the potential to transform these challenges into opportunities, fostering an accelerated transition towards a more inclusive and environmentally sustainable, climate-neutral, economy.

This chapter will summarise new evidence on productivity growth dynamics and the role of productivity for employment and wages, as well as the digitalisation of the economy and the green transition, uncovered in recent and ongoing work by the OECD. It will also discuss how the resurgence of industrial policies calls for additional analysis to measure and coordinate government action. The chapter is structured as follows.

Section 2 provides new evidence on widening productivity gaps, emphasising a divergence among firms. This includes an increasing heterogeneity between the most and least productive firms, as well as a deterioration in the relative productivity of small and micro firms. The section also discusses novel analysis linking challenges faced by the less productive and smaller firms in keeping pace with the rest to concerns for future aggregate productivity growth.

Section 3 extends the discussion to the role of productivity growth in supporting employment growth at both firm and aggregate levels and the importance of policies that promote catch-up and support contestable markets for boosting employment growth and resource reallocation. The chapter also delves into evidence on declining labour shares, indicating that the observed reduction in aggregate labour share can be, at least partly, attributed to the reallocation of value added to high-productivity, low-labour-share firms. While such reallocation can enhance productivity at an aggregate level, policymakers need to ensure that potential trade-offs between productivity growth and inclusiveness are carefully considered when designing policies. Policies that focus on the development of skills, diffusion of technologies and best practices could play an important role as they could help achieve double dividends by raising the productivity of less productive firms and empowering workers to benefit from and support the diffusion of technology.

Section 4 discusses the challenges and opportunities arising for the business sector from the green and digital transitions. Evidence indicates that the COVID-19 crisis, while accelerating the digital transition, may have exacerbated digital gaps, raising concerns about further productivity divergence. Indeed, firms that were more engaged in digitalisation and were more productive before the crisis were more likely to adopt digital applications. Additional evidence examining the diffusion of artificial intelligence (AI) also highlights adoption patterns that favour larger and more productive firms. Policies are necessary to accelerate a broad and inclusive digital transition, which should also align with the green transition, requiring a profound transformation of the economy and the business sector. Addressing these challenges requires boosting innovation, diffusion, business dynamics and reallocation, and simultaneously fostering inclusiveness and economic resilience.

In this context, the industrial strategies discussed in section 5 will also be paramount. That section presents insights from the OECD Quantifying Industrial Strategies (QuIS) project, which quantifies and analyses industrial strategies across countries.

2. Business dynamism, productivity and divergences

2.1 Slowing dynamism and creative destruction

The OECD DynEmp project offers compelling evidence regarding the decline in business dynamism across countries, evident from declines in entry rates, job reallocation rates and the share of young firms in total employment within narrowly defined industries (Calvino and Criscuolo, 2019; Calvino, Criscuolo and Verlhac, 2020). Updated data show that these trends persisted prior to the COVID-19 crisis, as illustrated in Figure 10-2. Additional evidence from the project indicates a diminishing share of start-ups (0-2-year-old firms) among micro firms (2-9 employment units) over time, which may reflect declines in entry rates but may also raise concerns about the capacity of young firms to scale up and grow out of the micro firms size group[2]. Such evidence on declining dynamism, together with concomitant increases in dispersion of productivity (discussed next), declines in the speed of diffusion (Berlingieri et al., 2020; Akcigit and Ates, 2020) and the rise in industry concentration and mark-ups documented by the OECD (Bajgar et al., 2019; Bajgar, Criscuolo and Timmis, 2021; Calligaris, Criscuolo and Marcolin, 2018; Criscuolo, 2021) points to a possible decline in creative destruction, and an increase in entrenchment at the top (Van Reenen, 2018; Bessen, 2022). This has raised concerns in the academic and policy arena about the future of innovation, independently of whether these trends are linked to technology factors (see for example (Bessen, 2022; Haskel and Westlake, 2018; Haskel and Westlake, 2022; Van Reenen, 2018) and OECD work reported in previous SRIP reports (Criscuolo, Goretti and Manaresi, 2022)), a worsening of competition enforcement (Philippon, 2019; Covarrubias, Gutiérrez and Philippon, 2019) or a combination of the two as discussed in Crawford, Valletti and Caffarra (2020) and references therein.

New and young firms may face significant challenges when competing with market leaders (Akcigit and Ates, 2020; Akcigit and Ates, 2021) and need to build their reputation and customer base, which requires them to charge lower prices (Foster, Haltiwanger and Syverson, 2008). This could discourage potential entrants and limit upscaling, in line with evidence of the decline in high-growth young firms (Decker et al., 2016). Barriers to the diffusion of technology and knowledge may prevent entrants and laggard firms from innovating, adopting existing knowledge or learning from the best performing firms, and may further limit experimentation and reallocation through creative destruction. Theoretical models and empirical evidence suggest that, in recent years, an increase in these challenges may be at the root of secular stagnation (Aghion and Howitt, 2023). As suggested by Akcigit and Ates (2021), leaders may have become better at preventing the diffusion of their knowledge, via the acquisition of patents for defensive purposes, which would discourage innovation efforts by non-frontier firms, especially laggards, and increase rents for leaders. Aghion et al. (2023) compare trends in performance of frontier superstar firms and laggards and hypothesise that, thanks to the digital revolution, superstar firms may have been able to accumulate social capital and know-how or develop networks in a larger fraction of sec-

2 The fact that the share of young firms among micro firms is declining could be related to two factors: i) the decline in entry rates which is associated with a lower number of micro-entrants relative to the total business population and ii) insufficient post-entry growth which would imply that firms stay in the micro-size class longer, changing the age composition of this group.

tors, while non-frontier firms could not, and this may have allowed the former to increase their mark-ups. By maintaining their position as superstars, they discourage innovation and entry, leading ultimately to decline in growth[3].

Empirical evidence in line with these theories has been growing. Early work by the OECD on the great divergences in productivity and wages, the role of digital technologies and the growth in intangible assets as possible drivers of these trends (OECD, 2015; Berlingieri, Blanchenay and Criscuolo, 2017) has been further corroborated in single-country studies. In particular, Bessen (2022), Autor et al. (2020) and De Loecker, Obermeier and Van Reenen (2022) further link rising concentration and mark-ups and declining industrial disruption to the growth of proprietary software and, more broadly, to digitalisation and globalisation.

In sum, larger gaps between leaders and laggards, stronger concentration of both sales and labour/talent, defensive use of intellectual property rights and higher entrenchment may represent important factors hampering the creative destruction process as they reduce the chances for start-ups and laggards to leapfrog the leaders, potentially reducing incentives for experimentation and innovation. These dynamics related to slower knowledge diffusion and increased market power are possibly amplified by the digital transition (Calvino, Criscuolo and Verlhac, 2020).

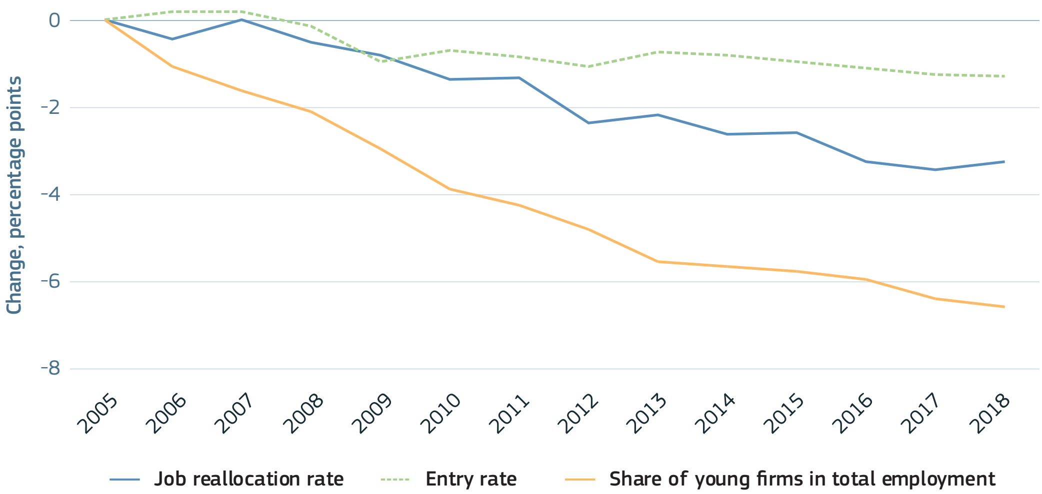
In this context of declining dynamism over the long term, dynamics of new business registrations and venture capital (VC) financing have been noticeable since the onset of the COVID-19 crisis (Berger, Dechezleprêtre and Verlhac, forthcoming). Following a large decline in registrations, many countries have experienced a rapid recovery and a surge in registrations that persisted in 2021. Overall, the impact of the crisis appears to have been mitigated and a 'missing generation' of new firms seems to have been avoided in most countries (with some noticeable exceptions such as Portugal). Therefore, business dynamics have shown significant signs of resilience during the COVID-19 crisis, in stark contrast with the 2008-09 crisis which demonstrated the potentially disproportionate impact of economic and financial disruptions on young firms. The VC market (further analysed in Berger, Dechezleprêtre and Verlhac (forthcoming)) also demonstrated resilience across various funding stages, regions and sectors and even reached peak values during the pandemic. The surge in registration and the peak in VC funding raises hopes that the pandemic may have triggered a wave of innovation.

Nevertheless, significant uncertainty prevails regarding whether these dynamics mark a turning point in the long-term trends of declining business dynamism across countries or simply a temporary uptick. Recent data from the OECD Timely Indicators of Entrepreneurship already suggest that this revival has been fading away, in a context marked by the Russian invasion of Ukraine in 2022, the related energy crisis, rising political and economic uncertainties and high inflation. In 2022, many

3 Note that dominant positions of superstar firms may not only discourage widespread innovation by disruptive innovators but may also slow down innovation by industry leaders as they become entrenched incumbents. If leaders dedicate more resources to avoiding competition, this may, in turn, reduce their productive innovation efforts, even though they initially gained their leading position through innovation and high efficiency. Aghion and Howitt (2022) further summarise mechanisms through which incumbents may avoid competition and deter innovation and growth. One mechanism (the 'automatic mechanism') arises from the fact that dominant firms with large market shares and large technological leads have little incentive to innovate in order to avoid competition, while the remote prospect of catching up and competing with leaders reduces the profitability of entry and innovation for other firms. a second mechanism relates to the strategic behaviour of leaders using their power to block innovation by potential rivals. This includes the use of pre-emptive mergers, strategic innovations and patent thickets, as well as lobbying that helps dominant firms raise regulatory barriers against potential rivals.

countries experienced a slowdown or even a decline in business registration relative to 2021, and these dynamics persisted over the first half of 2023, while bankruptcies returned to pre-crisis levels after the lows experienced during the pandemic. Mirroring the overall business dynamics, the VC market experienced a 'boom-and-bust' cycle as it reached peak values during the pandemic but subsequently reverted to pre-crisis levels towards the end of the pandemic. Therefore, reigniting business dynamics beyond the transient improvements experienced during the pandemic and its aftermath should remain a key policy objective.

Figure 10-2 **Declining business dynamism**



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Source: OECD DynEmp database, updated from Calvino, Criscuolo and Verlhac (2020).

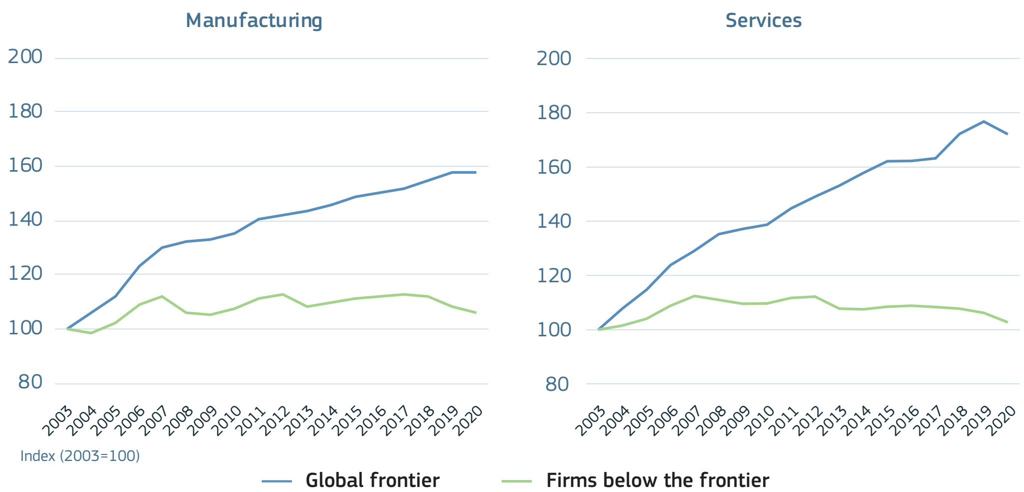
Note: This Figure reports average within-country-industry cumulative changes in the share of employment in young firms, changes in job reallocation rates and changes in entry rates based on the year coefficients of regressions within country-industry for the period 2005-18, including 16 countries: Austria, Belgium, Canada, Croatia, Denmark, Finland, France, Germany, Hungary, Italy, New Zealand, Norway, Portugal, Slovenia, Spain and Sweden. Each point represents cumulative change in pp since 2005.

2.2 New evidence on dispersion and the link between productivity divides and aggregate productivity growth

The widening of the productivity gap between firms at the frontier and others has occurred between the global frontier and the rest, but also between national frontier and non-frontier firms (Berlingieri, Blanchenay and Calligaris, 2017; Berlingieri, Blanchenay and Criscuolo, 2017; Corrado et al., 2021; Andrews, Criscuolo and Gal, 2016). Updated evidence shows that such divergence persisted over the period prior to the COVID-19 crisis, with increasing disparities between the global frontier and other firms (see Figure 10-3).

This widening dispersion in productivity mirrors a similarly divergent trend observed between firms of varying sizes. Berlingieri, Calligaris and Criscuolo (2018) documented substantial differences in productivity between firms of different sizes (in terms of employment), revealing more prominent disparities in manufacturing than in non-financial market services. Data from the OECD MultiProd project suggest that the productivity gaps between firms of different sizes have increased over time. In manufacturing industries, the productivity advantage of medium-sized and large firms relative to smaller firms has increased significantly over time, while the relative productivity of small and micro firms has deteriorated. In non-financial market service industries, the productivity gap between small and micro firms and the rest has also widened. Further evidence suggests that the productivity of both older and younger micro firms relative to larger firms has declined over time. This raises additional concerns about the widespread diffusion of technology and knowledge, especially among micro, small and medium-sized firms.

Figure 10-3 **Divergence in labour productivity between the global frontier and the rest**



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Source: André and Gal (2024). Updated calculations following the methodology in Andrews, Criscuolo and Gal (2016).
Note: Index (2003 = 100) of productivity at the frontier and below the frontier, approximated by changes in logs. Average across detailed industries using firm-level data and 3-year moving average. Labour productivity is defined as value added per employee. The global frontier is defined as the average of the productivity for the top 5 % of firms in the productivity distribution within each detailed (two-digit) NACE Rev.2 industry from 24 OECD countries for which firm-level data is available. 'Firms below the frontier' is the average productivity of all other firms within each industry. See more details in the paper cited in the source.

In light of the simultaneous long-term deceleration in aggregate productivity growth and the increasing divergence in micro-level productivity, recent work by the OECD explores the connection between these two phenomena. The analysis of Criscuolo et al. (forthcoming) delves into the question of whether policymakers, in their pursuit of economic growth, should be concerned about productivity divergence and the degree to which such divergence might indicate or exacerbate barriers to overall productivity growth. Specifically, it investigates the extent to which changes in divergence are associated with changes in productivity growth over subsequent years. This dynamic relationship between productivity and divergence can originate from several mechanisms.

On the one hand, the level of productivity dispersion may have direct effects on aggregate productivity growth as it may impact on the pace of reallocation, the incentives for innovation, and rates of market entry, which are linked to a set of mechanisms very similar to those discussed previously. More specifically, a widening of the productivity gap can induce a discouragement effect on the firms that fall further behind and a diminishing competition avoidance effect on the leaders, which widens their technological advantage (Akcigit and Ates, 2020). These mechanisms may be reinforced when markets become more dominated by leaders (in terms of market share and market power)[4].

On the other hand, rising dispersion may also be a consequence of different underlying mechanisms and forces such as innovation, technology diffusion or changes in the regulatory environment, which have different implications for productivity growth and shape the empirical link between productivity divergence and aggregate productivity growth.

The analysis of Criscuolo et al. (forthcoming) shows that counteracting mechanisms may indeed be at play and that rising dispersion may be both positively and negatively related to future productivity growth, depending on the prevalent forces. Rising dispersion at the top (i.e. between the most productive firms and the rest) appears to be linked to the presence of successful innovators and is associated with positive changes in aggregate productivity growth over subsequent years. On the other hand, rising dispersion at the bottom (between the least productive firms and the rest) appears to be related to slower technology diffusion and is associated with lower aggregate productivity growth.

Given these findings, the rise in productivity dispersion concentrated at the lower end (i.e. laggards falling behind) is a matter of concern. This divergence potentially plays a role in decelerating productivity growth, emphasising the need for policy intervention. To minimise the cost of divergence, policies may boost technology diffusion (absorptive capacities, skills, financial support to smaller and younger firms) while also ensuring that market selection and productivity-enhancing reallocation occur. At the same time, policies that favour innovation and boost productivity growth at the top can contribute to aggregate productivity growth despite rising dispersion at the top of the distribution, if markets remain competitive and contestable.

4 In this respect, digital and intangible intensive sectors deserve particular attention. Digitalisation and the growing role of intangible assets have reshaped the way firms produce and reach customers and have changed the way firms compete. While this may provide opportunities for new firms, it may also generate winner-takes-most dynamics and change market structures and the market power of leader firms. For instance, OECD evidence shows that intangible and digitally intensive sectors display higher increases in concentration, as well as in productivity and mark-up dispersion (Calligaris, Criscuolo and Marcolin, 2018; Bajgar, Criscuolo and Timmis, 2021; Corrado et al., 2021). Digitally intensive sectors further display lower levels of catch-up among laggard firms (Berlingieri et al., 2020). Ongoing OECD research (Calligaris et al., forthcoming) also shows that lower exposure to international competition is related to market concentration dynamics, as industries in which firms compete domestically have experienced higher increases in concentration. Taking account of larger markets (in sectors that compete globally) may further reinforce the positive relationship between intangible intensity and concentration, due to scale effects. Future work by the OECD Directorate for Science, Technology and Innovation will further investigate the link between AI, productivity and competition.

3. Productivity growth, employment, and wages

While policies should aim to revive productivity growth, the impact of productivity on employment and wages is the subject of ongoing debates, particularly in light of growing concerns about the potentially negative effects of technological progress on labour demand. Furthermore, declines in the aggregate labour share of value added call into question the extent to which the value created by firms and workers benefits the latter.

3.1 A positive link between productivity growth and employment

Some studies show adverse effects of robotisation on employment and wages (Graetz and Michaels, 2018; Acemoglu and Restrepo, 2020) which are related to the disappearance of routine tasks (Autor, Levy and Murnane, 2003). At the same time, technological change may also trigger favourable employment responses. New technologies may create demand for new tasks in the labour market (see Acemoglu and Restrepo (2016)), and firms that adopt productivity-enhancing technologies may become more competitive and increase sales, thereby increasing their use of inputs, including labour (Acemoglu, Lelarge and Restrepo, 2020; Aghion et al., 2020; Koch, Manuylov and Smolka, 2019)).

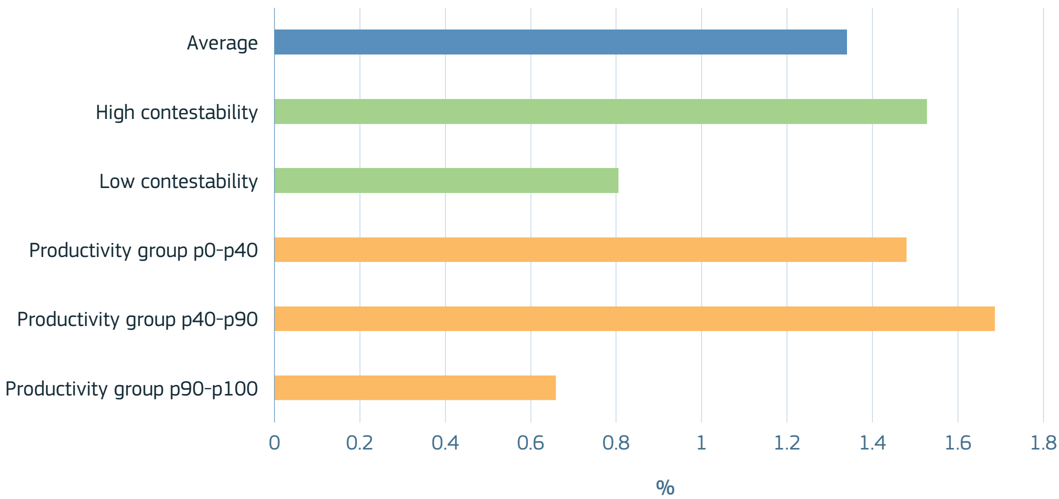
Overall, the extent to which there may be a trade-off between productivity and employment growth is an open empirical question, which has been addressed in a recent work by the OECD (Calligaris et al., 2023) using unique data from the MultiProd project. The work finds little evidence of a trade-off, and it rather suggests that productivity growth and labour demand are complementary rather than alternative policy targets.

The evidence across 12 countries suggests that this complementary relationship persists across levels of aggregation. Focusing on firm-level dynamics, firms at the top of the productivity distribution experience higher employment growth than less productive firms. However, after accounting for initial differences in productivity, firms that achieve greater increases in productivity also experience stronger employment growth than other firms, suggesting additional benefits in promoting productivity growth and catch-up. This result is presented in Figure 10-4, which illustrates the estimated micro-level response of employment to an initial increase in productivity. The estimated elasticity suggests that firms that initially experience 10% stronger productivity growth grow by an average of around 1.35% more in terms of employment over 5 years.

The results also point to the importance of the policy environment in shaping these relationships. Indeed, the positive relationship between initial productivity growth and subsequent employment growth appears to be stronger in environments characterised by higher market contestability, as proxied by lower mark-up gaps across firms within country-sectors. This result is illustrated by the second and third bar in Figure 10-4, which shows that the positive employment-productivity link is only around half as strong in less contestable environments as in environments that are more contestable. Therefore, competitive markets and environments that favour reallocation may foster greater employment gains associated with productivity growth. Additionally, while more productive firms tend to exhibit higher employment growth, results also indicate that the positive link between productivity growth and employment growth is more pronounced for non-frontier firms that are improving their productivity (see the last three bars in Figure 10-4). Combining these insights, results suggest that firms catching up in terms of productivity also tend to experience higher employment growth in a more competitive environment, indicating that upscaling might be easier for them in such environments, in line with the theories discussed in the previous section.

The analysis finds that the link between productivity growth and changes in employment and wages at industry level is weaker than at firm level (but tends to remain positive). This may be related to the fact that increasing employment among expanding firms tends to offset decreasing employment in shrinking or exiting firms. However, the analysis additionally finds that productivity gains at industry level contribute to stronger employment growth in downstream industries through domestic and global value chains, possibly linked to a decrease in prices of intermediate inputs associated with supplier productivity gains (see also Acemoglu, Akcigit and Kerr (2016)). This result points to the importance of considering the positive role that productivity improvements along the value chain can play, as they can spur employment growth at a more aggregate level.

Figure 10-4 A relative increase in multifactor productivity is positively associated with employment growth



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Source: Elaborations based on Calligaris et al. (2023).

Note: The Figure shows the estimated elasticity of 5-year employment growth to 1-year productivity growth at micro (firm) level i) on average, ii) in country-sector with high contestability (10th percentile, across country-industries, of the distribution of the mark-up difference between firms with high and median mark-ups) vs. low contestability (90th percentile of the mark-up difference distribution), iii) for different initial productivity groups defined according to the percentiles of the multifactor distribution. The estimated elasticity suggests that, on average, firms that initially experience stronger productivity growth by 10 % grow by around 1.3 % more in terms of employment over 5 years. This Figure illustrates the results of regressions based on a sample including 22 SNA A38 industries within manufacturing and non-financial market services across nine countries (Belgium, Croatia, Hungary, Italy, Japan, Latvia, the Netherlands, Portugal and Sweden). Observations are weighted by the number of firms represented in the full population, normalised at country level.

3.2 Productivity and labour share

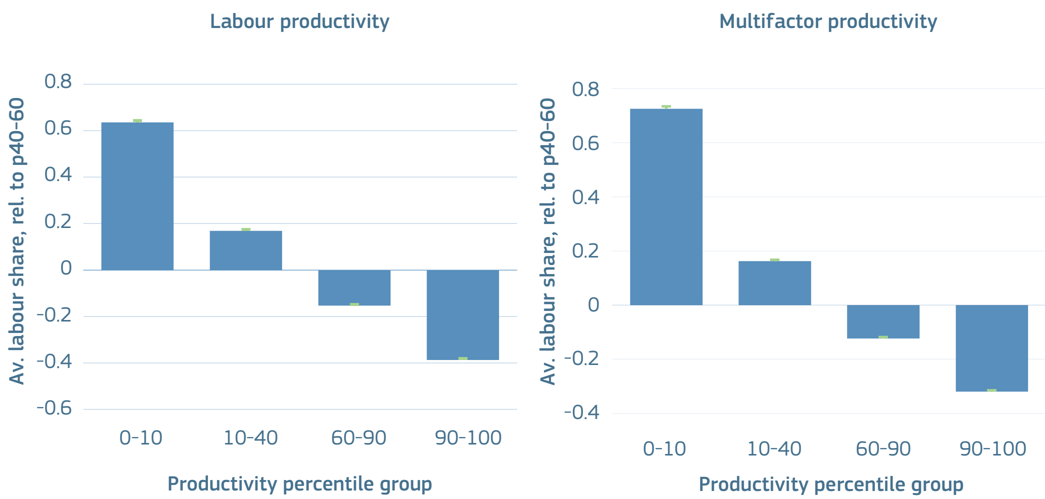
Beyond employment levels, the labour share of national income is an important indicator of the extent to which value added is shared with workers through the distribution of wages.

Existing evidence, mainly focused on the US, suggests that reallocation of resources towards high-productivity firms with low labour shares may have depressed the aggregated labour share in recent decades. This reallocation may be in favour of productivity superstars, i.e. the most productive firms in an industry (Autor et al., 2020), but there may also be a role for 'shooting stars', firms that benefit from a temporary boost in demand (Kehrig and Vincent, 2021).

Recent OECD work (Cho, Manaresi and Reinhard, forthcoming) extends the scope of the analysis of the nexus of productivity dynamics and labour share to cross-country level, providing novel evidence across 18 OECD countries based on the OECD MultiProd database.

The analysis provides several important insights that contribute to the existing literature. Firstly, there is a robust negative link between productivity and labour share, both at firm and industry levels. Figure 10-5 shows the difference in labour share across firms in different productivity quantiles relative to the median group and illustrates that more productive firms tend to have lower labour share (for both labour and multifactor productivity). This implies that firm-level rents from higher productivity are not fully passed on to the wage bill (see also Criscuolo et al. (2020)).

Figure 10-5 Firm productivity and labour share are negatively related



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Source: Cho, Manaresi and Reinhard (forthcoming).
Note: The Figure shows the difference in average firm-level labour share of each productivity group and the medium group of productivity. Based on regressions of average labour shares on an indicator variable for the productivity percentile group, controlling for fixed effects for the country-year and country-industry, and using the share of firms in the country-year as weight. Result is based on data for 18 countries: Austria, Belgium, Canada, Chile, Croatia, Estonia, Finland, France, Hungary, Indonesia, Italy, Japan, Latvia, Lithuania, Netherlands, Portugal, Slovenia and Sweden.

Secondly, some firms appear to have consistently low labour shares (they preserve a low labour share over at least 3 years). Firms with such a persistently low labour share are further found to be consistently among the most productive firms in their industry and can be considered ‘superstar firms’. Despite previous evidence showing an overall positive wage-productivity link (e.g. Berlingieri, Calligaris and Criscuolo (2018); Criscuolo et al. (2020)), these firms tend to pay low wages relative to their high productivity (for similar results for developing countries and different data sources, see Saumik and Hironobu (2019)). This raises concerns regarding the extent to which increases of productivity at the top are shared with workers.

Thirdly, the analysis shows that value added has been reallocated to firms with a persistently low labour share status and this contributes to reducing the aggregate labour share[5]. Reallocation to firms with a more transiently low labour share status has also occurred, although to a lesser extent, and reallocation to these firms seems to carry less weight in explaining aggregate trends.

The study suggests that structural and policy factors do matter when explaining differences in labour share trends across countries over time. In particular, the labour share declines more against a background of rising productivity gaps and falling entry rates. Falling labour shares are also linked to globalisation, in particular rising export intensity, and the digital transition as declining labour shares respond negatively to rising AI patent activity and information and communication technology (ICT) investment shares. These phenomena are found to be negatively linked to labour shares as they contribute to promoting reallocation to high-productivity, low-labour-share firms.

In conclusion, the new OECD cross-country evidence supports the view, originally derived from US data, that labour shares may be driven down by the increasing weight (in terms of value added) of productivity superstars. Although this reallocation may be grounded in higher competitiveness, technological advantage and efficiency, and lead to higher overall productivity growth, a significant policy concern is how to ensure that productivity rents derived from globalisation and digitalisation are shared more broadly with workers. This pressing concern might be even more relevant given the deterioration of the relative productivity of small and micro firms that tend to have higher labour shares.

For this, it is important to think of labour share as being the ratio of wage bill, i.e. average wage in the firm multiplied by the number of workers, to value added. Declining labour share at the top firms might therefore reflect not only a lower increase in the number of workers, which might derive from automation, but also a less than proportional increase in wages (in line with the negative link between productivity and labour share presented in Figure 10-4). The latter might reflect externalisation of part of the employment increase through outsourcing of some tasks and/or a lower wage increase for workers relative to the increase in productivity. Evidence discussed in Criscuolo et al. (2022) suggests that this is more likely in less dynamic business environments where workers are less mobile, for instance because of non-compete clauses (see work by Marx (2011) and Starr (2019)) and in environments where labour market concentration is higher (for evidence on the potential role of monopsony see e.g. Manning (2003), Azar, Marinescu and Steinbaum (2020); Marinescu, Ouss and Pape (2021); and Marinescu and Posner (2020)etc).

5 On average across countries, detailed industries and time, over a 10-year horizon, the share of firms with a persistently low labour share in industrial value added has increased by 2.2 pp in manufacturing and 1.8 pp in non-financial business services, which corresponds roughly to a 25 % increase relative to the sample period average in both macro sectors. According to a back-of-the-envelope calculation based on labour share differentials between persistently low-labour-share firms and other firms, this reallocation has been associated with reductions in the labour share of 1.1 pp in manufacturing and 0.8 pp in services, or -1.8 % and -1.3 % relative to a typical labour share of 0.6.

3.3 Promoting economic well-being through an inclusive productivity revival

Evidence for the link between productivity and employment, as well as the link with wages, suggests that boosting productivity is not a standalone economic objective, but has further socioeconomic benefits, in particular through employment and wage growth. Several policy areas may be leveraged to support employment creation and wage rises through productivity and should focus on i) fostering business dynamism and productivity, ii) strengthening the link between productivity and employment and iii) strengthening the link between productivity and wages. These objectives may be achieved through a comprehensive policy mix. Policies should support innovation to continue pushing the frontier of technology and knowledge outward and unlock new sources of productivity gains, while simultaneously ensuring the diffusion of technology and knowledge through a combination of incentives and capabilities and allowing creative destruction and reallocation.

- Firstly, ensuring open and competitive markets and a large market size could incentivise firms to invest in innovation, as such conditions guarantee returns on investment. Thus, continued efforts to achieve a single market and global level playing field are crucial for innovation. In this respect, the OECD indicator on regulatory barriers affecting trade in services within the European Economic Area (the intra-EEA STRI), shows that there is still relevant heterogeneity across sectors and countries as regards restrictions on foreign entry, restrictions to movements of people, barriers to competition, regulatory transparency and other discriminatory measures (Benz and Gonzales, 2019). Given the role of digitalisation in productivity dynamics and firm heterogeneity, policies should also focus on challenges related to digital trade and market openness (see e.g. López Gonzalez and Ferencz (2018)).

- Secondly, policy action needs to focus on capabilities, with a crucial role not only for investments in managerial and workers' skills allowing technology development but also for technology adoption among laggards to ensure that they have the necessary absorptive capacities.

- Thirdly, policies should ensure the conditions for creative destruction, in order to maintain incentives for innovation and adoption, and to support productivity-enhancing reallocation. To this end, policies should ensure a level playing field and the contestability of markets and reduce barriers to entry and growth. Competition and regulations that ensure a level playing field are key to incentivising entry and scale-up of younger firms. They are also key to ensuring healthy dynamics at the top with competition in the market, as well as a smooth and efficient selection of firms at the bottom, e.g. thanks to efficient bankruptcy legislation. To ensure a level playing field, competition authorities may play a role in the enforcement of and advocacy for competition neutrality of state intervention in order to prevent distortions of the competition law framework, the regulatory framework, public procurements or public support measures[6]. This also implies revisiting concepts, measurement and competition policies in specific sectors such as digital markets (OECD, 2022) or energy markets[7].

6 See the OECD December 2021 roundtable on the promotion of competitive neutrality by competition authorities: https://www.oecd.org/daf/competition/the-promotion-of-competitive-neutrality-by-competition-authorities.htm

7 See the OECD webpage 'Competition policy in the digital age': https://www.oecd.org/daf/competition-policy-in-the-digital-age/ and the November 2022 roundtable on competition in energy markets: https://www.oecd.org/competition/competition-in-energy-markets.htm

- Fourthly, policies can promote spillovers both across firms and across sectors. Spillovers across firms can be spurred not only by increasing absorptive capacity through managerial quality and worker skill but also through fair and transparent design of intellectual property regimes. In particular, this requires setting pro-competitive licensing arrangements that strike a balance between protecting inventors' or creators' rights and fostering innovation diffusion and follow-on or cumulative developments, as well as close scrutiny by competition authorities of licensing practices that have been identified as having potentially anticompetitive effects, such as field-of-use restraints, grant backs, no-challenge clauses and patent hold-ups (see OECD (2019) and (2019), and also Haskel and Westlake (2022))[8]. Policies can also promote spillovers across sectors by supporting integration with resilient global and domestic value chains and facilitating connections to the most productive supplier industries via mobility of workers, open trade and foreign direct investment.

- Finally, policies should ensure that productivity gains and their benefits are shared widely across firms and workers. This requires strengthening education and training to increase the supply of skills, in particular those in high demand (e.g. STEM workers) and those that are complementary to technology adoption (e.g. digital and soft skills of employees, managerial capabilities) while improving labour market matching of jobseekers to vacancies, including through enhanced worker mobility and lower labour market concentration. While digital technologies may be associated with lower aggregate labour share due to reallocation of value added to low-labour-share firms, promoting reskilling, upskilling and job mobility could help displaced workers to find jobs at firms paying higher wages. Furthermore, while firm performance and workers' qualifications play a key role in wages, there is room for well-designed policies to encourage wage-setting practices that raise wages and reduce wage inequality without adverse effects on employment and output (Criscuolo et al., 2022). This could help to ensure that potential productivity improvements within firms are passed on to workers, including lower skilled workers, through the sharing of productivity-related rents. In this respect, while productive, high-paying firms may benefit from domestic outsourcing, this may cause concern as regards job quality and earnings in low-wage occupations due to reduced sharing of productivity-related rents. Appropriate collective agreements that consider inter-industry occupational wages may, for instance, contribute to preventing cases of outsourcing that exploit different wage levels for the same occupations in different industries without enhancing productivity (OECD, 2021).

8 See also the OECD June 2019 roundtable on the treatment of licensing by competition law and policy: https://www.oecd.org/daf/competition/licensing-of-ip-rights-and-competition-law.htm, and the 2014 roundtable on competition, intellectual property and standard setting: Competition, Intellectual Property and Standard Setting - OECD.

4. COVID-19 and the accelerating digital and green transitions for the business sector

A significant trend associated with the COVID-19 shock has been the surge in the use of telework as firms quickly adapted to remote work arrangements (Criscuolo et al., 2021). This surge was accompanied by an acceleration in the adoption of digital technologies across various sectors, reflecting a broader trend towards increased reliance on digital tools. The entrepreneurial landscape also witnessed a notable resilience, even marked by an increase in business formation across many countries, with individuals exploring innovative business ventures and solutions in response to the challenges posed by the pandemic.

Nevertheless, important challenges persist. The macroeconomic landscape continues to bear the imprint of inflation. While enduring repercussions of the crisis linger, policymakers face the imperative of addressing long-standing challenges tied to the digital and green transitions. The formulation and implementation of effective industrial policies also become paramount, given their pivotal role in navigating these multifaceted challenges.

4.1 Uneven adoption of digital technologies during the COVID-19 crisis

The COVID-19 crisis has spurred the adoption of digital technologies, albeit differently across firms. An upcoming analysis by the OECD (forthcoming) leverages a comprehensive commercial database from Spiceworks Ziff Davis to examine digitalisation at firm level during the pandemic across 20 European countries. Drawing on this unique cross-country data source on digital product installations by firms, which are linked to IT expenditures and information on firm financials, the analysis reveals that the integration of digital technologies experienced a rapid acceleration during the pandemic.

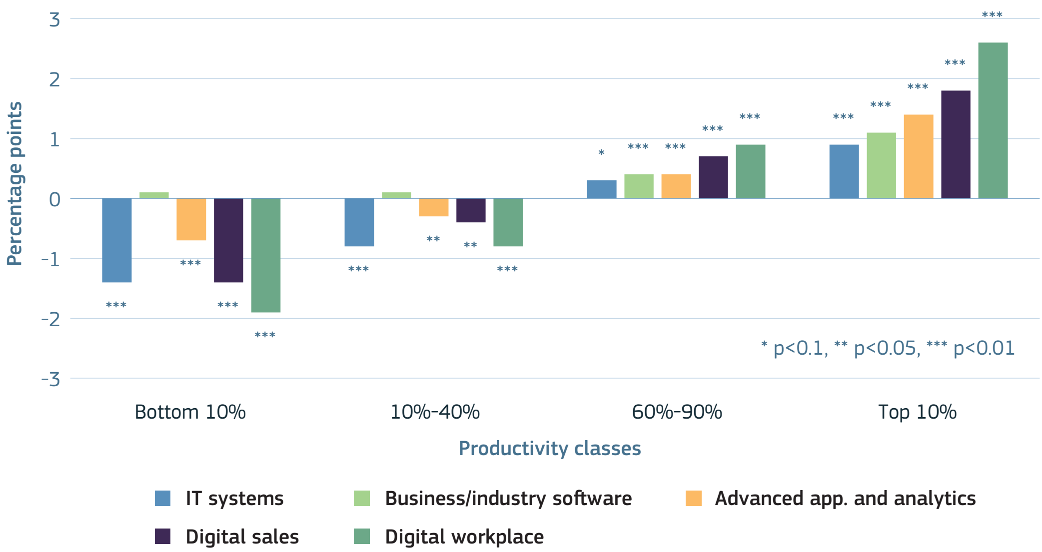
Focusing on detailed applications grouped into five technological classes, the analysis shows that a significant share of firms introduced new digital technologies during the pandemic, with the highest shares introducing 'IT systems', followed by 'digital sales' and 'digital workplace' (respectively around 80 %, 50 % and 45 %)[9].

Nevertheless, existing disparities have played a crucial role in determining firms' capacity to respond to the crisis through digital adoption. Firms that exhibited higher levels of productivity, larger size and a greater emphasis on digitalisation prior to COVID-19 saw a more pronounced increase in their adoption of digital technologies in the aftermath of the pandemic shock. Notably, firms with elevated levels of digitalisation before the pandemic, as measured by a novel digitalisation index used in the analysis, and higher complementary factors (e.g. IT staff) were generally better positioned to introduce new digital products during the crisis. Furthermore, businesses that were already more productive before COVID-19 were also more inclined to embrace digital applications that gained traction during the pandemic, such as digital commerce, collaborative software, cloud services and analytics (Figure 10-6).

9 The five technological classes analysed are advanced applications and analytic, digital sales, digital workplace, industry/business software, and IT systems

These trends may amplify winner-takes-most dynamics and exacerbate the divides previously documented in this chapter, i.e. between the top-performing firms and the rest of the business population and between large and small and micro firms.

Figure 10-6 Firm productivity in 2019 and likelihood of introducing new digital products during the pandemic



Science, research and innovation performance of the EU 2024

Source: Calvino, Criscuolo and Ughi (2024).

Note: The Figure displays the relationship between firm labour productivity (in 2019) and the probability of introducing new digital products in 2020 and/or 2021, for each digital technology class ('IT systems', 'digital sales', 'digital workplace', 'advanced applications and analytics', 'business/industry software'). For each technology class, the estimated regression model is a linear probability model that employs a dummy for digital technology class adoption as dependent variable and includes – in addition to the productivity group – size class, age class, and other complementary factors (IT staff and an ex-ante digitalisation index) as main independent variables. The technology class dummy is equal to 1 if the firm introduced a new digital product for the given technology class in 2020 and/or 2021. The labour productivity proxy is computed as (log) turnover over employment in 2019. Productivity groups are computed within country-sector (two-digit NACE sectors). Productivity coefficients are computed with respect to the 40 %-60 % productivity group. Each regression includes two-digit sector-country fixed effects and employs robust standard errors. Results for the 'missing productivity' group are not reported. Results are robust to the log of labour productivity in 2019, excluding plants at the top 1 % of the productivity distribution, employing a logit model as the main regression model, and to the use of a different proxy for digitalisation as control. In the figure, results are ordered with respect to the magnitude of coefficients of digital classes for the productivity group 'top 10 %'.

4.2 Navigating the AI landscape: AI adoption across firms

A notable change in the digital landscape that has characterised the last few years has been the acceleration in the diffusion of AI, which is already changing the demand for skills and may play an important role in tackling societal challenges, such as those related to health and climate change. AI has a strong potential to affect the economic landscape radically and widely, with relevant implications for several economic and social areas. Often considered a general-purpose technology, its applications can potentially bring significant improvements to adopters and users.

In this context, Calvino and Fontanelli (2023) depict a profile of AI adopters across countries, leveraging unique data for 11 countries collected from firm-level surveys in the framework of the AI Diffuse project, which gathers information on AI use by firms. While AI adoption is still largely incomplete, the analysis further emphasises the characteristics of adopters, the role of complementary assets such as intangibles or digital infrastructure and the links between AI utilisation and productivity and highlights key stylised facts.

The analysis of AI adoption unveils crucial patterns. Larger firms are more inclined to adopt AI technologies as they may benefit from scale advantages and are better equipped to leverage the full potential of AI through intangible and other complementary assets. Concurrently, young firms tend, to some extent, to exhibit higher rates of AI adoption, in line with their role for driving innovation particularly in the context of emerging technological paradigms such as AI.

In terms of sectoral patterns, Calvino and Fontanelli (2023) find that AI adoption is noticeably concentrated in the ICT and professional service sectors, underscoring a sectoral imbalance. This hints that, at the early stages of AI diffusion, its broader potential as a general-purpose technology is yet to be fully realised, especially beyond selected service sectors.

In a similar way to the findings for digital technologies previously discussed, significant links emerge between AI use and complementary assets. Intangibles, including ICT skills, digital capabilities and infrastructure, play a pivotal role in fostering AI adoption. Firms demonstrating general skills and engaging in innovative activities also exhibit positive associations with AI adoption, emphasising the importance of absorptive capacity.

Interestingly, more productive firms are also more inclined to adopt AI, yet the productivity advantage is intricately linked to complementary assets. When factoring in the role of these assets, the initially observed productivity premia are reduced. This underscores the critical contribution of complementary assets in influencing the productivity landscape associated with AI adoption.

The polarised adoption of AI, predominantly by industry leaders, raises concerns about potential future gaps in the business landscape. This trajectory, coupled with AI's reinforcement of existing advantages, has economic and societal implications and raises the question of interventions through industrial strategies, as discussed in the final section of this chapter.

4.3 Did COVID-19 help to accelerate the green transition?

The COVID-19 crisis and the associated lockdowns across the world led to a massive drop in economic output. Governments responded by implementing rescue and recovery packages and other fiscal measures to support economic activity, in addition to protecting public health. In the 2 years following the start of the pandemic, national governments dedicated up to USD 30 trillion (about EUR 28 trillion) to economic stimulus as a response to the crisis.

This massive intervention by public authorities around the world could give an important impulsion to the development and deployment of low-carbon technologies. Encouraging a low-carbon shift has been a priority in the aftermath of the COVID-19 pandemic. Consequently, many governments integrated a significant environmental dimension into their stimulus packages. The EU, for example, required that 37% of the Next Generation EU stimulus package be targeted at supporting the green transition.

Recent work conducted by the OECD (Aulie et al., 2023) shows that countries around the world – members of the OECD, the EU and the G20 – included in these fiscal packages USD 1.29 trillion (about EUR 1.2 trillion) worth of measures for the development and deployment of low-carbon technologies. This means that, on average, OECD countries committed to spending the equivalent of 2% of 1 year's GDP on low-carbon technologies. The sectors which received the largest share of funding were energy (39%) and transportation (35%). In contrast, only 4% of total funding was allocated to industry. The vast majority of spending supported the deployment and adoption of mature technologies, while development of early-stage and emerging technologies received less than 15% of spending.

Aulie et al. (2023) reported the results of a modelling exercise to analyse the impact of the post-COVID-19 low-carbon fiscal spending (green fiscal push scenario) on greenhouse gas emission (GHG) reductions towards 2050. GHG emissions in OECD and EU countries are projected to have decreased by 9% in 2030 and 11% in 2050 compared to a reference scenario in which no such spending occurred.

This reduction will be triggered by both support for adoption and support for research, development, and demonstration (RD&D), with the role of the latter increasing considerably over time. In 2030, only 5% of the emission reductions will have been triggered by RD&D support measures, but this proportion will increase to 26% in 2050. This is due to increases in the productivity of clean technology; significant cost reductions in, for example, batteries, hydrogen, wind power and solar photovoltaics; and the diffusion of knowledge spillovers across borders. By 2050, a dollar spent on RD&D will induce cumulative emission reductions six times higher than would the same dollar invested to support adoption. This illustrates the key role of R&D for the green transition, particularly in the context of high concentration of many critical raw materials necessary to produce renewable energy capital goods (wind turbines, solar panels, etc.). Innovation to develop leading-edge manufacturing capacities for the production of renewable energy goods can reduce dependencies on non-OECD economies, while avoiding or limiting the cost of reshoring production units currently located in low-wage economies. Innovation can also play a role in reducing dependencies thanks to the development of alternative materials or new recycling processes for critical raw materials.

The model also looks at the aggregate effects of the green fiscal push scenario on GDP and employment: although small, they will be positive across EU and OECD countries. This positive effect will mainly be driven by productivity improvements induced by R&D investments and learning-by-doing. The EU will benefit the most from the positive effects of low-carbon investments: GDP gains for the EU will reach +1.1% in 2035. In North America, the GDP effect will be positive at +0.4% in 2035, driven by the impact of the Inflation Reduction Act in the US. Employment projections mirror those for GDP and show employment increases of 0.85% for the EU and 0.2% in North America by 2035.

Recent OECD work (Dechezleprêtre and Vienne, forthcoming) also investigates the link between air pollution and productivity and further underlines the economic benefits of policies contributing to air pollution reduction through lower emissions. Existing studies have already shown that air pollution can negatively affect workers' productivity (Zivin and Neidell, 2012), but they consider particular settings (e.g. garment factories in India). Using a large-scale firm-level dataset spanning all European countries, combined with weather and air quality data based on firm location, the findings of this study present causal evidence for a negative effect of air pollution on labour productivity. The effect, driven by firms in the manufacturing sector and in some service industries, appears economically relevant, suggesting important co-benefits of the green transition in terms of higher worker productivity and, thus, economic growth. At the aggregate level, earlier OECD analysis suggests that these effects translate into a negative impact on regional-level GDP (Dechezleprêtre, Rivers and Stadler, 2019).

5. The importance of coherent industrial strategies for inclusive and sustainable growth

The increased attention to climate neutrality and sustainability is evident in the focus of industrial strategies beyond COVID-19 resilience packages, as shown in a recent study by the OECD that makes a novel attempt at quantifying industrial strategies (Criscuolo, Lalanne and Díaz, 2022). The QuIS project is indeed the first to quantify industrial strategies across nine OECD countries over the 2019-2021 period.

The development of this project reflects important recent developments in the economic policy arena, as industrial strategies can further complement the broad policy mix aimed at boosting productivity in an inclusive way discussed in section 3. Notwithstanding scepticism and the recognition of potentially important drawbacks of targeted industrial policies, many economists are reconsidering the role of targeted policies because of economic, technological and societal needs (Rodrik, 2008; Mazzucato, 2018; Bloom, Van Reenen and Williams, 2019). Three main reasons justify this renewed interest (see Criscuolo et al. (2022)).

- Firstly, the presence of market imperfections implies that policy interventions, even those that may introduce distortions, can in fact enhance public welfare when they help achieve a second-best allocation[10].
- Secondly, the rapid development and magnitude of technological opportunities and societal challenges necessitate both public impetus/guidance and large-scale private investment. In this respect and as mentioned above, AI is expected to become pervasive in the economy but may also need new rules and new governance frameworks. Governments can also play a role in preventing initial investment gaps in this rapidly evolving environment from leading to entrenchment of incumbent adopters, notably by promoting technology diffusion to improve the productivity of laggard sectors and firms and ensuring efficient allocation and competitive markets.
- Finally, the productivity slowdown, the accompanying increase in productivity dispersion and the decline in labour share presented earlier in the chapter, as well as the increase in wage inequality (Berlingieri, Blanchenay and Criscuolo, 2017; OECD, 2021) place special emphasis on the role of industrial policies in ensuring positive social outcomes. Industrial policies are often praised for reducing geographical and income inequalities and counteracting wage polarisation (Rodrik and Sabel, 2019). The COVID-19 crisis has reinforced these arguments in favour of industrial strategies and put additional emphasis on the importance of climate-neutrality targets, as discussed in the previous section. Furthermore, the risk of disruptions to global value chains, illustrated by the challenges related to the COVID-19 crisis and the heightened geopolitical tensions, have prompted the emergence of economic resilience (in particular of supply chains) and strategic autonomy as new objectives of industrial policy.

10 For instance, inefficient sectoral allocation revealed during crises may justify interventions to favour reallocations. In addition, in some cases, governments have resorted to industrial policies to compensate sectors or firms for the potential loss of competitiveness resulting from foreign policies, including tax, trade and foreign direct investment policies, that are perceived as unfair (see Criscuolo et al. (2022) and references therein).

The ongoing and expanding QuIS project provides a unique source of information on the amount spent on different policy instruments as it gathers and centralises information from publicly available data from many different and decentralised sources on industrial policy expenditures. But importantly, it also classifies them along four dimensions: scope (horizontal vs. targeted measures), instrument type (grants and tax expenditures vs. financial instruments), eligibility criteria areas (e.g. green, sectoral, technology, skills etc.) and selectiveness (see also Figure 10-7).

Figure 10-7 Classification of industrial policy expenditures in the OECD QuIS project

Scope	Instrument Types	Eligibility Criteria	Selectiveness
Horizontal	Subsidies and Tax Expenditures	Digital	Non-discretionary
Targeted	Grants and subsidies	Green	Selective
	Tax expenditures	Sectoral	First-come first-served
	Financial Instruments	Technology	
	Loans and loan guarantees	SMEs and young firms	
	Venture capital	R&D	
		Jobs / skills	

Source: Criscuolo, Lalanne and Diaz (2022).

This quantification effort is a crucial first step in understanding the importance of developing a coherent non-distortionary industrial strategy to support economic growth that is both inclusive and sustainable.

With the same purpose, the OECD has also developed a framework that highlights the role of demand-oriented instruments (e.g. product regulation and public procurement) and different supply-oriented instruments that aim at increasing the productivity growth of heterogeneous firms (within-firm tool) and support the efficient allocation of resources across firms (between-firm instruments). The latter distinction is a key novelty of the framework that makes it possible to analyse how industrial strategy can foster or hinder the Schumpeterian creative destruction dynamics, a key concern in light of the evidence discussed in this chapter.

One important concern with industrial strategy, as highlighted in recent theoretical models (e.g. Acemoglu et al. (2018)), is that to be effective, it needs to remain competition enhancing and non-distortive. For this goal to be achieved, two key features of an industrial strategy need to be ensured.

The first is coherence and complementarity across the different policy instruments deployed within the industrial strategy and with other policy areas (e.g. competition). Firstly, complementarity is required between investment incentives and policies ensuring access to inputs, such as skill and transfer policies, as they enhance the effectiveness of investment incentives and contribute to increasing the absorptive capacities of the least productive firms, thereby fostering technological diffusion. Secondly, complementarity between instruments affecting firm performance (within) and instruments affecting the static and dynamic allocation of resources across firms (between) is also crucial. In the same vein, complementarity should be ensured with competition policy and framework instruments that enable the entry and exit of firms, allow the most productive firms to grow and incentivise innovation. For instance, state aid might end up favouring some firms over others, in particular incumbent large firms over new or young firms or supporting inefficient or failing firms. This may lead to the survival of less productive firms, impairing reallocation to more productive or new firms. Therefore, the design of such policies is also crucial in order to benefit firms more broadly (e.g. the design of R&D tax incentives with refund provisions which may also support young firms that initially do not generate profits). Theoretical evidence suggests that this complementarity is key for translating firm-level innovation into macroeconomic growth (Acemoglu et al., 2018).

The second relates to the role of sound governance of the strategy in limiting the risk of capture and attenuating information asymmetries (Romer, 1993) and thus avoiding hindering competition and innovation. In particular, it is necessary to favour inclusiveness, notably by ensuring that young firms, and other important stakeholders are invited to participate in the design of whole-of-government industrial strategies and that, to the extent possible, the specifications are technology neutral and do not discriminate between domestic and foreign firms and between incumbents and potential entrants. For this reason, potential general equilibrium effects (sometimes unintended) should also be considered. In addition, ex-ante provisions for ex-post evaluations and plans for regular refit of the instruments and the strategy should be an integral part of any industrial strategy and subsequent reorientations.

In this context, the QuIS project offers a conceptual framework and harmonised measurement of industrial policies, with detailed information on industrial policy expenditures, their composition, their mode of delivery and the characteristics of their beneficiaries. The project lays the ground for cross-country comparisons and evaluation of the effectiveness and efficiency of policies. As such, it is a key tool to promote international coordination, which is another key feature of well-designed industrial strategies.

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CHAPTER 11

INNOVATION AND ADOPTION OF DIGITAL AND GREEN TECHNOLOGIES

Julie DELANOTE, Péter HARASZTOSI, Alessia DE SIMONE, Christoph WEISS, Marco ZEPPI
(European Investment Bank)[1]

1 The views expressed in this chapter are those of the authors, and do not necessarily reflect the views of the European Investment Bank.

Abstract

This chapter focuses on corporate investment in innovation and the adoption of green and digital technologies. Based on the latest results of the EIB Investment Survey (EIBIS), it compares the performance of EU firms relative to their US peers and also looks at differences across the different cohesion regions within the EU. First, the analysis finds that the EU has a lower share of firms that invest in innovation than the US. Second, it shows that EU firms are closing the gap in the adoption of advanced digital technologies with their US peers, a trend mainly driven by firms in more developed regions. Third, the chapter argues that investment in climate change is an area in which the EU has been able to keep its competitive edge over the US. To better assess Europe's position in the innovative landscape, the chapter also discusses factors that can support or hamper firms' investment in the structural transformation, such as digital infrastructure, a dynamic innovation environment, business regulations and access to finance.

1. Introduction

Europe's future prosperity and competitiveness depend on investing in innovation and addressing the challenges of climate change. While the current policy debate mainly rotates around global competition and resilience, the flexibility of Europe's economy to adjust and transform will also rely on the efficiency of the operating environment. The aim is to foster a smarter, more competitive Europe by creating an inclusive environment that incentivises EU firms to accelerate the twin green and digital transition.

Against this background, this chapter focuses on corporate investment in innovation and the adoption of green and digital technologies. Based on the latest results of the EIB Investment Survey (EIBIS), we compare the performance of EU firms relative to their US peers in the adoption of technologies. We also examine differences between the different cohesion regions within the EU and how to create an environment that enhances the adoption of innovation. This chapter does not discuss how to enhance the frontier of innovation or the global innovation leadership race.

First, we find that the EU has a lower share of firms investing in innovation than the US. We also highlight the differences in innovation activities across different EU regions. Second, we show that EU firms are closing the gap in the adoption of advanced digital technologies with their US peers, a trend mainly driven by firms in more developed regions. Third, we argue that investment in climate change is an area in which the EU has been able to keep its competitive edge over that of the US. Finally, to better assess Europe's position in the innovative landscape, the chapter discusses factors that can support or hamper firms' investment in the structural transformation, such as digital infrastructure, a dynamic innovation environment, business regulations and access to finance.

2. Data

The evidence reported in this chapter is based on EIBIS: 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 12,000 businesses in all EU countries, and 800 businesses in the US since 2019. Using a stratified sampling methodology, the survey is designed to be representative at the levels of country, sector (manufacturing, construction, services and infrastructure) and firm-size class (micro, small, medium and large).[2]

EIBIS data are collected in a consistent manner and with the same methodology for a large number of firms across all EU countries

2 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); and large (250 employees). Using various administrative databases, Brutscher et al. (2020) provide evidence on the representativeness of EIBIS for the business population of interest.

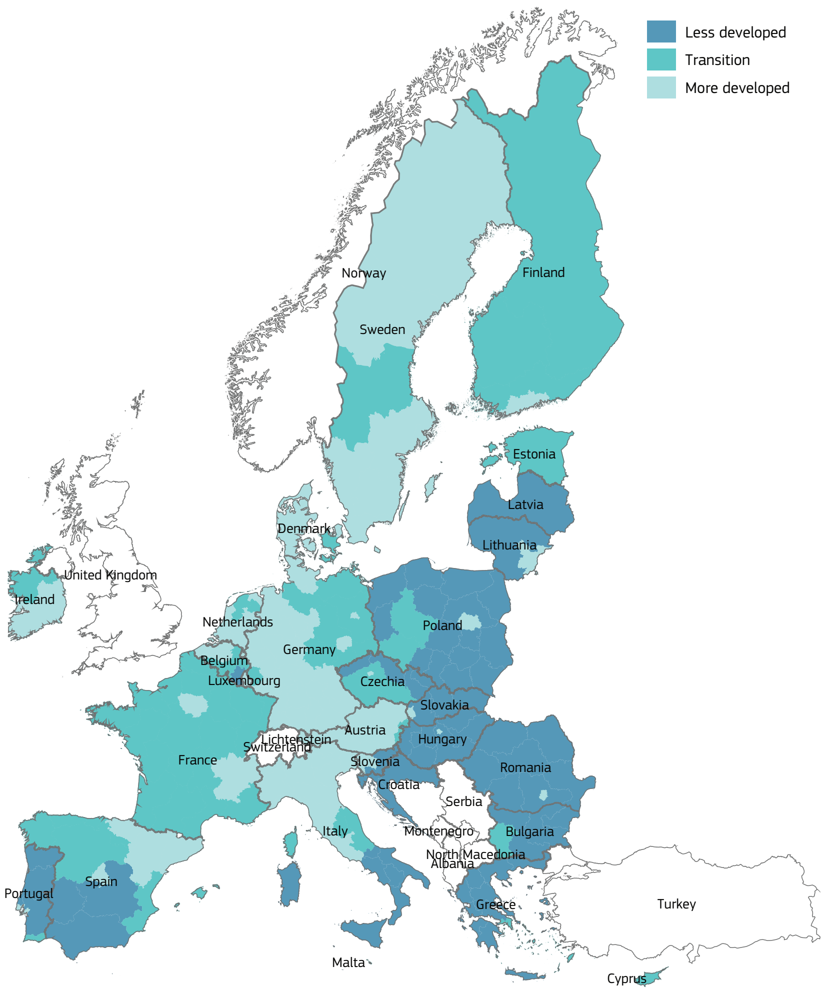
and the US, thus allowing a comprehensive comparative analysis of investment activities in diverse institutional settings. EIBIS also gathers qualitative information on firms' investment in the development or introduction of new products, processes or services, the use of advanced digital technologies, and their investments to tackle the physical and transition risks associated with climate change.

This chapter aims to compare both the performance of EU firms relative to their US peers and the performance across different EU regions, as economic convergence lies at the heart of EU policy. The analysis focuses on investment in innovation, the use of advanced digital technologies, and investments to tackle climate change.

In the following discussion, we refer to NUTS2 regions with GDP per capita above the EU average as 'more developed' or 'non-cohesion' regions; to those with GDP per capita between 100 % and 75 % of the EU average as 'transition' regions; and to those with incomes below 75 % of the EU average as 'less developed'.[3] Figure 11-1 shows an overview of this classification of regions.

3 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.

Figure 11-1 Classification of EU regions based on EU cohesion policy



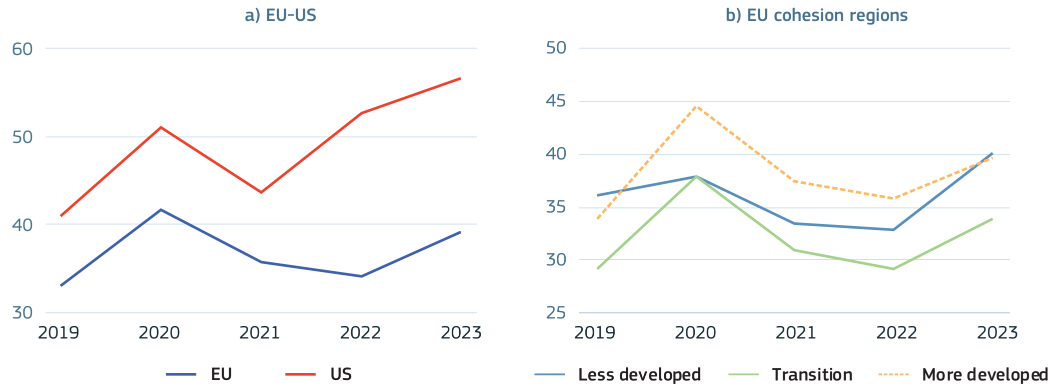
Science, research and innovation performance of the EU 2024
Source: European Commission's Directorate-General for EU Regional and Urban Policy.

3. Investment to develop or introduce new products, processes or services

The EU has a lower share of firms that invest in developing or introducing new products, processes or services than the US. After a slowdown following the COVID-19 crisis, the share of EU firms investing in innovation increased to 39% in 2022, compared to 57% in the US (Figure 11-2a). This evidence from EIBIS confirms the findings of the European Innovation Scoreboard 2023 (European Commission, 2023) and OECD data, in which the US scores better than the EU on several indicators related to R&D and innovation.

There is also a sizeable persistent innovation gap between transition regions and more developed regions. In transition regions, only 34% of firms report investing in the development or introduction of new products, processes or services, while this share is as high as 40% in more developed regions (Figure 11-2b). This recent uptake of investment in innovation in less developed regions is a positive signal, and could be a key contributor for these regions to alleviate the innovation divide across the EU (European Commission, 2022a).

Figure 11-2 Development or introduction of new products, processes or services (% of firms)

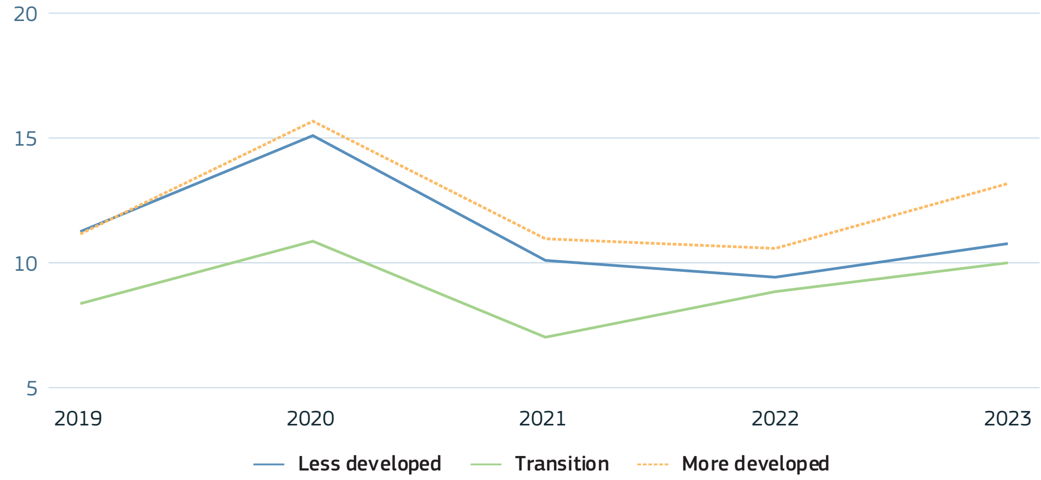


Science, research and innovation performance of the EU 2024

Source: EIBIS 2019-2023.
Note: Firms are weighted by value added.

The share of firms investing in innovation in Figure 11-2 measures a combination of two types of innovation: firms can invest to develop innovations that are new to their market, or adopt and adapt technologies that already exist in their market and are used by other companies. The difference between the innovation activities of firms in less developed regions and transition regions is mainly driven by this latter type of innovation; namely, the adoption of innovation that is new to their company. When focusing on the share of firms that invest in innovations new to the market, the recent increase in investment in less developed regions is absent. Instead, more developed regions seem to have increased their gap with the less developed regions (Figure 11-3).

Figure 11-3 Development or introduction of new products, processes or services that are new to the market (% of firms), for cohesion regions

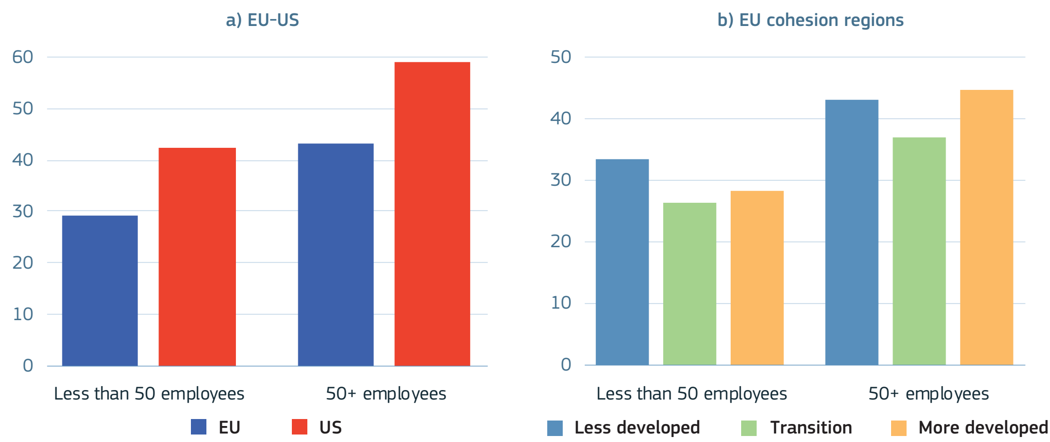


Science, research and innovation performance of the EU 2024

Source: EIBIS 2019-2023.
Note: Firms are weighted by value added.

Larger firms tend to be more innovative. The share of EU small firms (with less than 50 employees) that invest in innovation is only 30%, compared to 43% in the US (Figure 11-4a). The positive relationship between firm size and investment in innovation is also apparent across different cohesion regions (Figure 11-4b). Small firms in less developed regions are making a strong effort to invest in the adoption of innovation.

Figure 11-4 Development or introduction of new products, processes or services (% of firms), by firm size



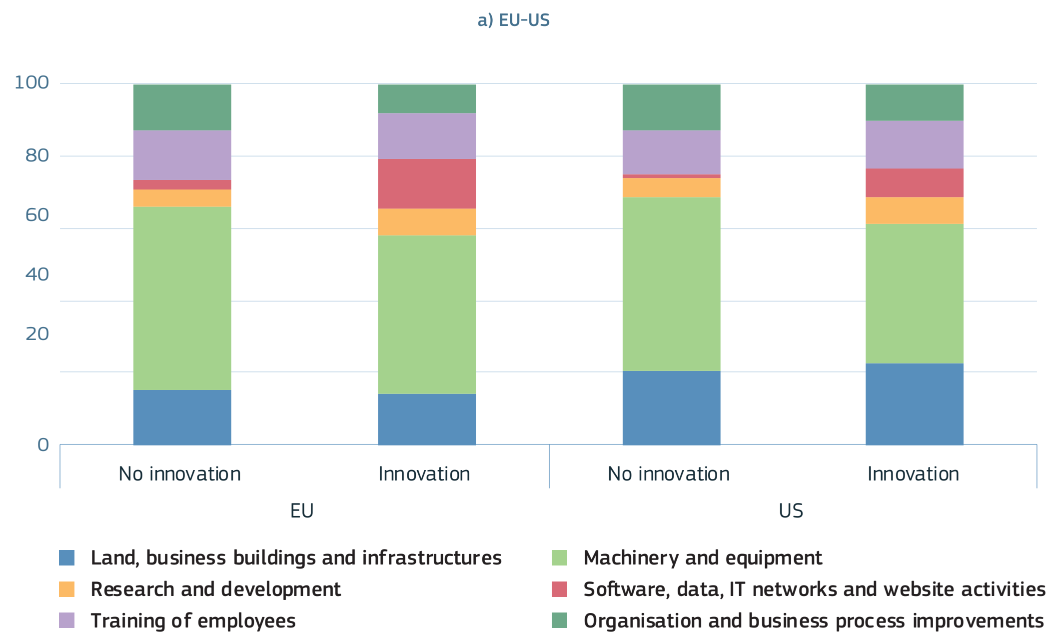
Science, research and innovation performance of the EU 2024

Source: EIBIS 2023.
Note: Firms are weighted by value added.

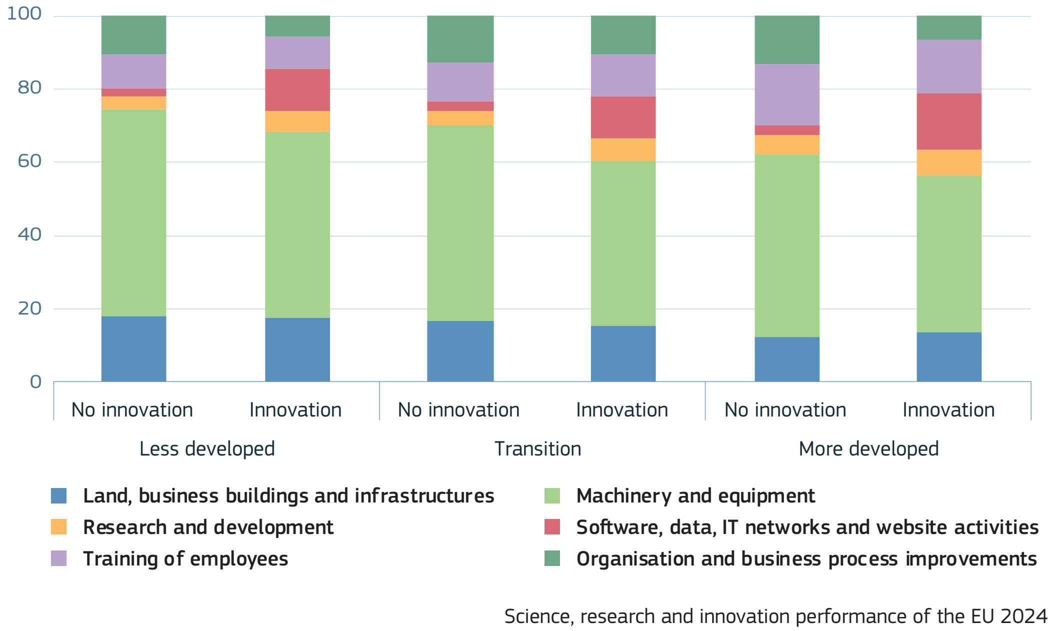
Innovation activities are associated with investment in intangibles. Firms that allocate a greater share of investment to intangibles (R&D, software and data, training of employees, organisational and business process improvements) tend to innovate more (Figure 11-5). R&D investment appears to be the key driver of this positive correlation between intangible assets and the introduction or development of new products, processes or services. For example, innovative EU firms allocate about 14% of total investment to R&D, compared to only 3% for non-innovative firms. This pattern is visible when comparing the US and the EU, and across the different EU regions.

Investments to develop products, processes or services new to the market are often risky, with highly uncertain returns. They encompass a large share of sunk costs; once the investment is effectuated, it is, to a large extent, irreversible. Innovative firms are also more susceptible to difficulties in access to finance due to market failures; for example, information asymmetries between investors and innovating companies, or the lack of appropriability of innovation (Arrow, 1962; Stiglitz and Weiss, 1981; Dixit and Pindyck, 1994). Based upon this rationale, innovation is therefore often supported by public authorities. In addition, during an economic downturn, tightening financing conditions and financial constraints can have a negative effect on innovation activities, especially for firms in sectors that depend more heavily on external finance (Aghion et al., 2012).

Figure 11-5 **Innovation and investment in intangible assets (% of total investment)**



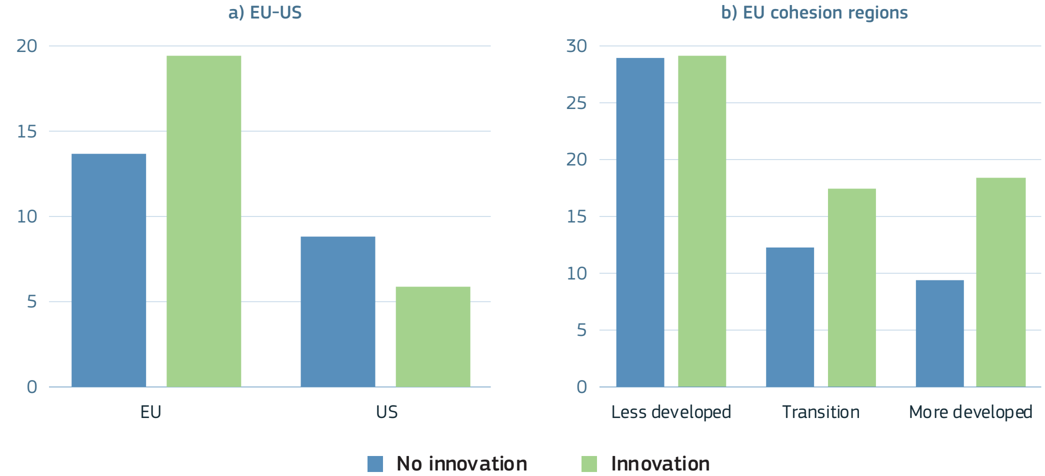
b) EU cohesion regions



Source: EIBIS 2023.
Note: Firms are weighted by value added.

Innovative EU firms using external finance are more likely than non-innovative firms to use grants to finance their investments. This differs from the US, where the opposite pattern can be observed (Figure 11-6a). This suggests that EU grants tend to be more targeted to innovation than in the US. In addition, firms using external finance in less developed regions were more likely to receive grants, independent of their innovation status (Figure 11-6b). This is in line with the availability of co-financing differing across regions, with poorer regions having the possibility to receive more financial support overall, which also target non-innovative firms.

Figure 11-6 Share of grants (% of firms using external finance)

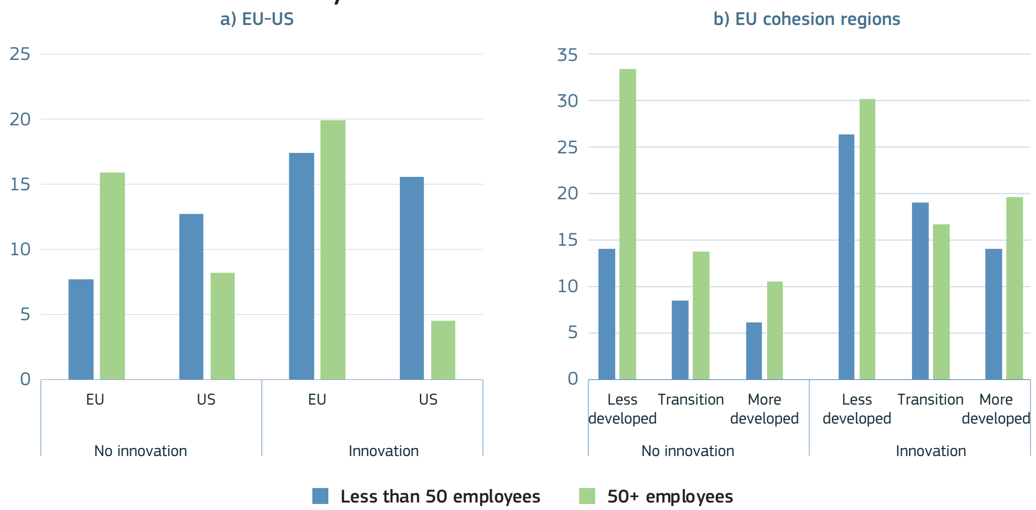


Science, research and innovation performance of the EU 2024

Source: EIBIS 2023.
Note: Firms are weighted by value added.

In the EU, large firms using external finance are more likely to report that they received grants than small firms. In the US, the opposite pattern is observed, as smaller firms are more likely to use grants than large firms. In addition, among EU innovators, small and large firms are almost equally likely to receive grants. In the US, small innovators are much more likely to use grants than large innovators (Figure 11-7a). In the US, the policy support through grants focuses on small firms, in particular small innovators. Focusing on the different cohesion regions shows that, among non-innovators, large firms are more likely to receive grants than small firms, especially in less developed regions (Figure 11-7b).

Figure 11-7 Share of grants (% of firms using external finance), by firm size and innovation status

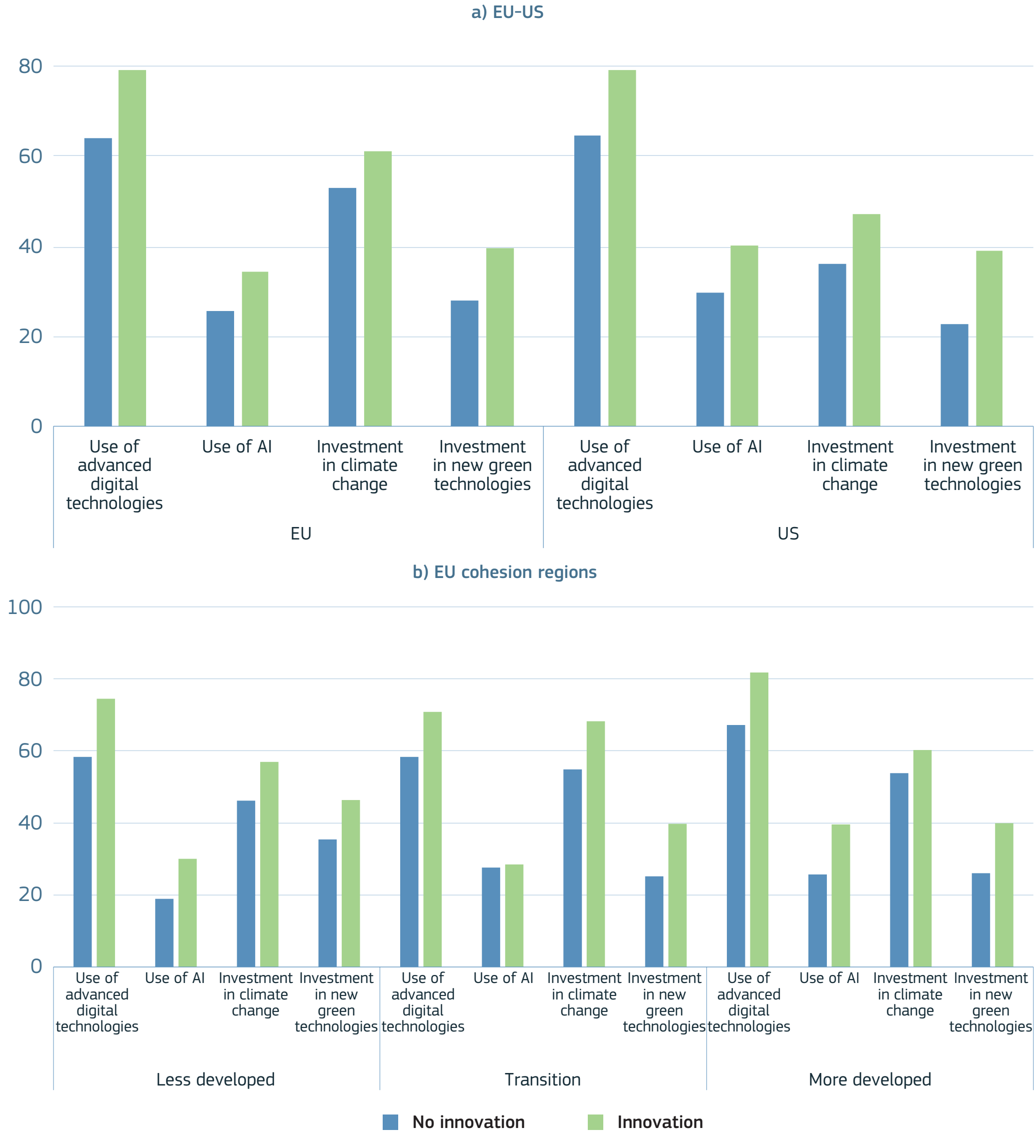


Science, research and innovation performance of the EU 2024

Source: EIBIS 2023.
Note: Firms are weighted by value added.

Innovation, digitalisation and the green transition go hand in hand. Innovative firms are also those that digitalise more and invest more in climate change (Figure 11-8a). This confirms the role these companies can play in the future resilience and competitiveness of the EU and the criticality of supporting innovation. Indeed, innovative companies can better thrive in an environment where investment in these areas is increasingly important. This relationship between innovation and the twin digital and green transition is also strong across cohesion regions (Figure 11-8b).

Figure 11-8 Innovation and firm performance (% of firms)



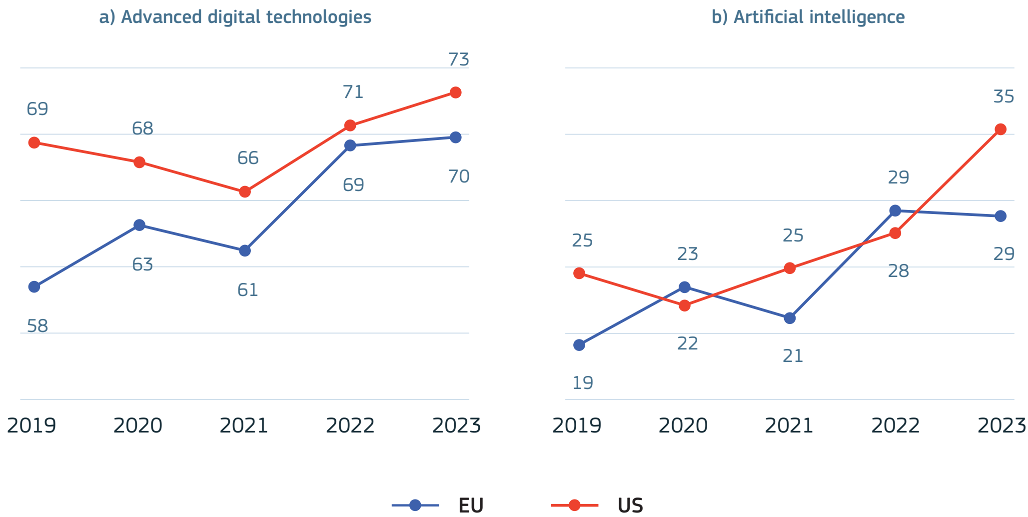
Source: EIBIS 2023.

Note: Firms are weighted by value added.

4. Adoption of digital technologies

Strengthening the competitiveness of the European economy through the twin green and digital transition is not only about innovation at the technological frontier, but also the adoption and deployment of these technologies more broadly. The latest results from EIBIS show that EU firms are accelerating the adoption of advanced digital technologies, after putting these processes on hold in the first year of the pandemic. The share of EU firms implementing advanced digital technologies reached 70% in 2023, compared with 73% in the US (Figure 9a). To ensure no persistent gap is created with their US peers, EU firms must remain vigilant and reinforce the use of artificial intelligence (AI), which is a key digital technology (Figure 11-9b).

Figure 11-9 Use of advanced digital technologies and artificial intelligence (% of firms)

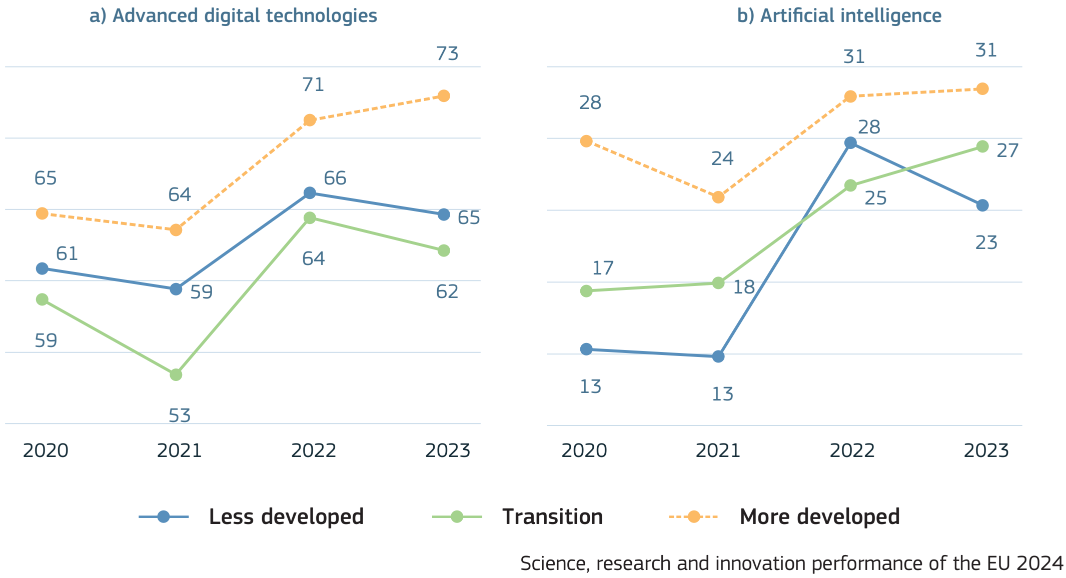


Science, research and innovation performance of the EU 2024

Source: EIBIS 2023.
Note: Firms are weighted by value added.

Digital adoption rates are higher in more developed regions. Technology adoption patterns reflect industrial specialisation and depend on digital infrastructure, and the availability of human capital. The transition and less developed regions consistently lag behind the more developed regions over time. In addition, Figure 11-10 shows that firms in the more developed regions mainly drive the digital technology adoption in the EU. More developed regions lead in adopting AI, a digital area that has also been increasingly embraced by transition and less developed regions.

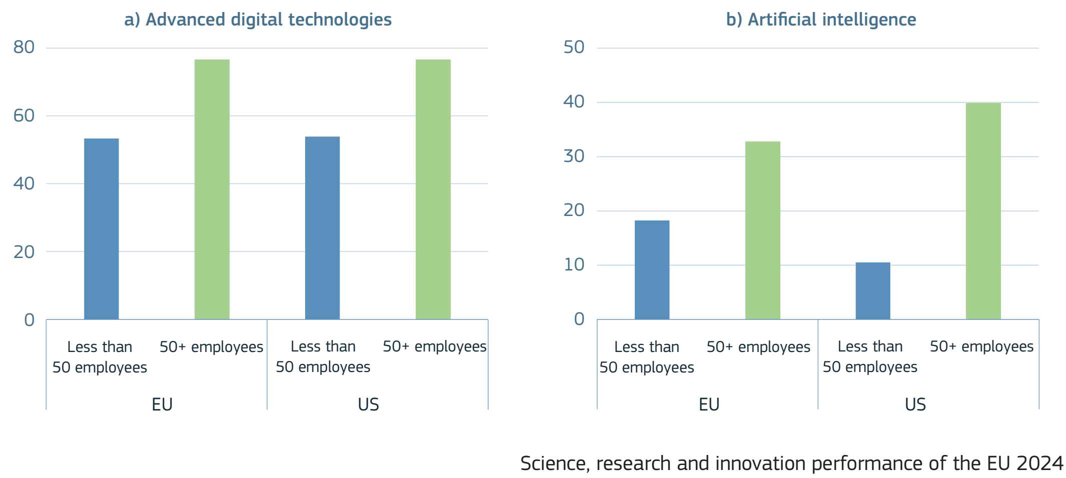
Figure 11-10 Use of advanced digital technologies and artificial intelligence (% of firms)



Source: EIBIS 2023.
Note: Firms are weighted by value added.

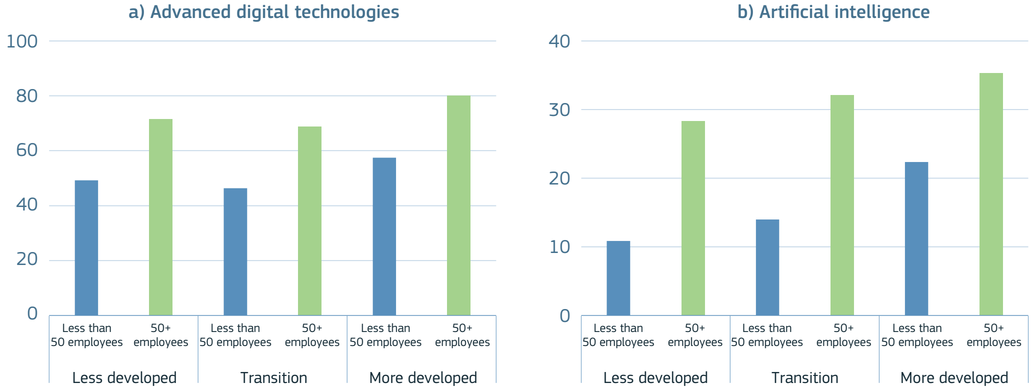
Figure 11-11a shows that large firms are more likely to make use of digital technologies. When focusing on AI, the gap in adoption rates between small and large firms is wider in the US than in the EU (Figure 11-11b). The same relationship between the use of digital technologies and firm size holds across the different regions across the EU (Figure 11-12).

Figure 11-11 Use of advanced digital technologies and artificial intelligence (% of firms), by firm size, EU-US



Source: EIBIS 2023.
Note: Firms are weighted by value added.

Figure 11-12 Use of advanced digital technologies and artificial intelligence (% of firms), by firm size



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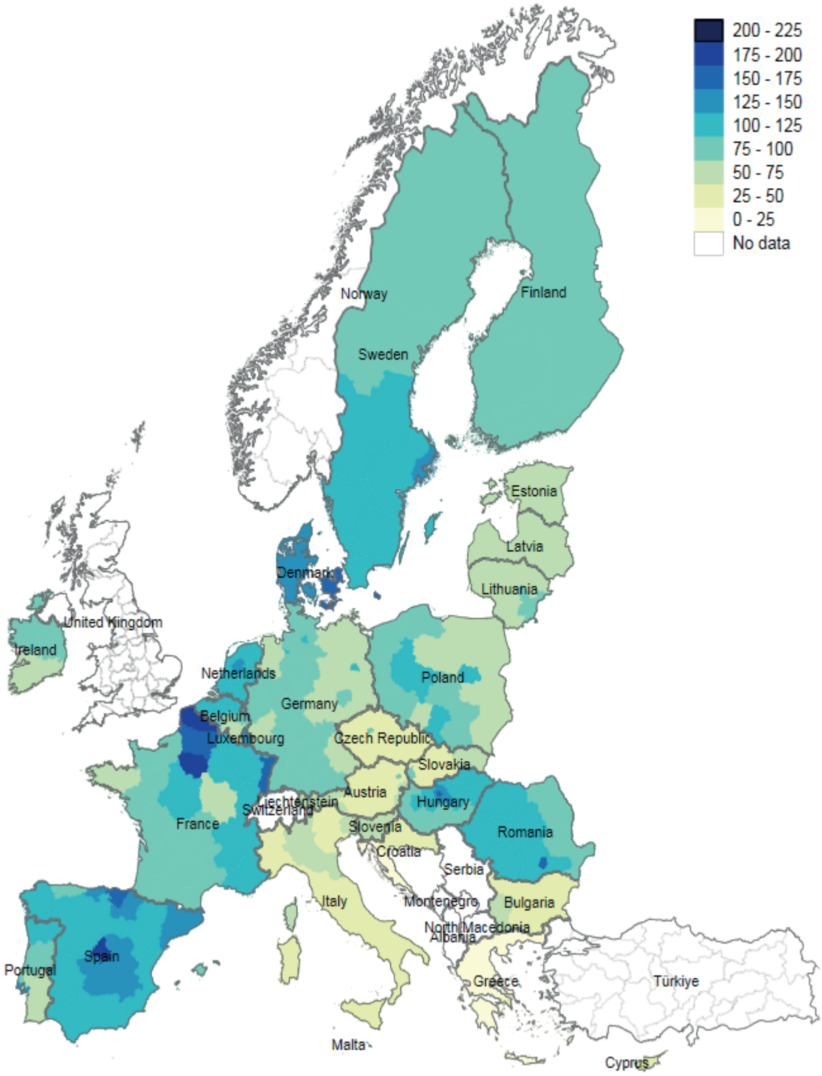
Source: EIBIS 2023.

Note: Firms are weighted by value added.

Digital infrastructure plays a critical role in economic activity, particularly for firms using advanced digital technologies. 12 % of EU firms surveyed in the latest EIBIS consider access to digital infrastructure as a major obstacle to investment. A key consideration here is internet access and speed. Using data on average internet download speeds, Figure 11-13 shows that significant differences exist in the quality of digital infrastructure between different EU regions and countries.

Figure 11-13 Internet download speed in the EU in 2021 (megabits per second)



Science, research and innovation performance of the EU 2024

Source: Authors' calculations based on Ookla.

Note: The figure shows data from 2021 and is based on more than 82 million internet speed tests during this period. Average internet download speed in a NUTS2 region is based on tests performed using the website Speedtest.net, and is measured in megabits per second. The original data is provided at the level of Mercator tiles (approximately 610.8 meters by 610.8 meters at the equator), which is aggregated to NUTS2 level averages, using the number of tests as weights.

The returns from digitalisation are larger for firms located in regions with better digital infrastructure and faster internet speed. This is illustrated by the positive interaction between firms' use of advanced digital technologies and high download speed in a regression analysis (Table 11-1). This underpins how complementary public and private digital investment can improve firm performance and economic resilience.

Additionally, several different performance metrics confirm that adopting digital technologies pays off at the firm level. Firms that have embraced Big Data and AI technologies are, on average, larger and pay higher wages to their employees. These effects are even stronger for firms using AI, thereby highlighting the benefits of using advanced digital technologies in terms of firm performance. Overall, this also supports previous empirical evidence on the positive effect of digital adoption and the use of AI on innovation and firm productivity (Gal et al.; 2019; Acemoglu et al., 2022; Rammer et al., 2022; EIB, 2023).

Table 11-1 Digital adoption, digital infrastructure and firm productivity

Dependent variable:	**Labour productivity**
Use of advanced digital technologies	0.150***
	(0.013)
Regions with high download speed	0.112***
	(0.014)
Digital x high download speed	0.032*
	(0.018)
Sample size	42 515
R-squared	0.254

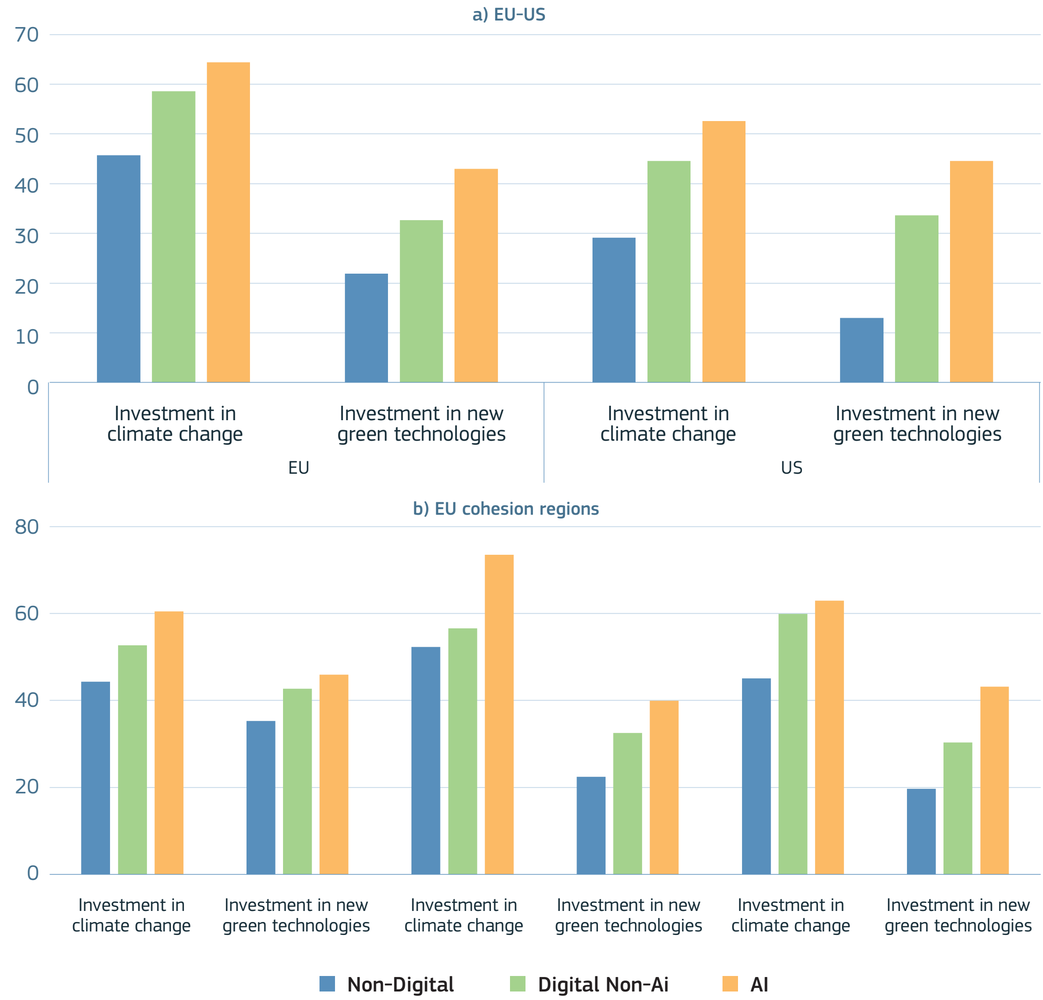
Science, research and innovation performance of the EU 2024

Source: Authors' calculations based on EIBIS (2019-2023) and Ookla (2021).

Note: EU firms. Labour productivity is in natural logarithm. The ordinary least square (OLS) regression controls for firm size, firm age, country and sector (three groups of EU countries and four macroeconomic sectors). Regions with high download speeds: NUTS 2 region, with average download speeds higher than the median download speed across all regions (based on Ookla data). Robust standard errors are in parentheses. Statistical significance: *** p-value<0.01, ** p-value<0.05, * p-value<0.1.

Digital technologies –especially AI – could catalyse green innovation and transformation. Indeed, as shown in Figure 11-14, firms adopting AI technologies are more likely to invest in green innovation and transformation. This suggests that the contribution of digital technologies to a firm's eco-innovation is mainly driven by investment in AI application areas (Rotman, 2019; Montresor and Vezzani, 2023). As such, the next section concentrates on investment in the green transition – another key structural transformation challenge for the EU.

Figure 11-14 Digitalisation and investment to tackle climate change (% of firms)



Science, research and innovation performance of the EU 2024

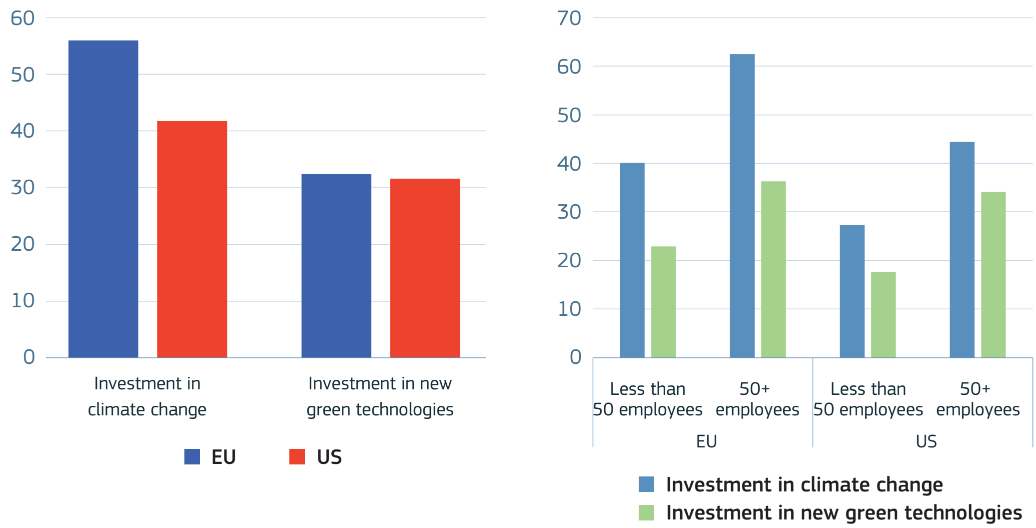
Source: EIBIS 2023.
Note: Firms are weighted by value added.

5. Adoption of green technologies

The EU has a higher share of firms that invest in tackling the impacts of weather events and reducing carbon emissions than the US. However, the share of EU and US firms that invest in new, less polluting business areas and technologies are similar (Figure 11-15a). As such, investing in new green technologies is especially important if the EU wants to maintain a competitive edge in this area. Previous evidence has shown that Europe excels in patenting green technologies, unlike its position in digital technology innovation (EIB, 2024); while this is encouraging news, EU firms must invest to adopt these new green innovations more broadly.

Large companies mainly drive investments in climate change and digital innovation and transformation. Figure 11-15b indicates that, just like in the case of digitalisation, there is a positive relationship between firm size and investment in the green transition. This relationship also holds across the different cohesion regions across the EU (Figure 11-16).

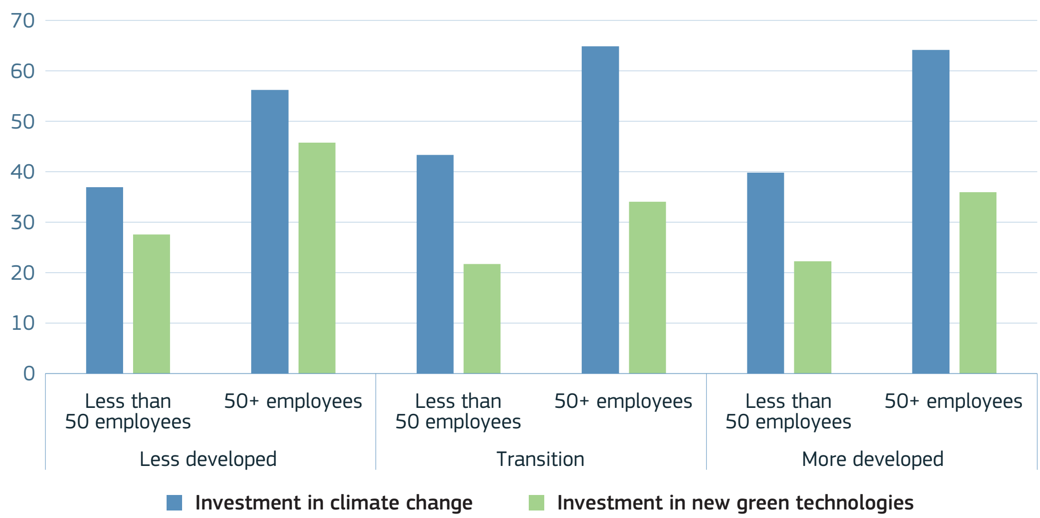
Figure 11-15 Investment to tackle climate change (% of firms)



Science, research and innovation performance of the EU 2024

Source: EIBIS 2023.
Note: Firms are weighted by value added.

Figure 11-16 Investment to tackle climate change (% of firms), by firm size, cohesion regions

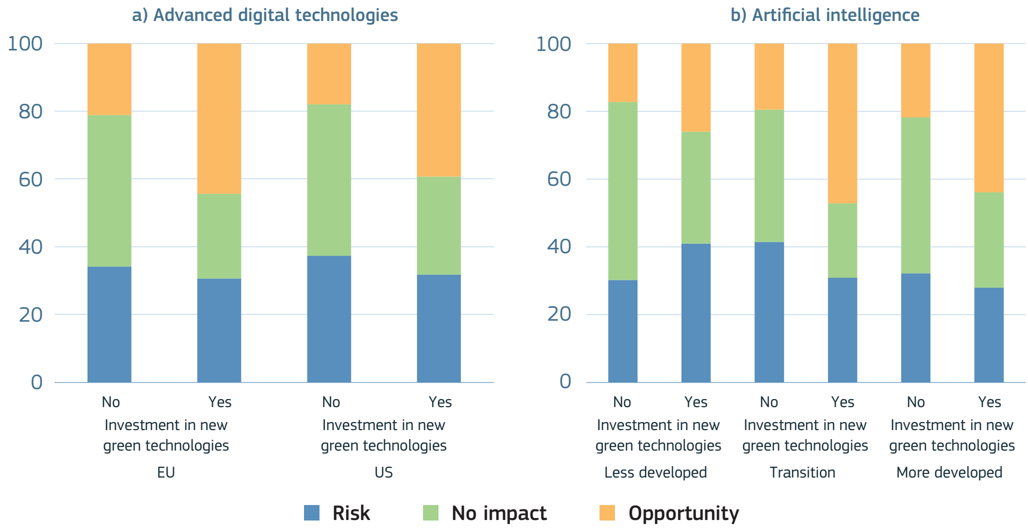


Science, research and innovation performance of the EU 2024

Source: EIBIS 2023.
Note: Firms are weighted by value added.

Firms investing in green innovation and transformation are more likely to see the transition risk to a net zero emission economy as an opportunity. Almost half of firms that invest in less polluting business areas and technologies see the transition to stricter climate standards as an opportunity, a difference of 20 percentage points compared to firms not making such investments (Figure 11-17a). This supports the view that investing in green innovation and transformation is an important driver of a successful climate change transition. The same pattern holds across the different cohesion regions, even if the firms investing in new green technologies in less developed regions are more likely to consider the transition a risk than firms in transition and more developed regions (Figure 11-17b).

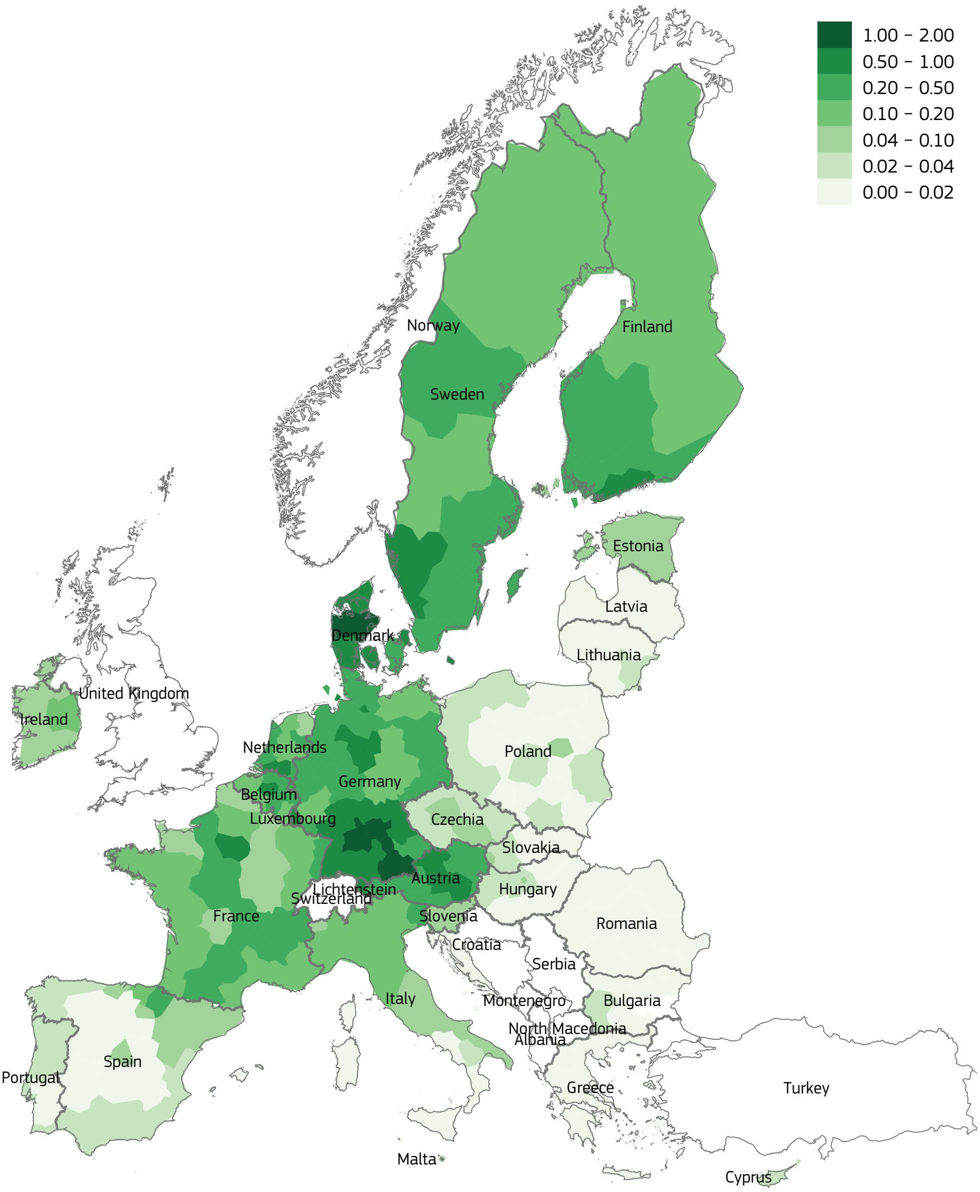
Figure 11-17 Green innovation and transition risk (% of firms)



Source: EIBIS 2023.
Note: Firms are weighted by value added.

The innovative environment can play a critical role in firms' investment in innovation, as well as local and aggregate economic activity. A vast literature supports this, highlighting the role of knowledge spillovers on firm-level innovation and the importance of ecosystems inducing innovation (Audretsch et al., 2022; European Commission, 2022b). The green innovation intensity of a region – as measured by patents in green technologies – can be used as a proxy for the innovative quality of a green ecosystem. Figure 11-18 illustrates significant differences in green innovative intensity across different EU regions and countries.

Figure 11-18 **Green tech patents (% of population in the region)**



Science, research and innovation performance of the EU 2024

Source: Authors' calculations are based on PCT patents (PATSTAT), in collaboration with ECOOM, KU Leuven, and Eurostat.

Note: Green tech patents are measured as the cumulative patent count across 2011-2020. Population is the regional population in 2020, divided by 1 000. The values should thus be interpreted as a ranking and not interpreted at face value.

The returns from green innovation and transformation are greater for firms located in regions with a more robust green innovative environment. Being embedded in a region with a higher intensity of green innovation relative to the total population provides additional productivity gains to those that invest in green innovation and transformation. This is illustrated by the regression output in Table 11-2, showing a positive interaction effect between investing in new, less polluting business areas and technologies and a greener innovative environment, which further underlines the importance of the broader ecosystem for innovation performance. Table 11-2 also shows that investments in new, less polluting business areas and technologies are associated with higher labour productivity, even when the green innovativeness of the region is not taken into account. This also holds when assessing the impact of investment in climate change at large and its impact on productivity. This evidence is well aligned with an emerging body of literature, emphasising the productivity-enhancing effects of investments in climate (Stern and Stiglitz, 2023).

Table 11-2 Green innovation, regional green innovation and firm productivity

Dependent variable:	**Labour productivity**		
Investment in new green technologies	0.139***		0.093***
	(0.017)		(0.026)
Region with a high share of green innovation (relative to total population)		0.451***	0.426***
		(0.024)	(0.026)
Investment in green tech x green innovative region			0.083**
			(0.033)
Sample size	23 422	21 469	21 356
R-squared	0.149	0.187	0.189

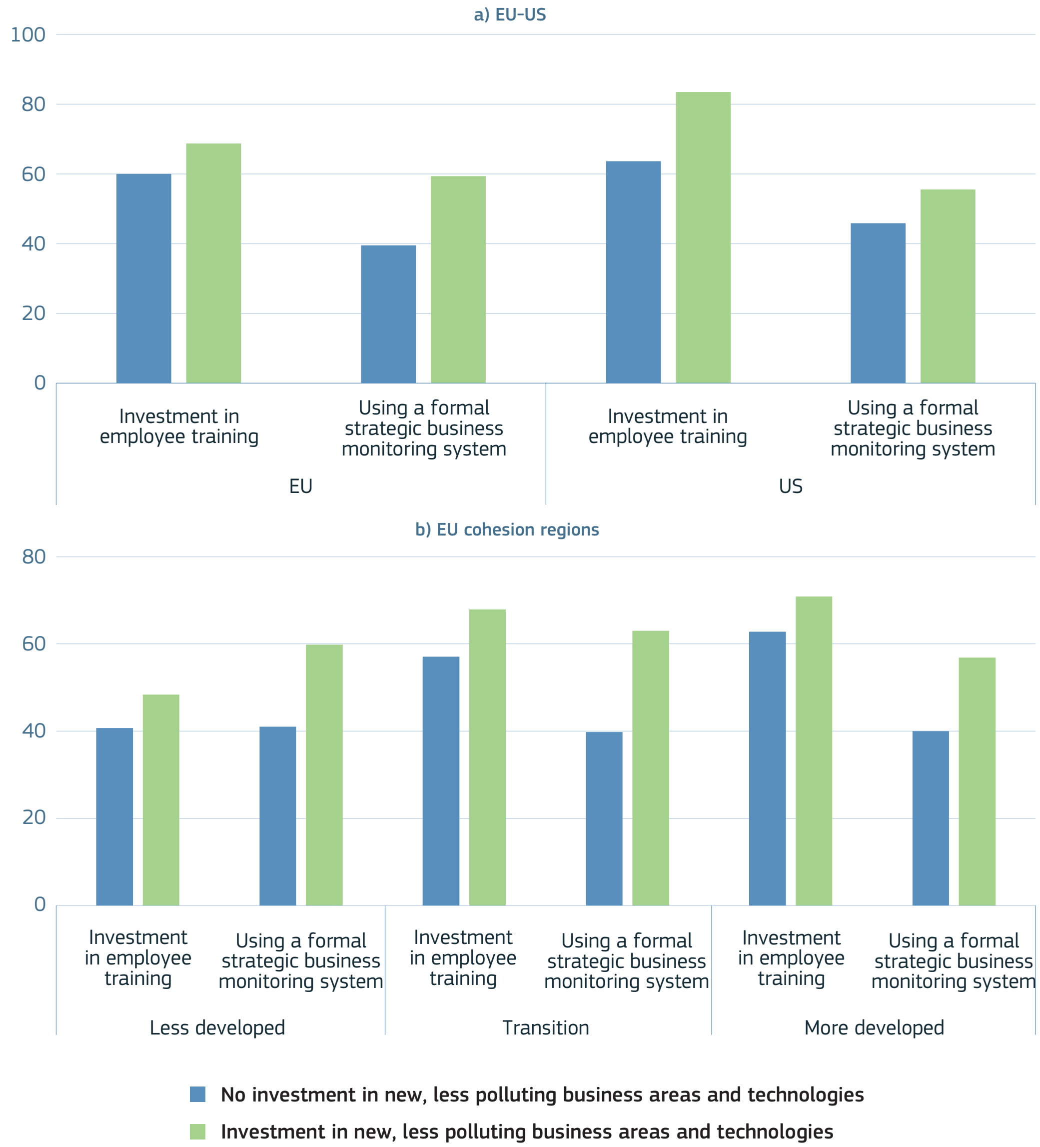
Science, research and innovation performance of the EU 2024

Source: Authors' calculations based on EIBIS 2022-2023 and PATSTAT.

Note: EU firms. Labour productivity is expressed in natural logarithms. The ordinary least squares (OLS) regressions control for firm size, country and sector (three groups of EU countries and four macroeconomic sectors). Robust standard errors are in parentheses. Statistical significance: *** p-value<0.01, ** p-value<0.05, * p-value<0.1.

Next to having a positive impact on productivity, investing in green innovation also fosters other firm performance metrics. For example, investment in green innovation and transformation consistently results in a higher use of advanced management practices and more investment in employee training, both in the EU and the US (Figure 11-19a), as well across the different European cohesion regions (Figure 11-19b).

Figure 11-19 Green innovation and firm performance indicators (% of firms)



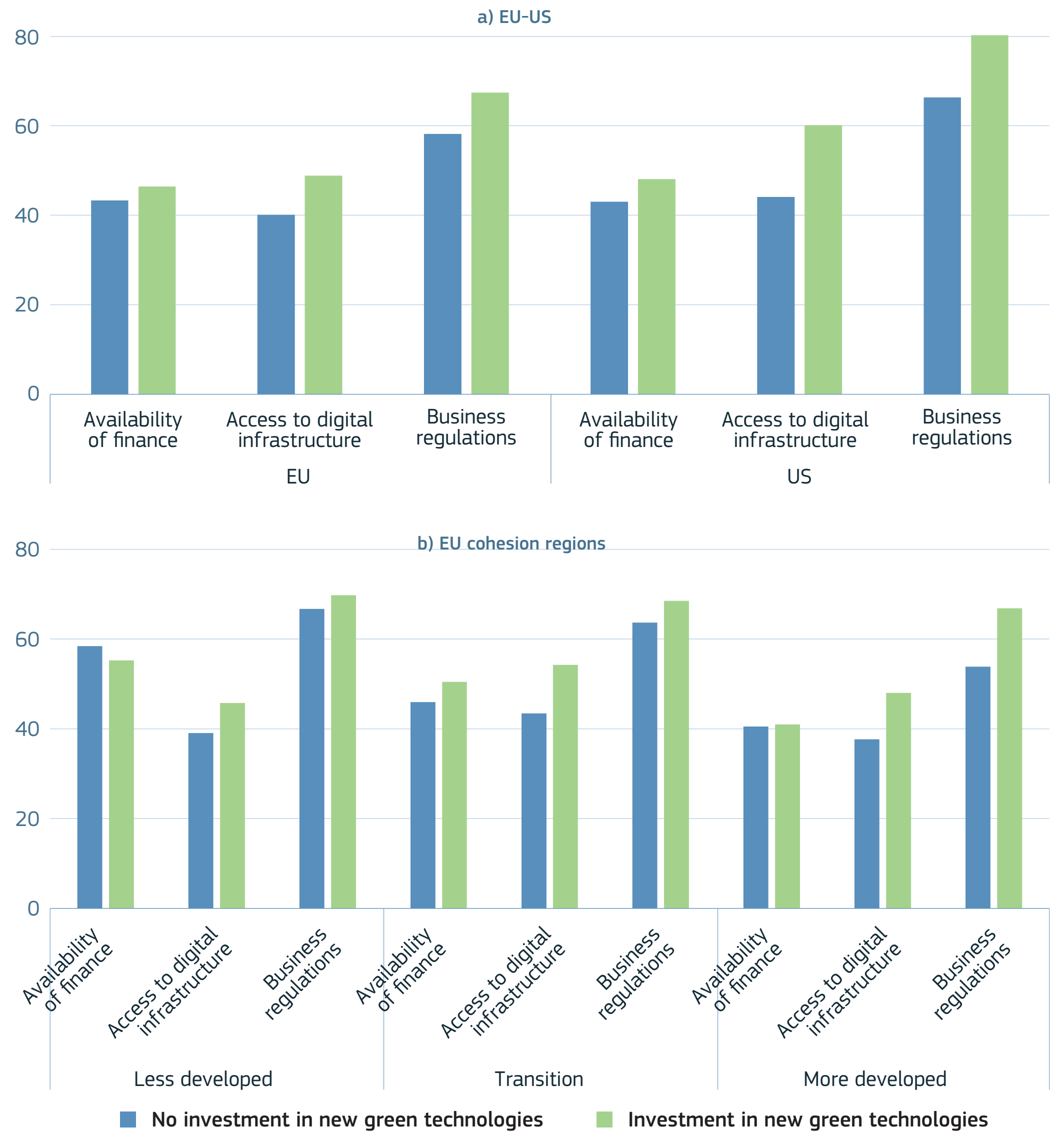
Science, research and innovation performance of the EU 2024

Source: EIBIS 2023.

Note: Firms are weighted by value added.

Firms investing in new, less polluting business areas and technologies object slightly more to almost all obstacles related to their investments than other firms. The main difference is seen within business regulations and digital infrastructure, with firms investing in green innovation and transformation complaining almost ten percentage points more than other firms (Figure 11-20). This points to a need for policymakers to alleviate regulatory uncertainty for businesses willing to undertake green investments. Indeed, if emerging digital technologies are properly employed and barriers to their adoption are reduced, they could play a major role in tackling environmental challenges (Intergovernmental Panel on Climate Change (IPCC), 2022).

Figure 11-20 Obstacles to investment and investment in new green technologies (% of firms)



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Source: EIBIS 2023.
Note: Firms are weighted by value added.

6. Conclusion

The EU policy agenda is increasingly emphasising the need to enhance and preserve the global competitiveness of European firms; for this, investing in innovation and addressing the challenges of climate change are crucial. As such, the agenda aims to foster a more competitive and smarter Europe by creating an inclusive environment that incentivises firms across the EU to accelerate the twin green and digital transition.

Europe is challenged in the global innovation landscape, and a successful twin transition of the EU economy will require a widespread uptake of new green and digital technologies, as they are key drivers of competitiveness and resilience to economic disruption and climate change. While EU firms are catching up with their US peers in the use of digital technologies, they should remain vigilant and invest more, particularly in the adoption of Big Data analytics and AI, which is positively associated with firm performance and job creation and can be a catalyser for green innovation and transformation. Policy support for the adoption and diffusion of technologies is important for the innovation landscape to flourish and is complimentary to EU investment in frontier innovation and the global innovation leadership race.

The structural transformation of the EU seems to be mainly driven by companies in its more developed regions. Nevertheless, poorer regions do show signs of catching up in certain innovation areas, such as in the adoption of AI. Investment in key digital and green areas prove to be crucial for firm performance across all EU regions. Additionally, in the age of the twin green and digital transition, the flexibility of Europe's economy to adjust and transform will not only rely on the intensity of investments in these areas, but also on the efficiency of the operating environment.

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