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.

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[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.

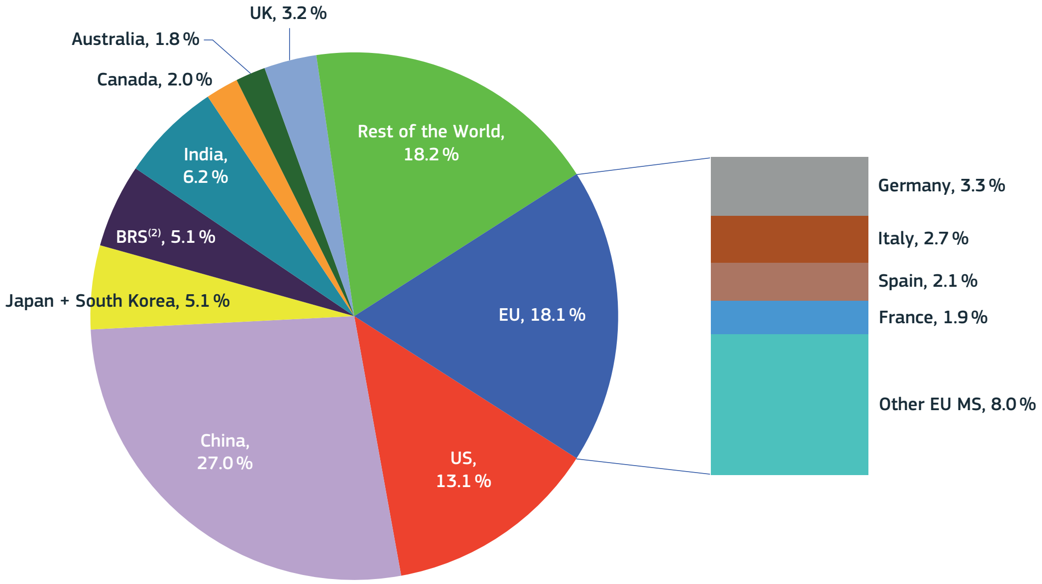
1. Scientific output

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.

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[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.

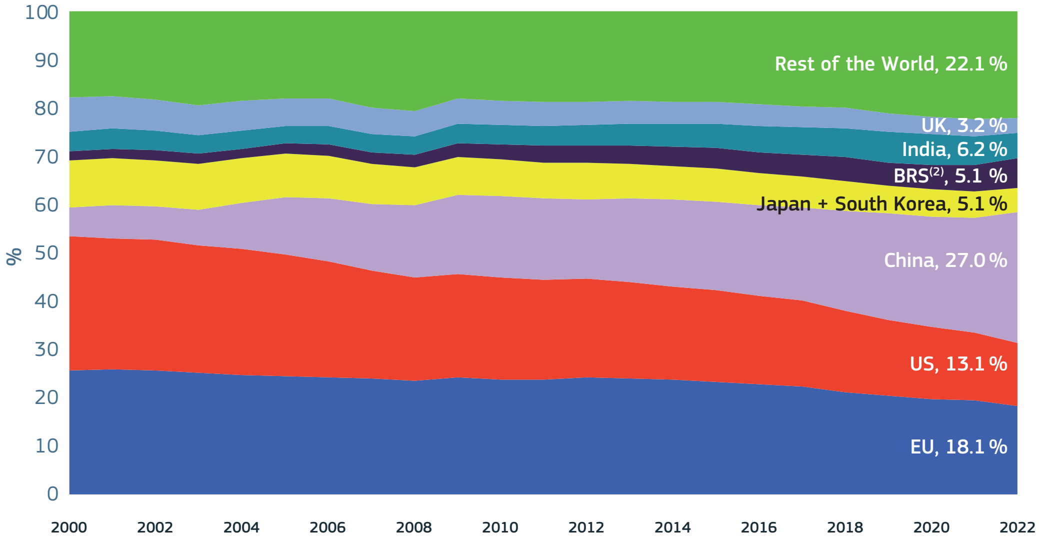
China's emergence as a leading scientific nation can be attributed to several factors, such as an increase in international collaborations and scientific mobility, as well as increased funding. Mobility is supported by programmes designed to encourage scientists working abroad to return to China. These 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

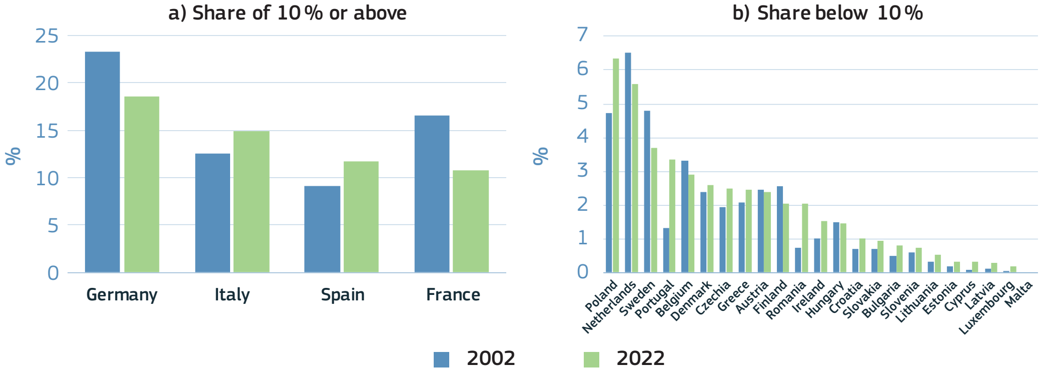


Science, research and innovation performance of the EU 2024

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



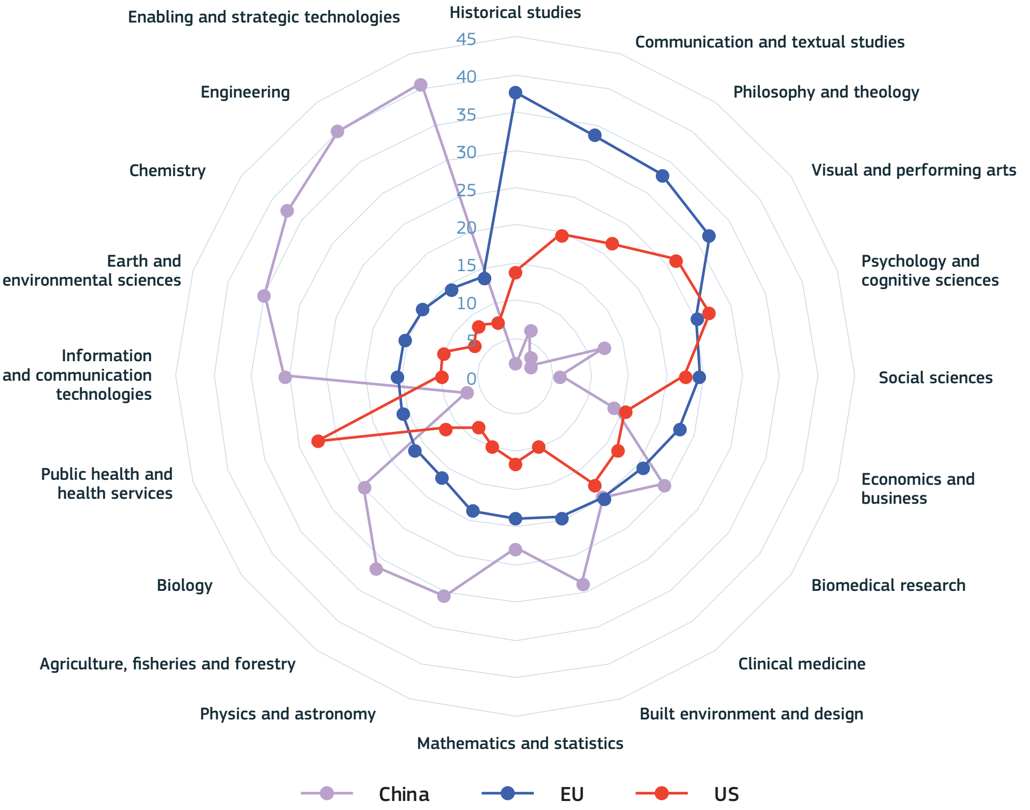
Science, research and innovation performance of the EU 2024

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.

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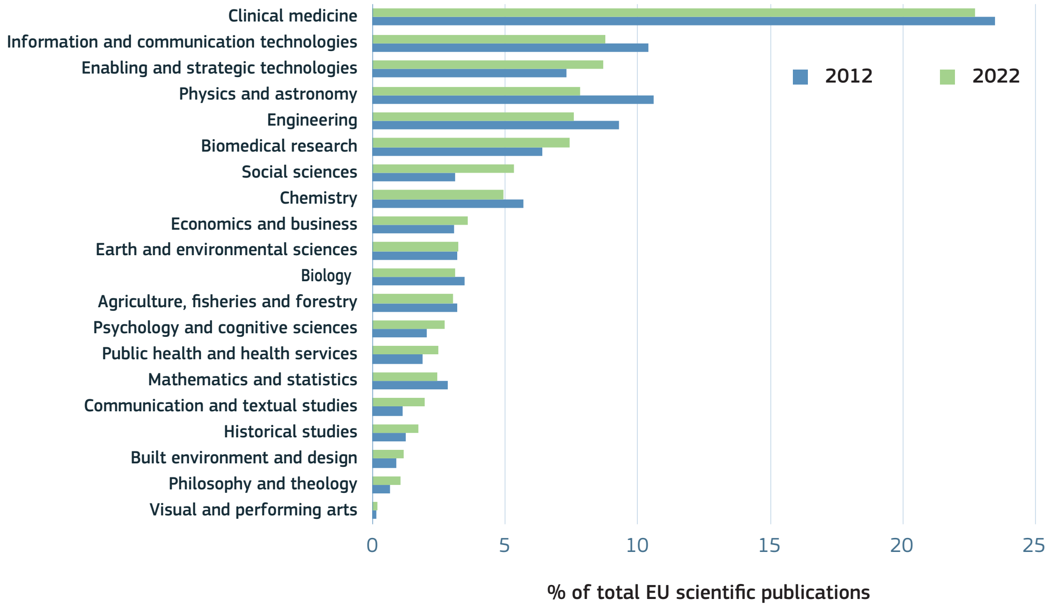
[3] The classification developed by Science-Metrix, which is used here, encompasses five domains: applied sciences, arts and humanities, economics and social sciences, health sciences, and natural sciences, and 20 scientific fields reported in figure 3.1-4.

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.

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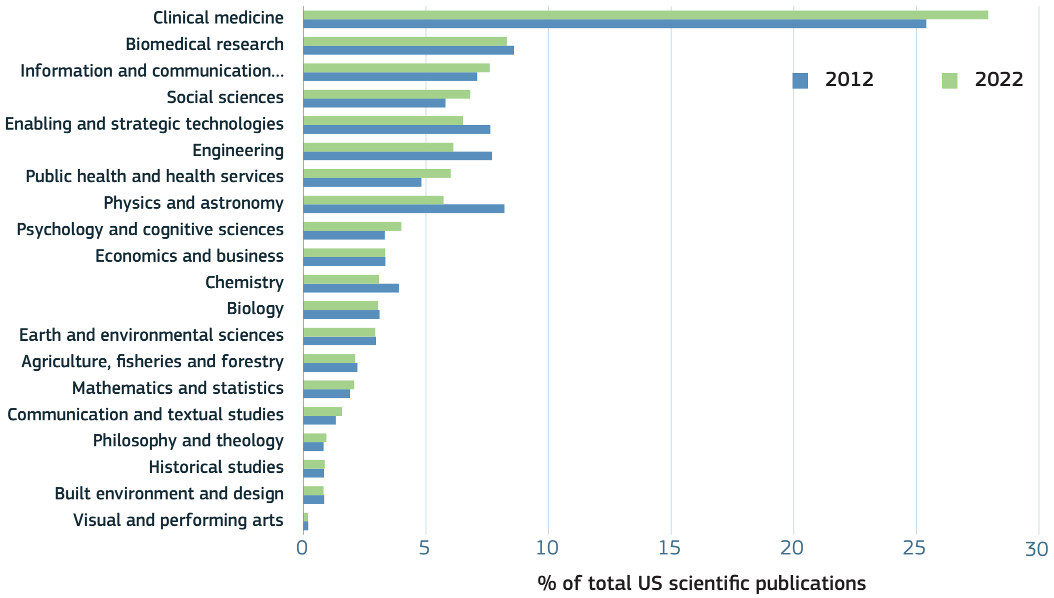
[4] UNESCO datafile ‘Other policy relevant indicators’: http://data.uis.unesco.org/

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.

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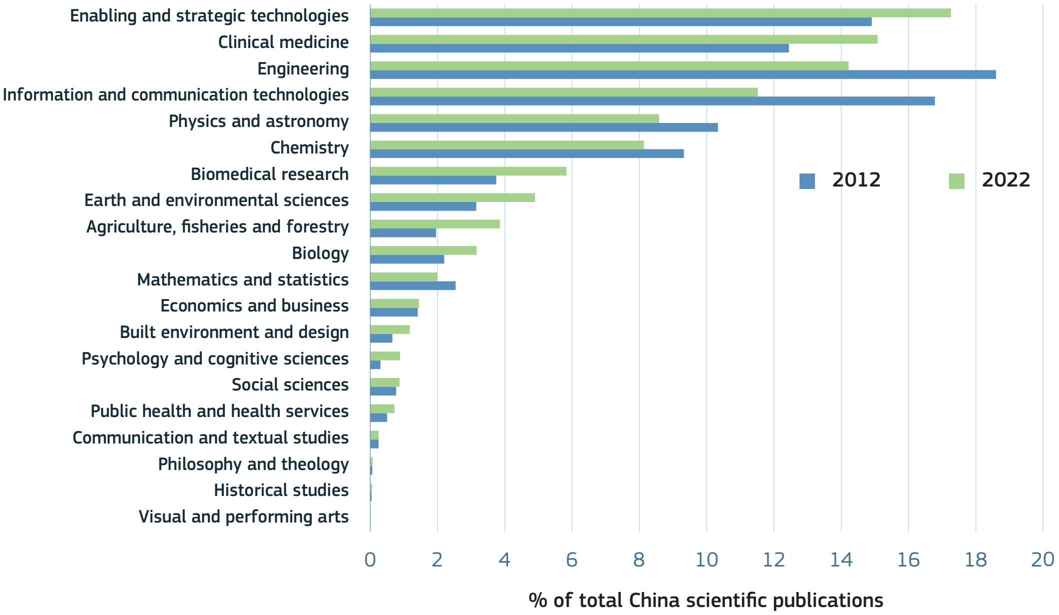
[5] Open access refers to the practice of providing online access to scholarly information that is free of charge to the user and reusable.

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

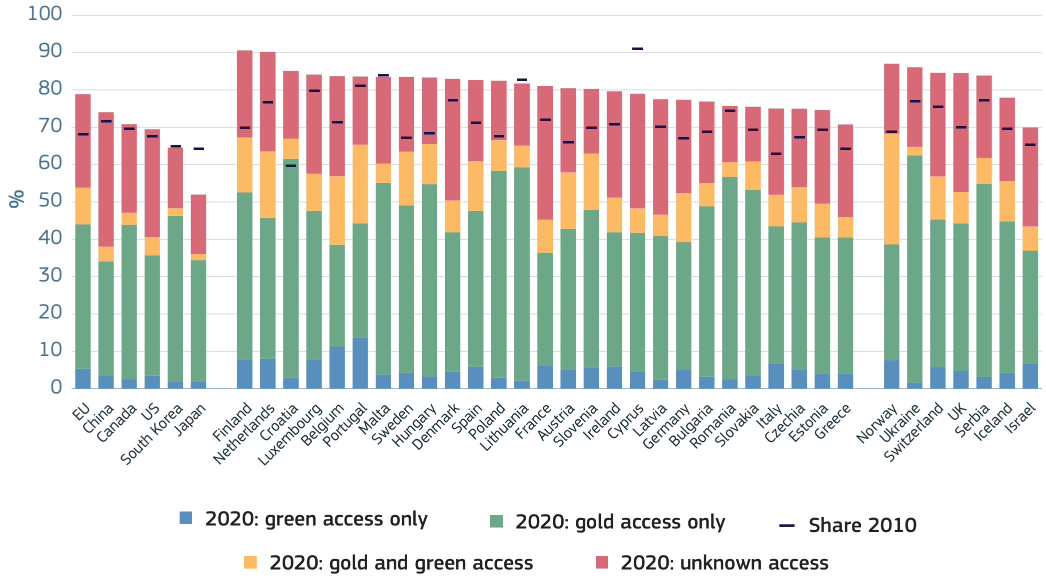


Science, research and innovation performance of the EU 2024

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

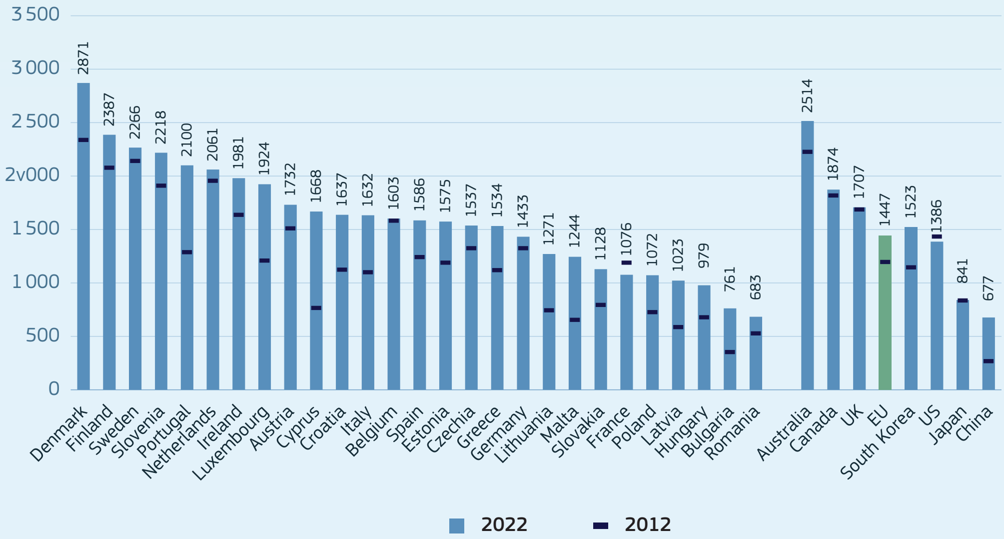
Note: (1) Full counting used. OpenAIRE has adopted Unpaywall's approach to defining open access types. Gold open access involves publishing in fully open access journals, which are defined by one or more of the following criteria: the journal is in the Directory of Open Access Journals (DOAJ); it has 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**

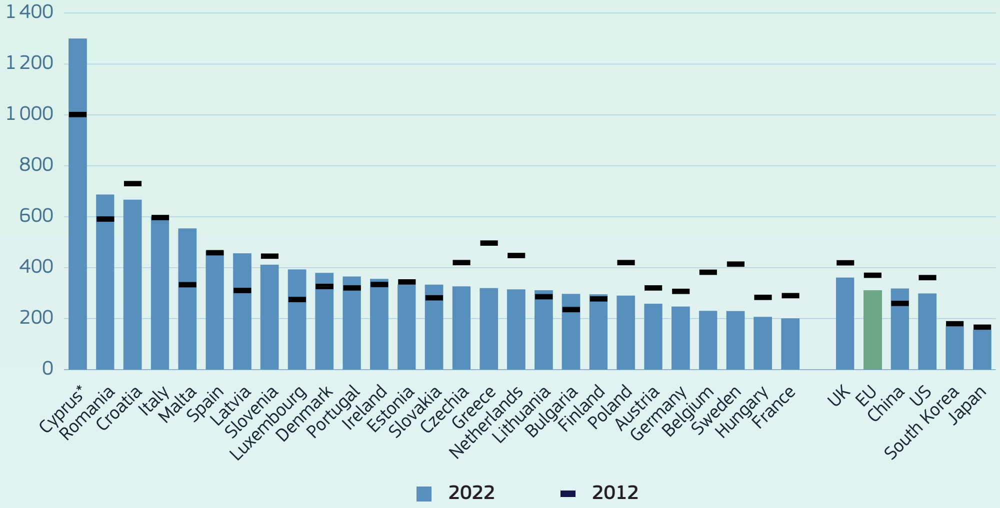


Science, research and innovation performance of the EU 2024

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



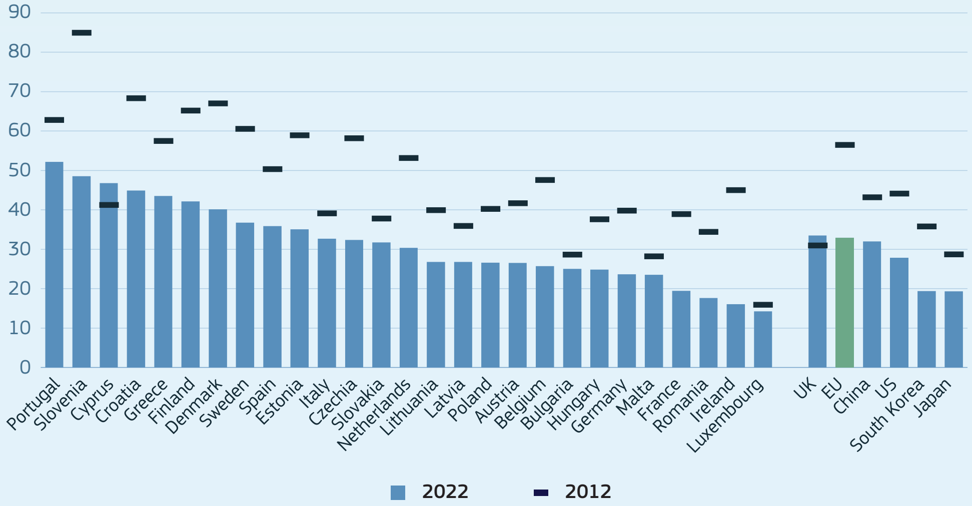
Science, research and innovation performance of the EU 2024

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.

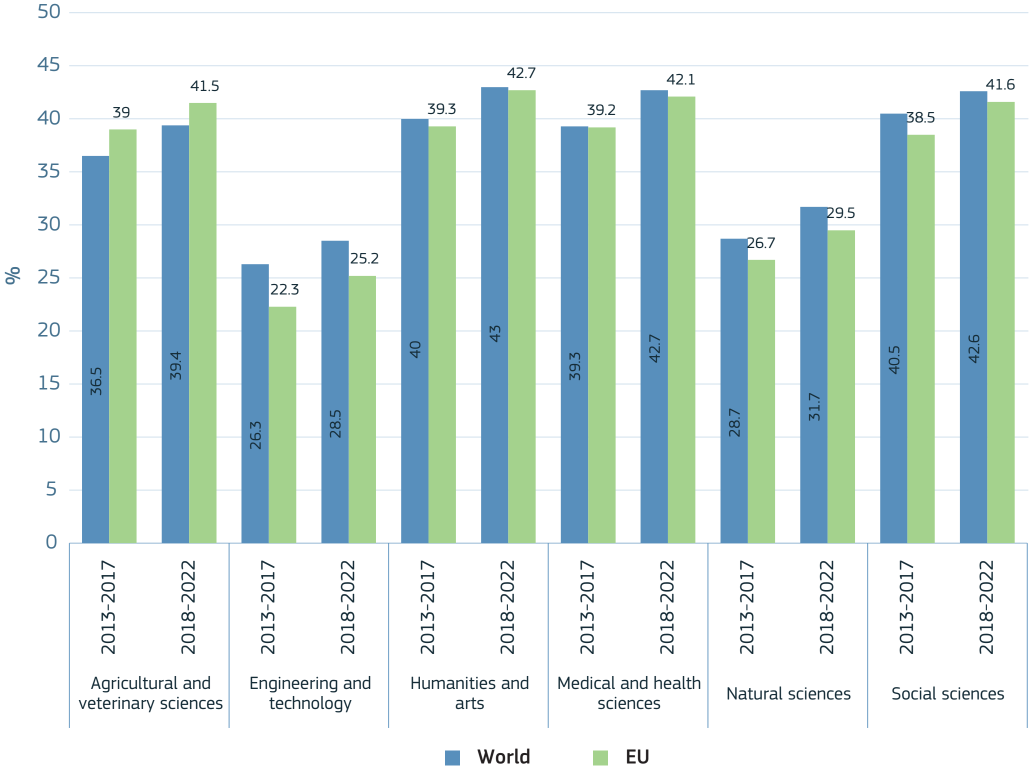
The gender dimension in scientific authorship

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.

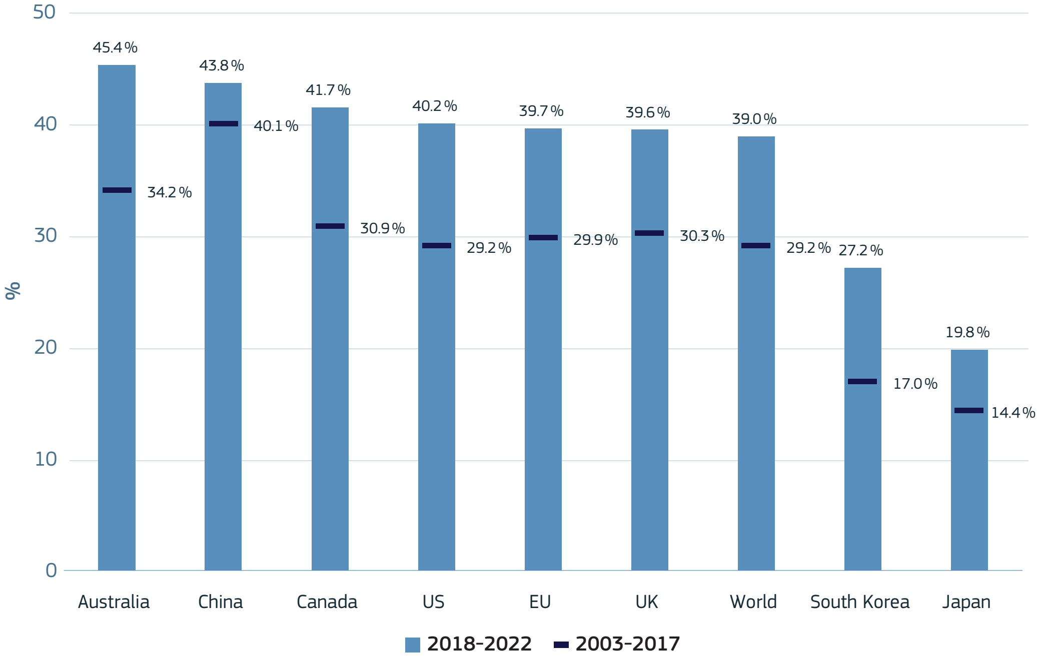
Figure 3.1-12 Average share of female authors for publications with at least one EU author, by R&D field, 2013-2017 and 2018-2022



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

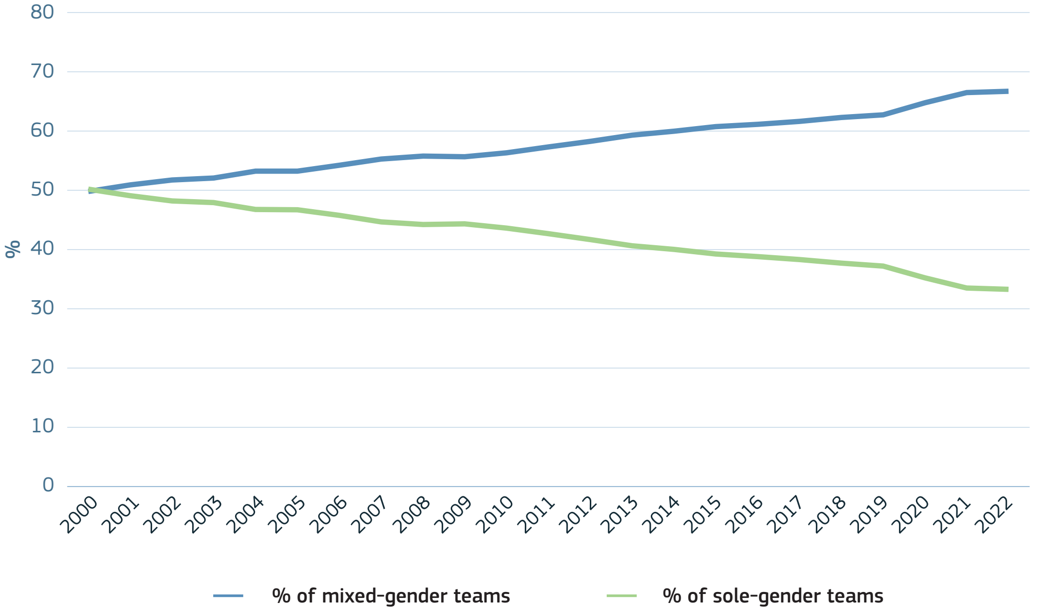


Science, research and innovation performance of the EU 2024

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.

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[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).

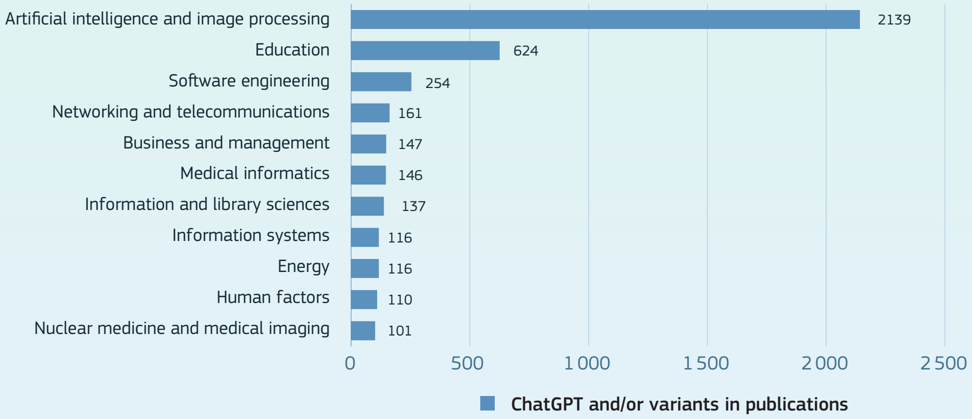
In 2023, 7 023 publications (0.2 % of all Scopus publications) refer to ChatGPT for various purposes. About 34.4 % of these publications directly mentioned ChatGPT in their title, abstract or keywords. In addition, 72 % of papers referencing ChatGPT did so through references to other publications that 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).

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[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

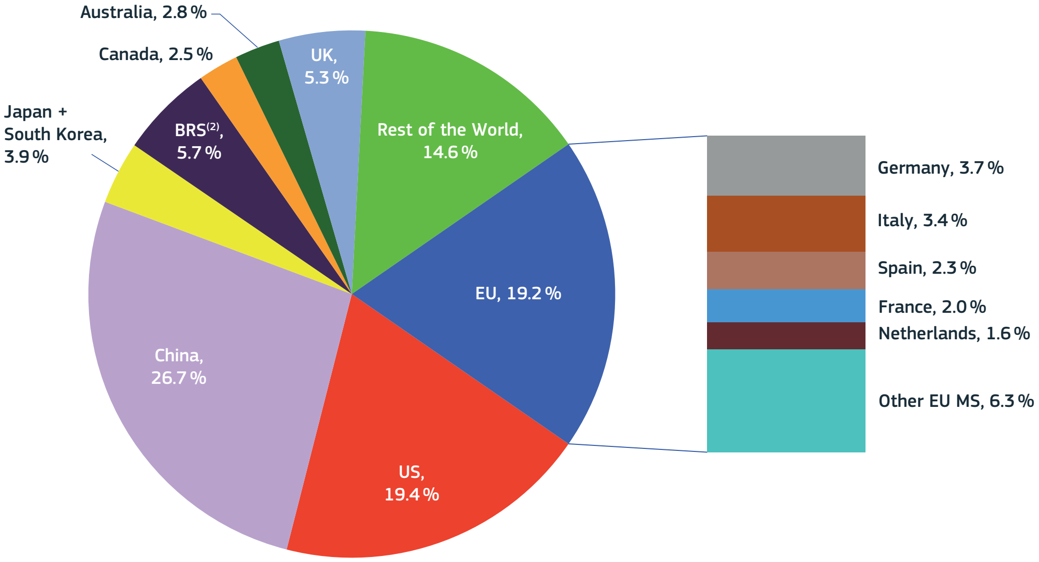
[10] https://research-and-innovation.ec.europa.eu/news/all-research-and-innovation-news/guidelines-responsible-use-generative-ai-research-developed-european-research-area-forum-2024-03-20_en

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)

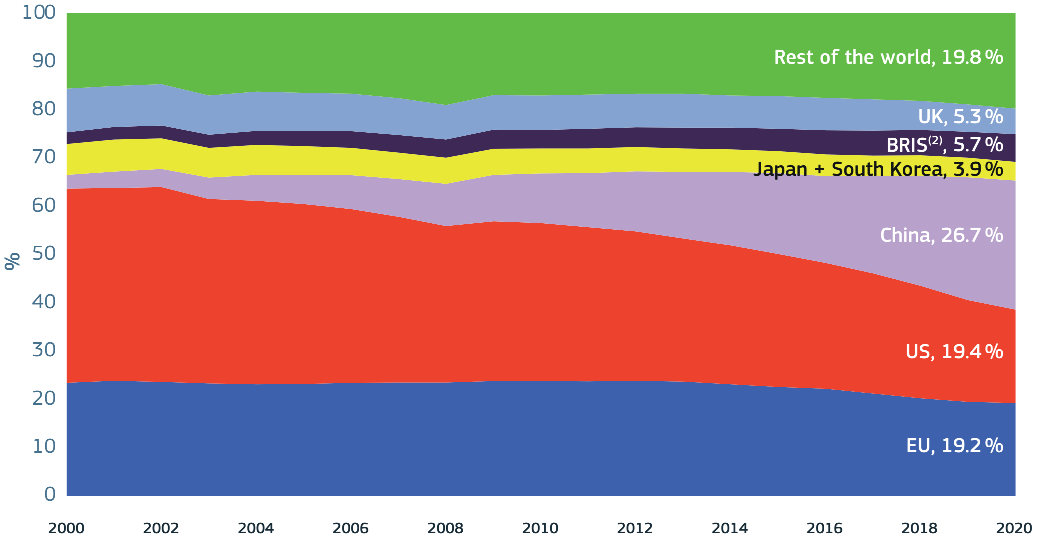


Science, research and innovation performance of the EU 2024

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).

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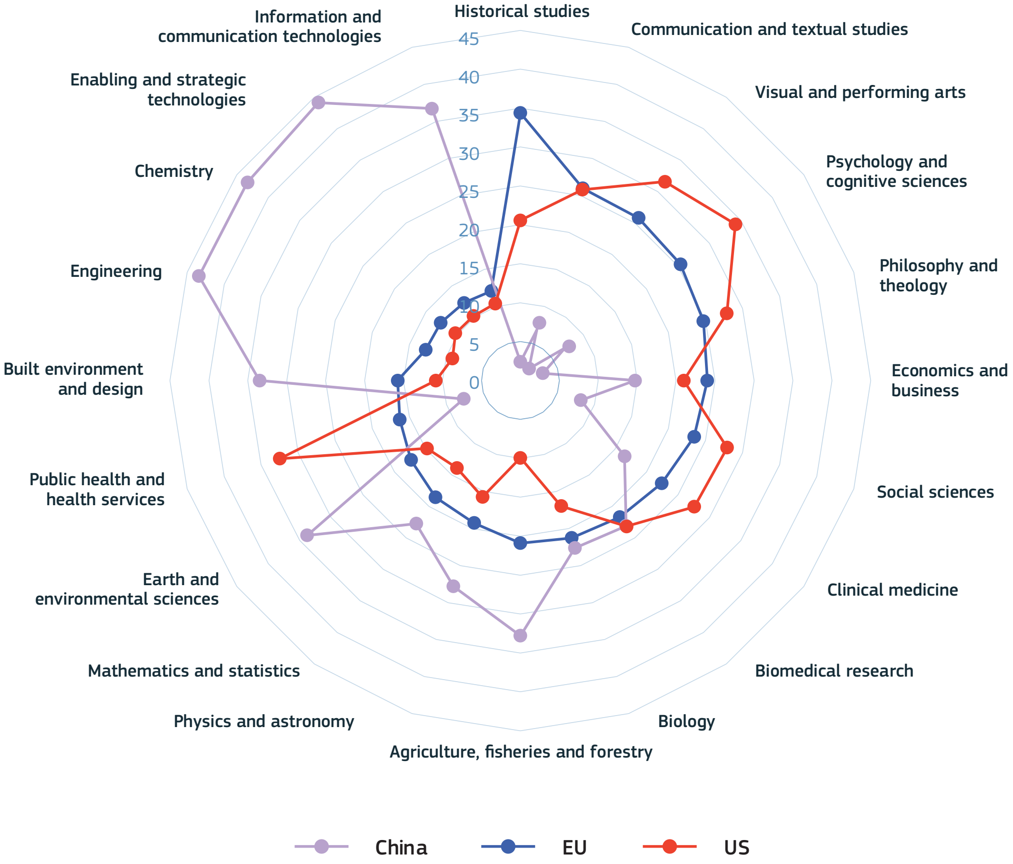
[11] Brazil, Russia, India and South Africa

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



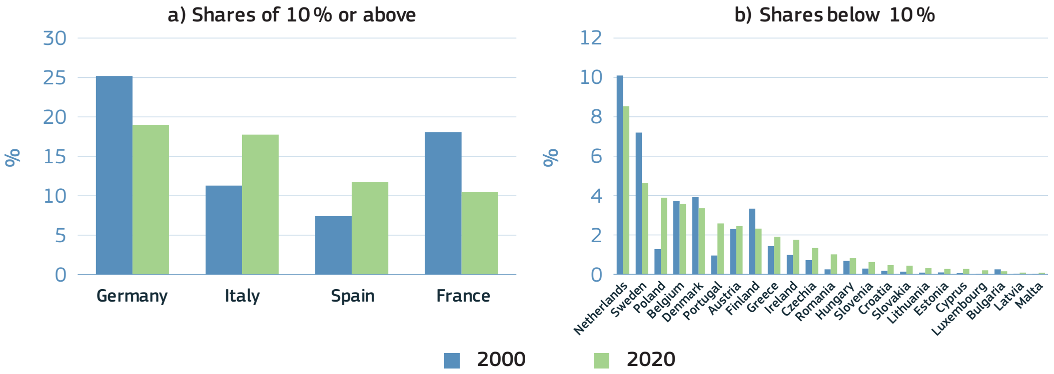
Science, research and innovation performance of the EU 2024

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.

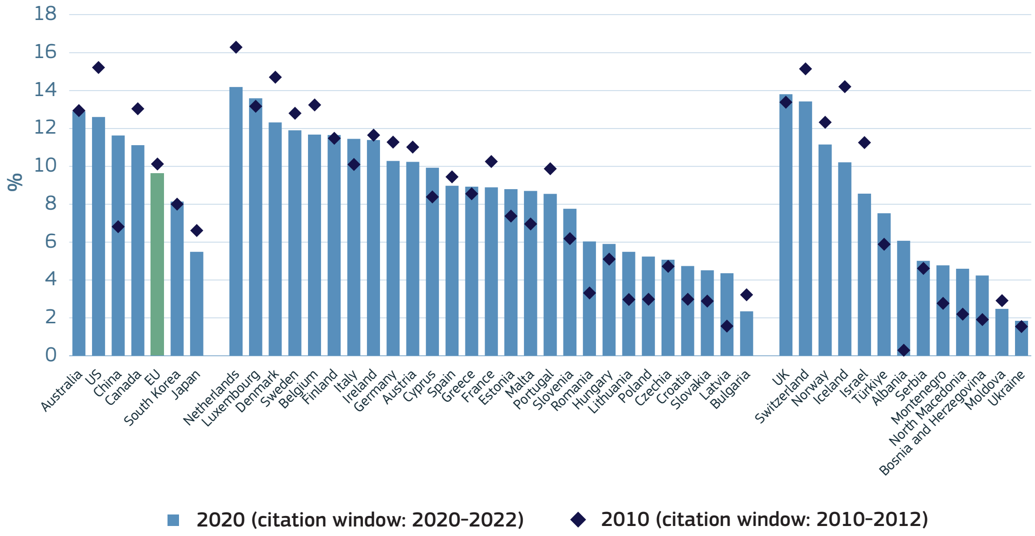
Note: (1) Fractional counting was used to assign publications to countries/aggregates.

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



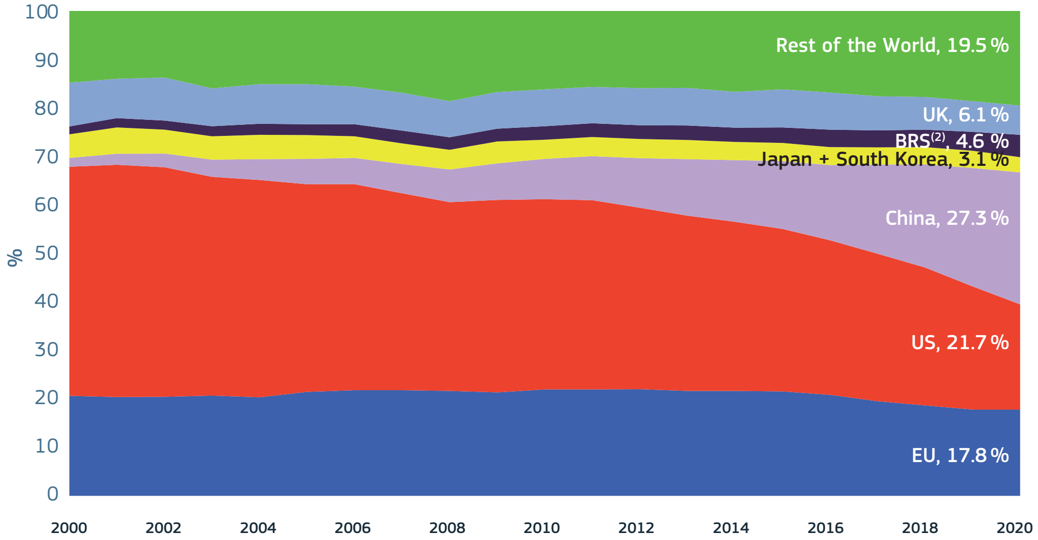
Science, research and innovation performance of the EU 2024

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)



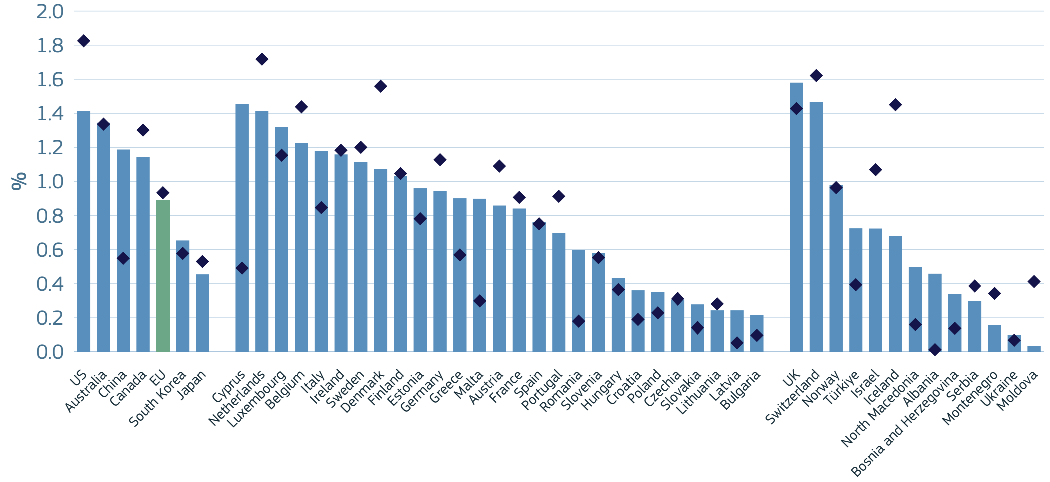
Science, research and innovation performance of the EU 2024

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

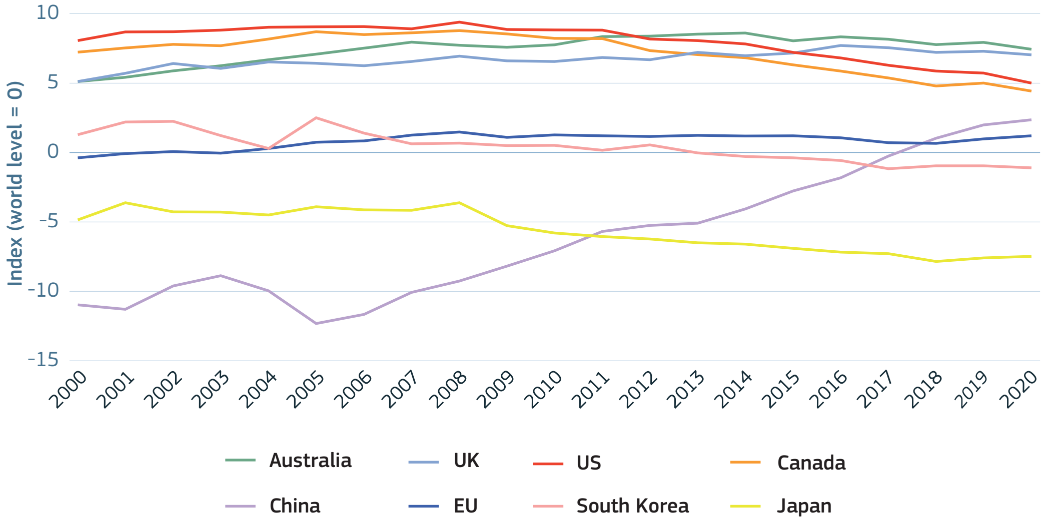


Science, research and innovation performance of the EU 2024

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).

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[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

Over **13 000** top researchers funded since the ERC creation in 2007

Over **220 000** articles from ERC projects published in scientific journals

Over **100 000** researchers and other professionals employed in ERC research teams

Over **930** research institutions hosting ERC grantees – universities, public or private research centres in the EU or Associated Countries

Over **2 400** patents and other IPR applications generated by ERC funding

93 nationalities of grant holders

Over **400** start-ups identified as founded or co-founded by ERC grantees

14 Nobel Prizes,
6 Fields Medals,
11 Wolf Prizes

and other prizes awarded to ERC grantees

Source: ERC.

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[16] https://erc.europa.eu/projects-statistics/scientific-prizes

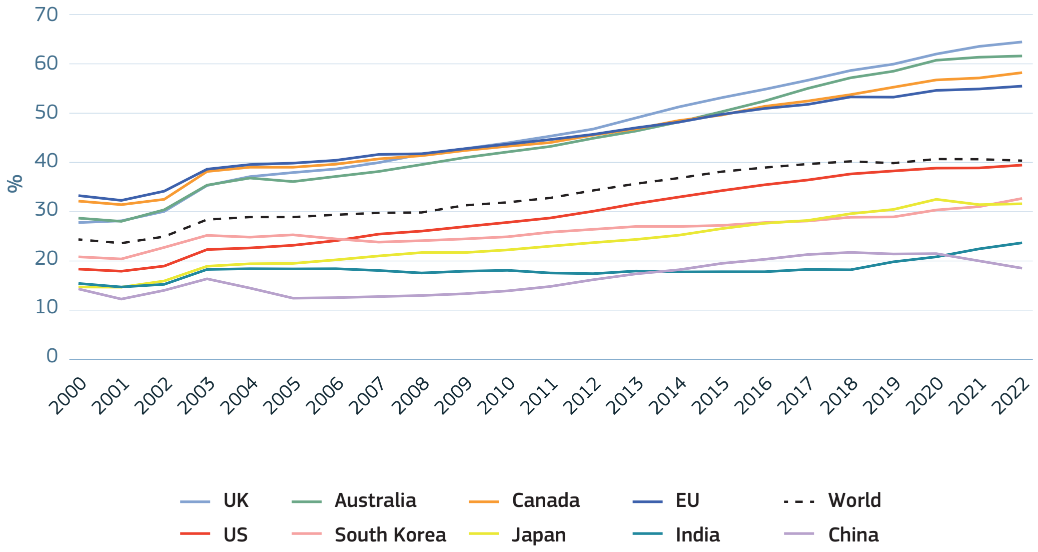
[17] https://erc.europa.eu/projects-statistics/mapping-erc-frontier-research-an-overview

[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

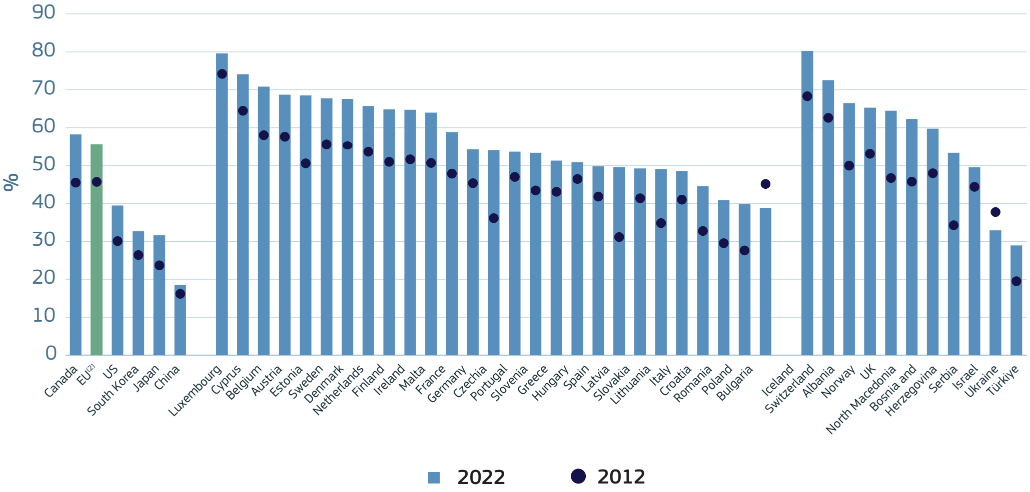


Science, research and innovation performance of the EU 2024

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).

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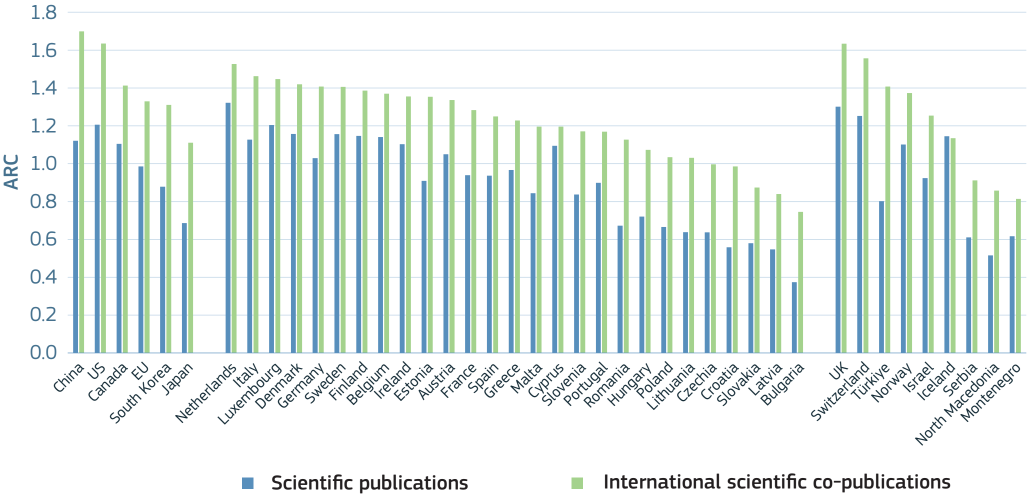
[19] The ARC used by Science-Metrix is an indicator of the scientific impact of papers produced by a given entity (e.g. a country or an institution) which takes into consideration the fact that citation behaviour varies between fields. For a paper in a given subfield, the citation count is divided by 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).

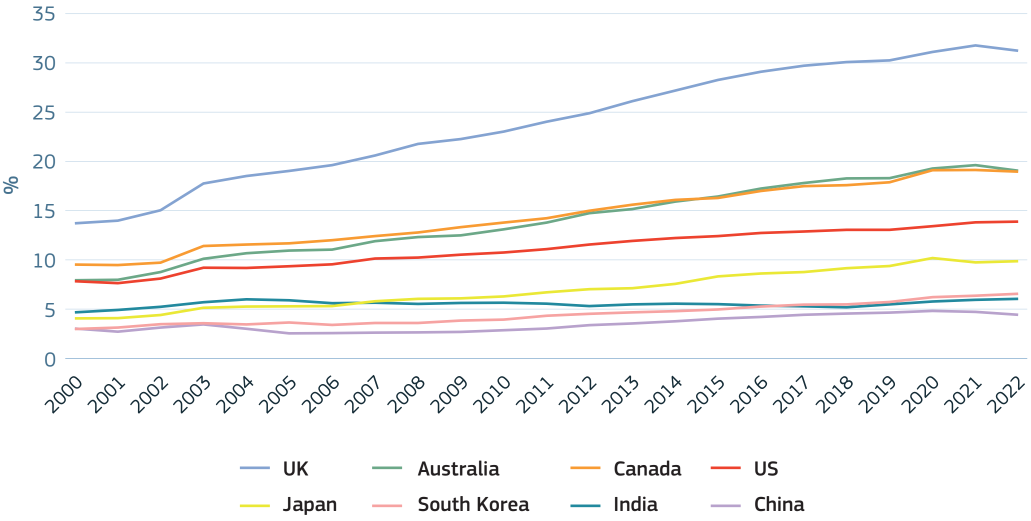
Figure 3.1-27 **Average of relative citations (ARC), 2020 (citation window: 2020-2022)**



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**

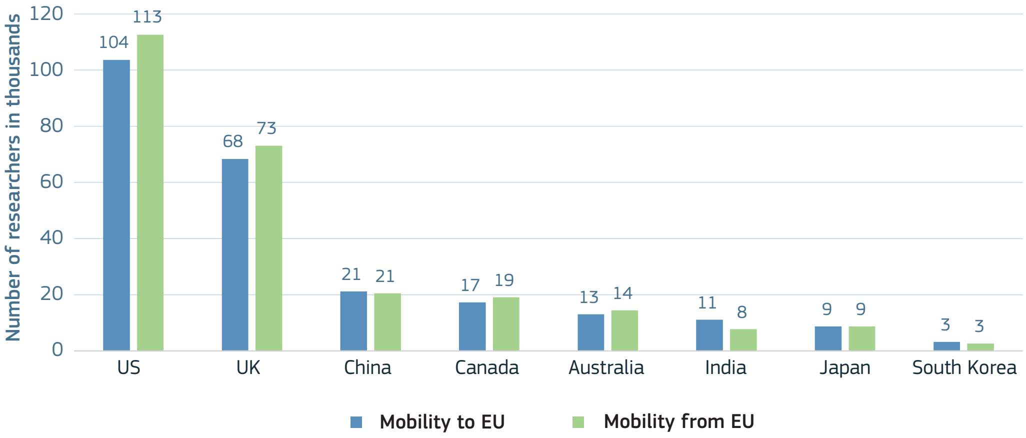


Science, research and innovation performance of the EU 2024

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]

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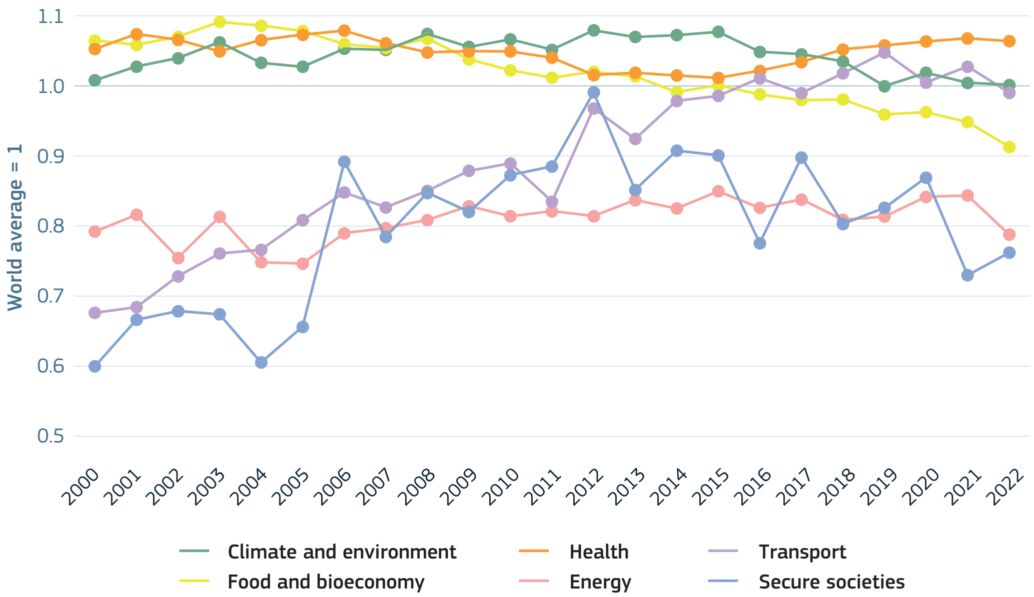
[20] The Horizon 2020 Societal Grand Challenges are: health, demographic change and well-being (health); food security, sustainable agriculture and forestry, marine, maritime and inland water research, and the bioeconomy (food and bioeconomy); secure, clean and efficient energy (energy); smart, green 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

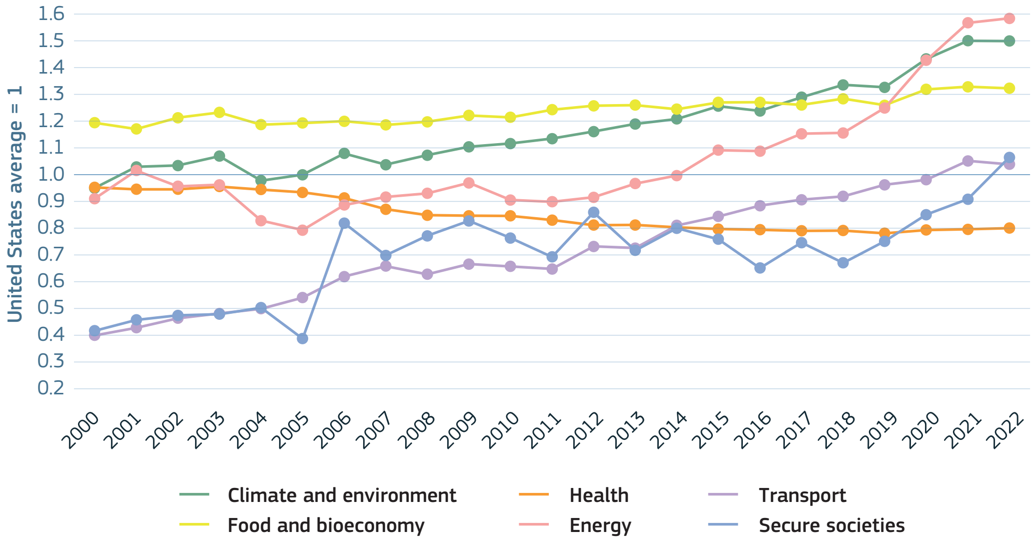


Science, research and innovation performance of the EU 2024

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.

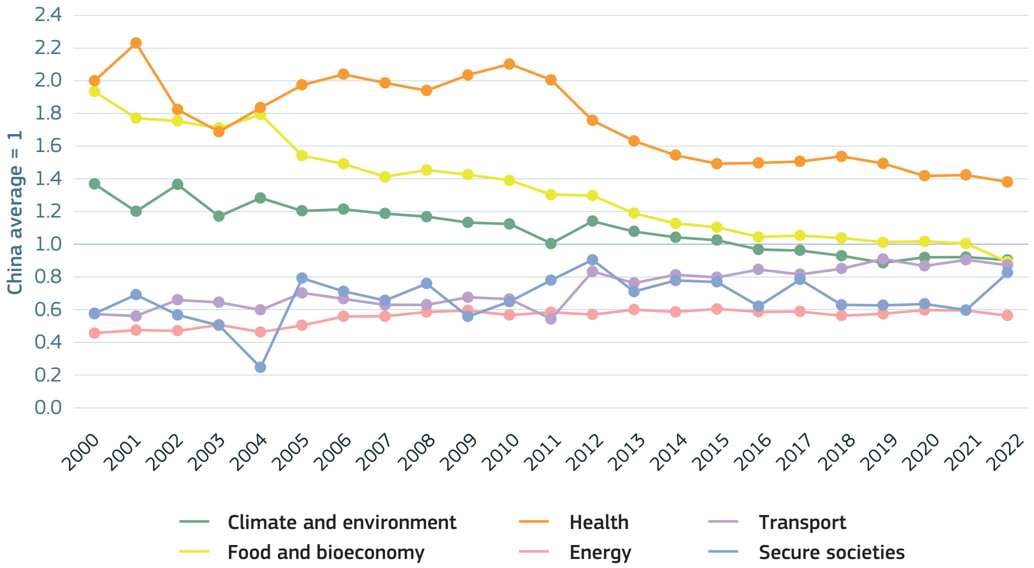
Figure 3.1-31 EU Specialisation Index compared to the US, 2000-2022



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%).

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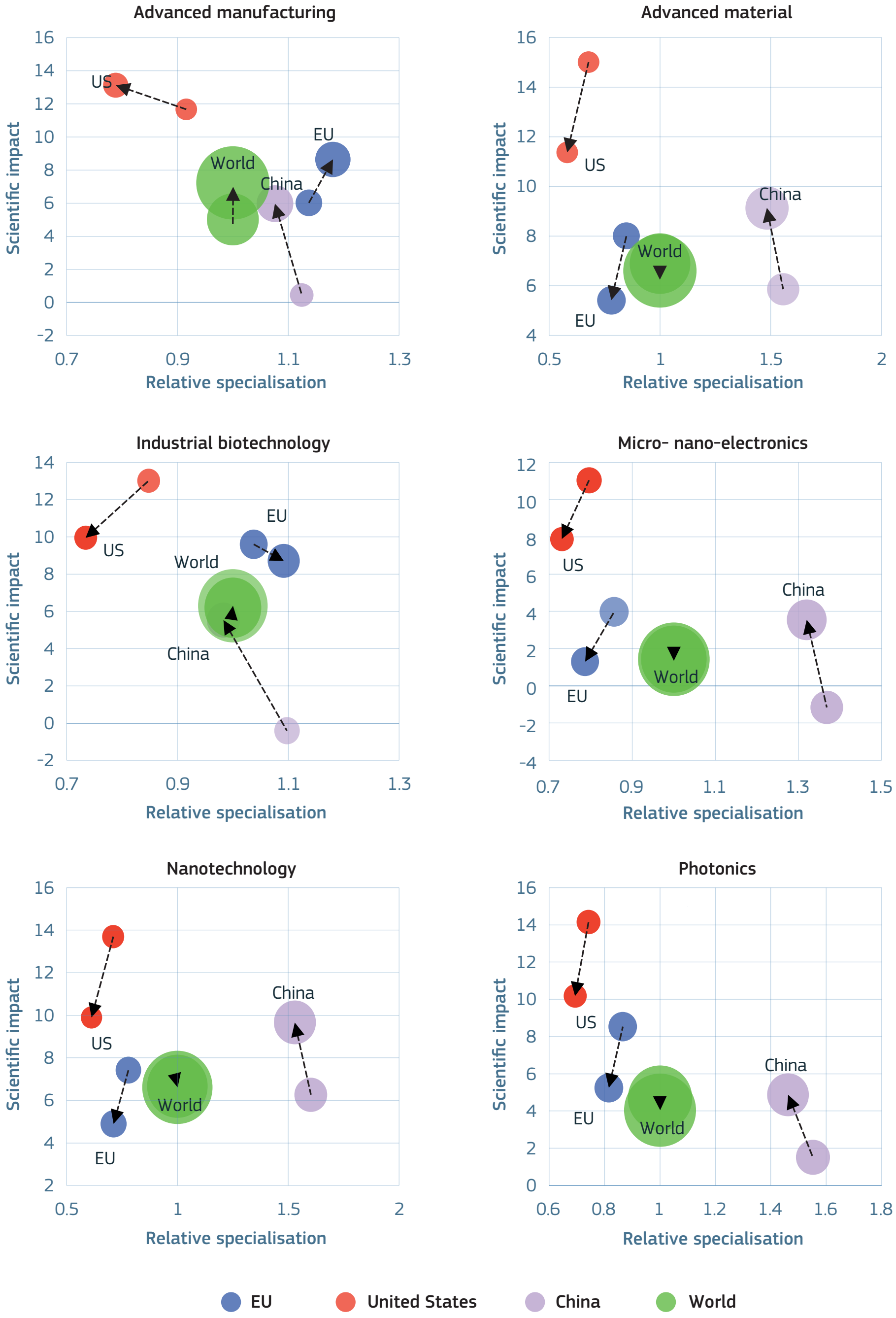
[22] The definition of KETs used here is a group of six technologies, identified in the KET Communication COM (2012) 3413: micro and nanoelectronics, nanotechnology, industrial biotechnology, advanced materials, photonics, and advanced manufacturing technologies.

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.

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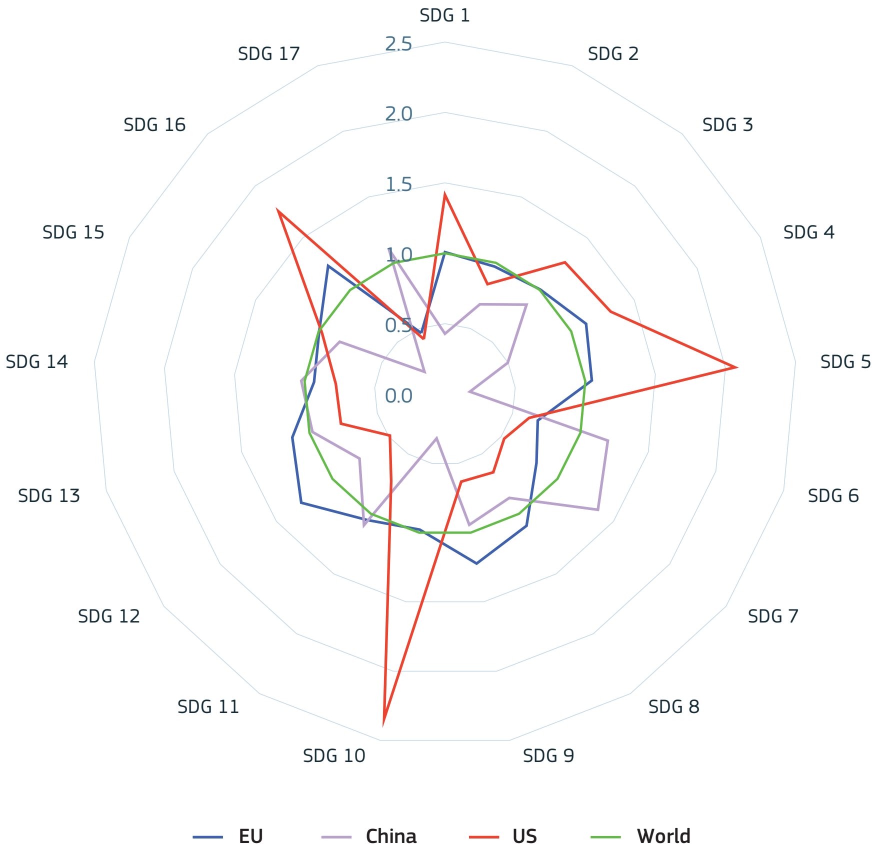
[23] Each with six indicators and incorporating multi-purpose indicators for efficient monitoring.

[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.

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[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

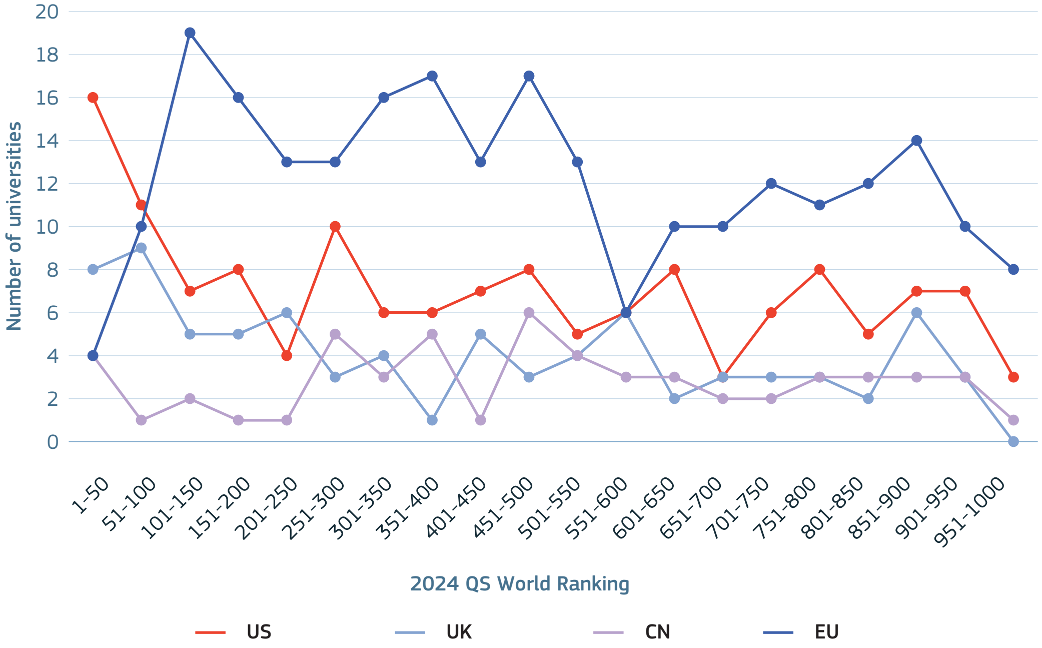
55	Ludwig-Maximilians-Universität München	DE	48	Delft University of Technology	NL	52	Utrecht University	NL
59	Sorbonne University	FR	50	Karolinska Institutet	SE	55	Universität Heidelberg	DE
61	KU Leuven	BE	58	Paris-Saclay University	FR	59	Technical University of Munich	DE
71	Paris-Saclay University	FR	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 Universitätsmedizin 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.

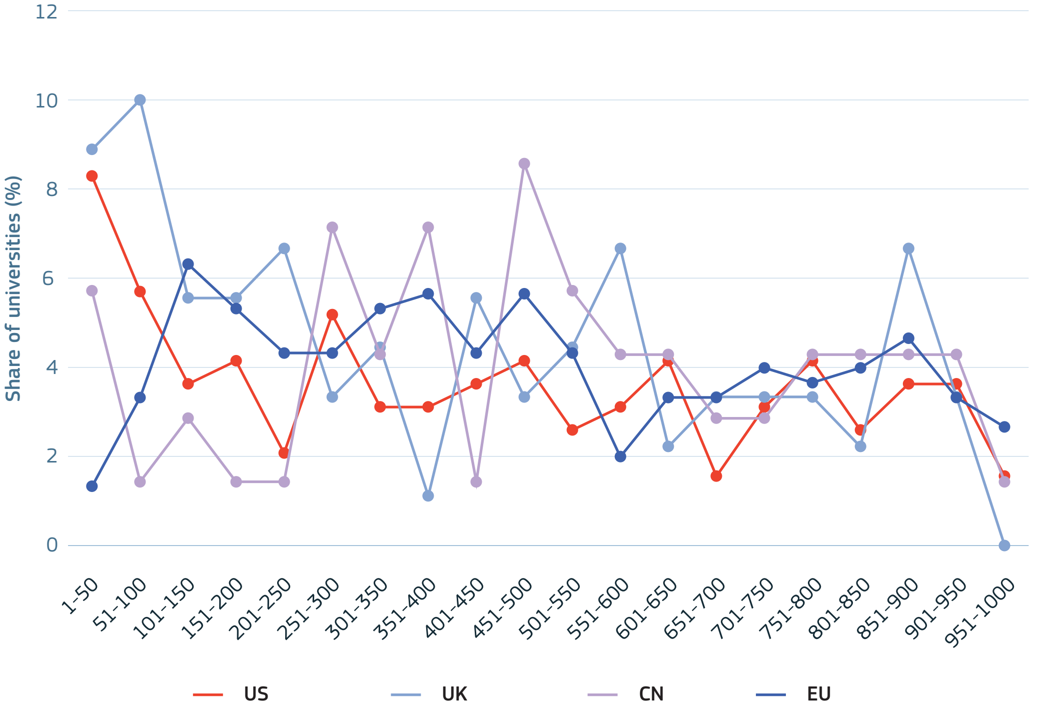
Figure 3.2-1 Distribution of university quality (in absolute terms) around the world



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.

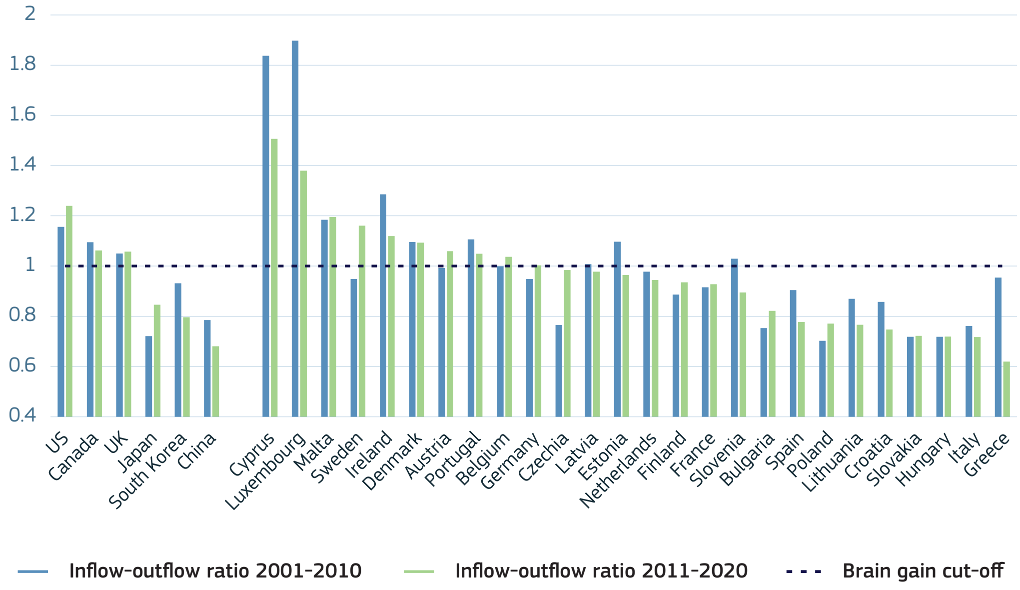
One significant recent development affecting European academic mobility is the UK's decision to leave the EU. The UK has been a pivotal player in the European Research Area (ERA), and its departure poses a challenge to ERA's attractiveness to international researchers. While brain drain is sometimes 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.

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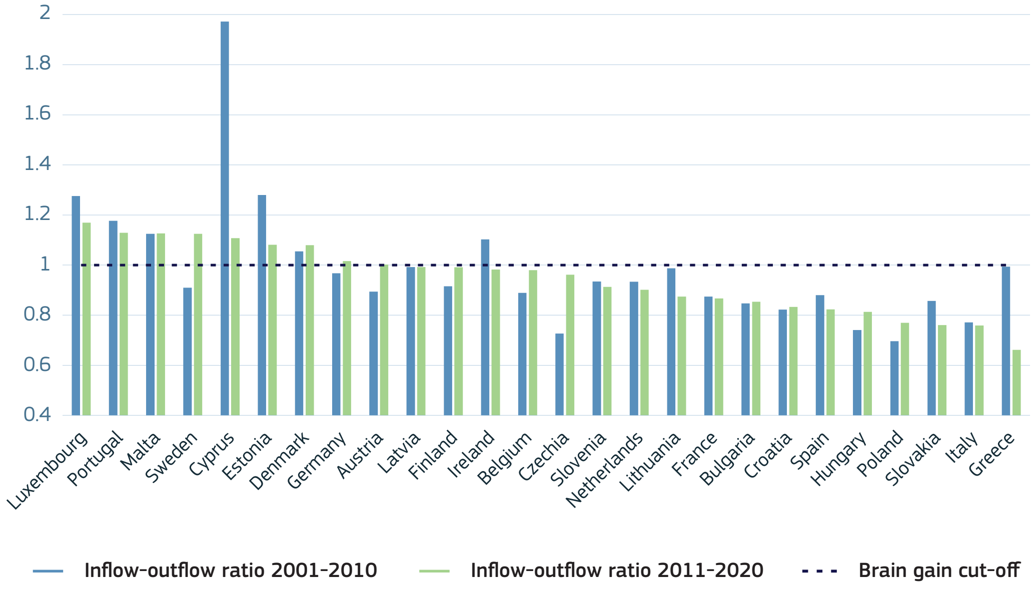
[4] Relative brain drain is measured as (researcher inflow)/(researcher outflow).

[5] Absolute brain drain is measured as researcher inflow- researcher outflow.

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

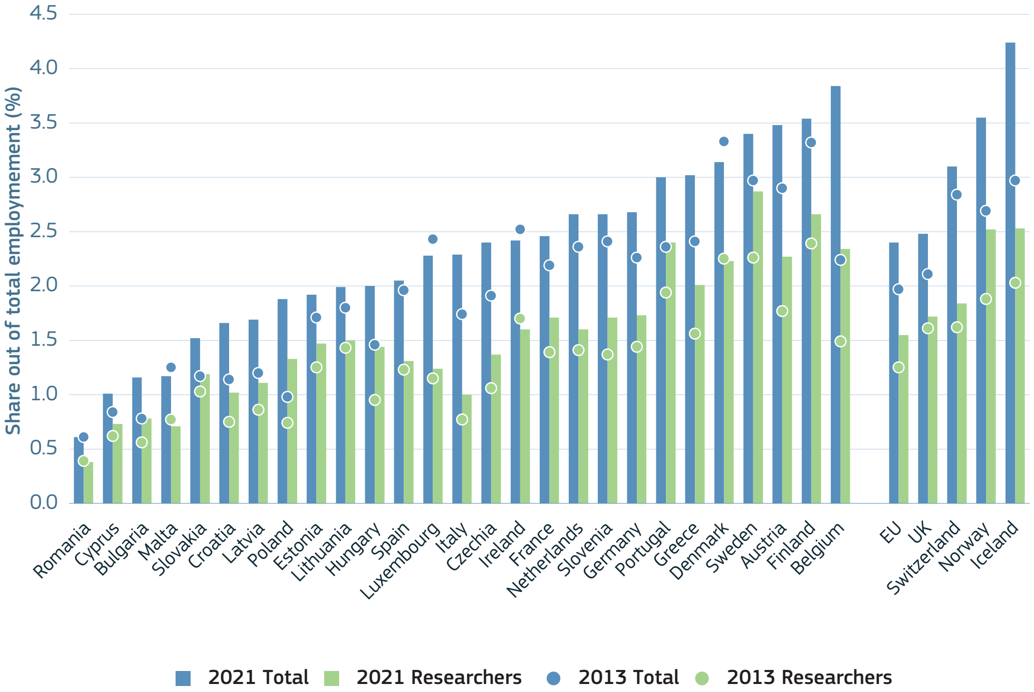


Science, research and innovation performance of the EU 2024

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



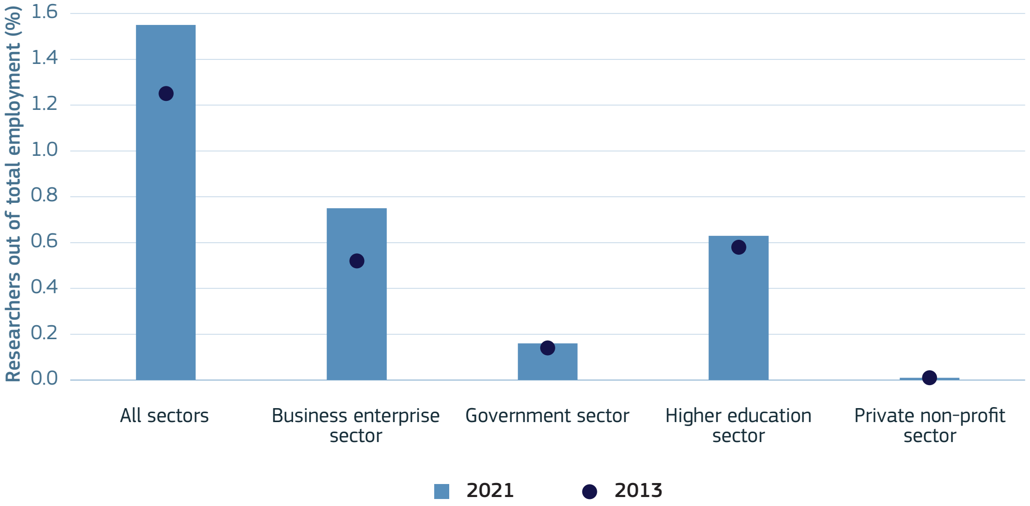
Science, research and innovation performance of the EU 2024

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)

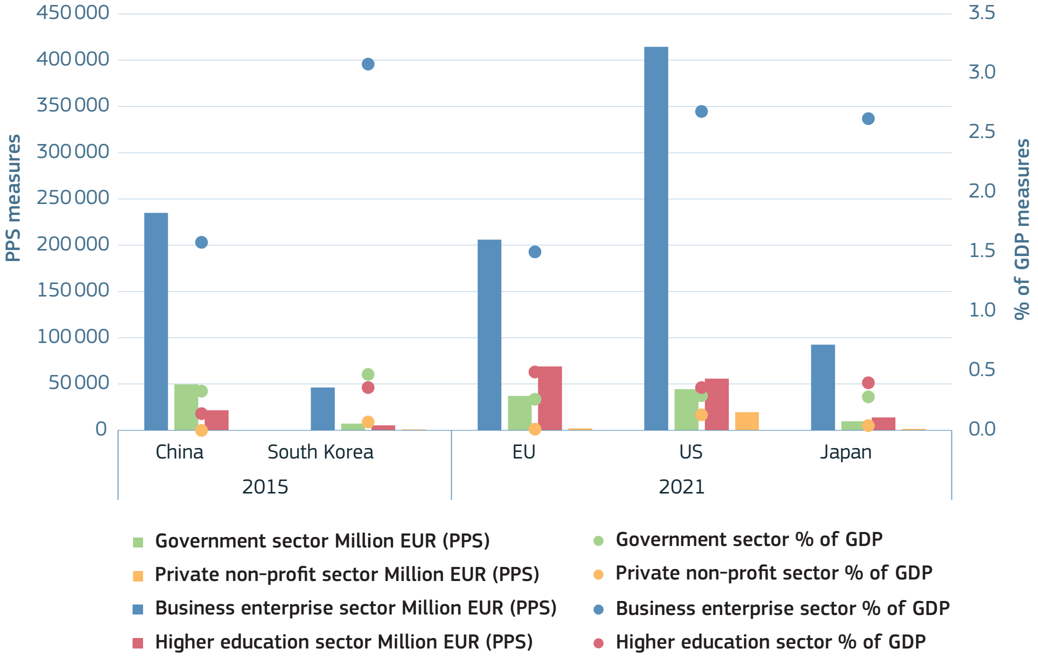


Science, research and innovation performance of the EU 2024

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).

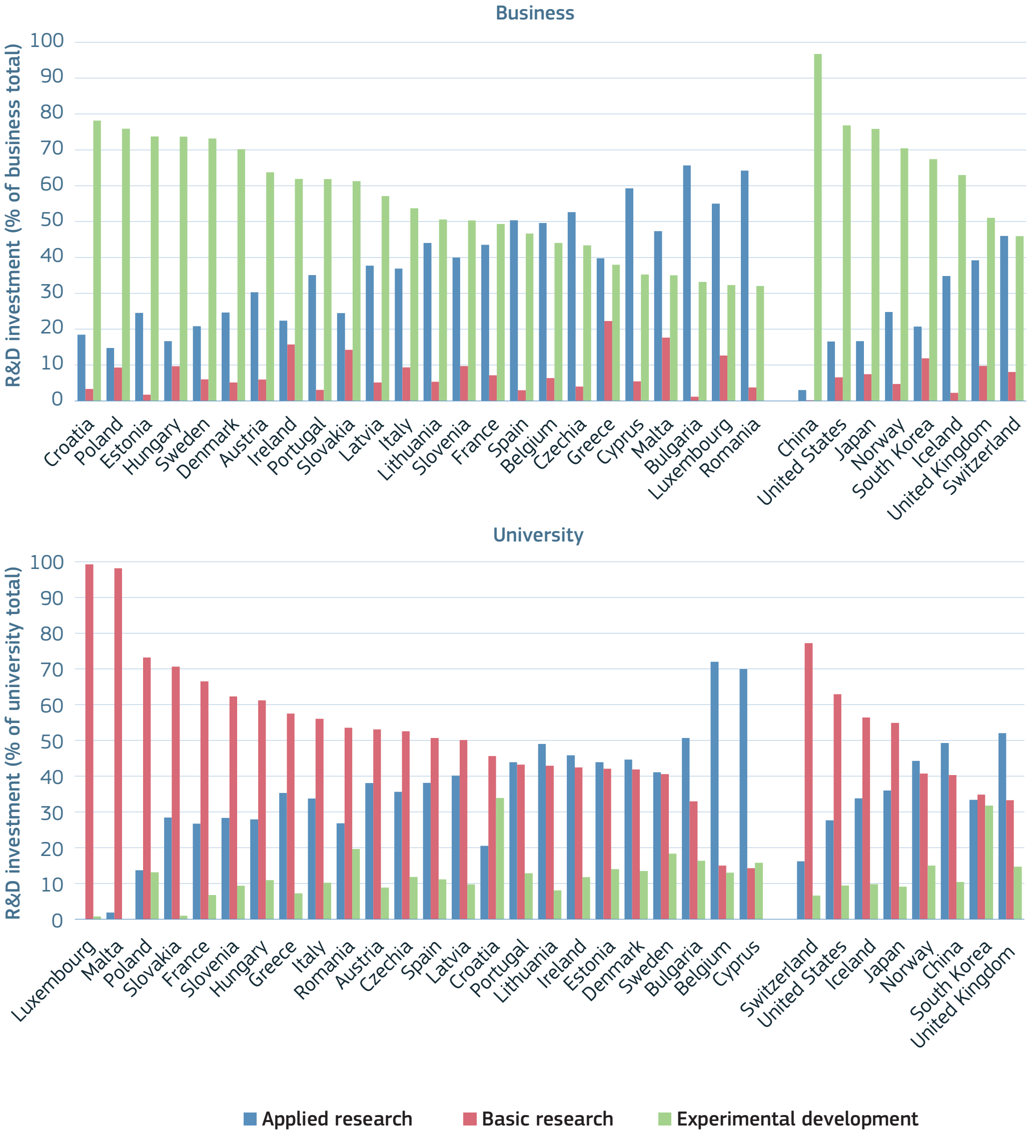
Figure 3.2-7 R&D investment by sector around the world



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

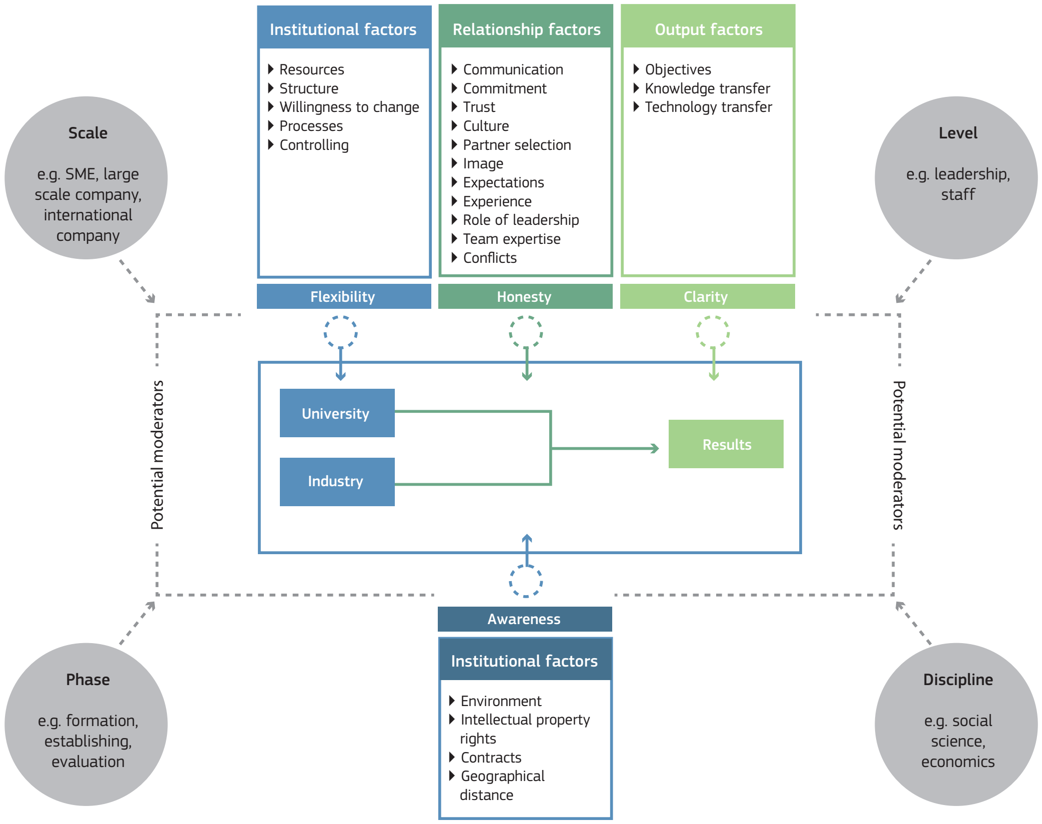


Science, research and innovation performance of the EU 2024
Source: DG Research and Innovation, Common R&I Strategy and Foresight Service, Chief Economist Unit, based on Eurostat data (online data code: rd_e_gerdact).

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).

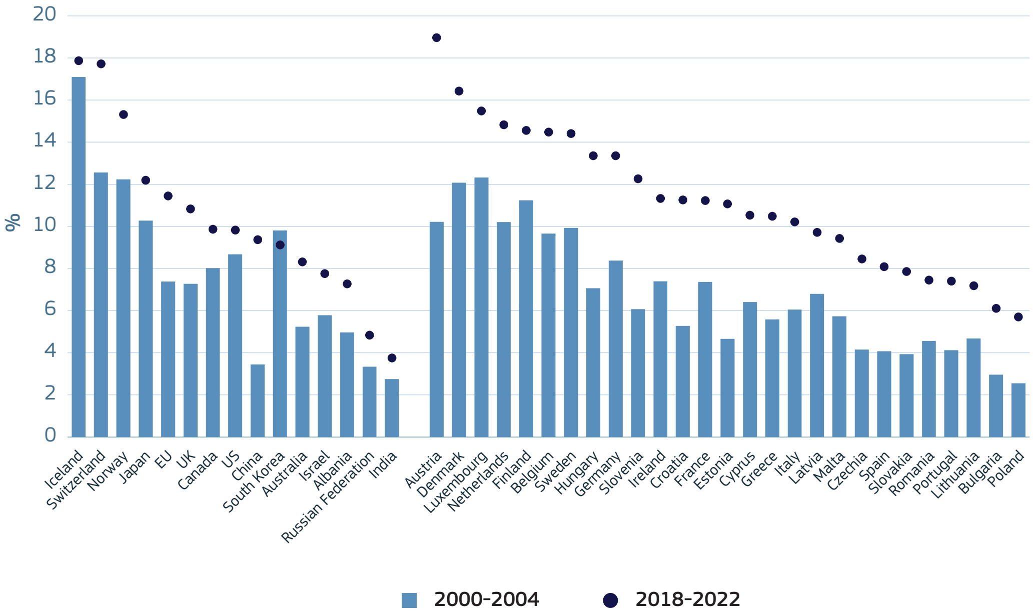
Figure 3.2-9 What makes industry-academia collaboration succeed?



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]

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[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).

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

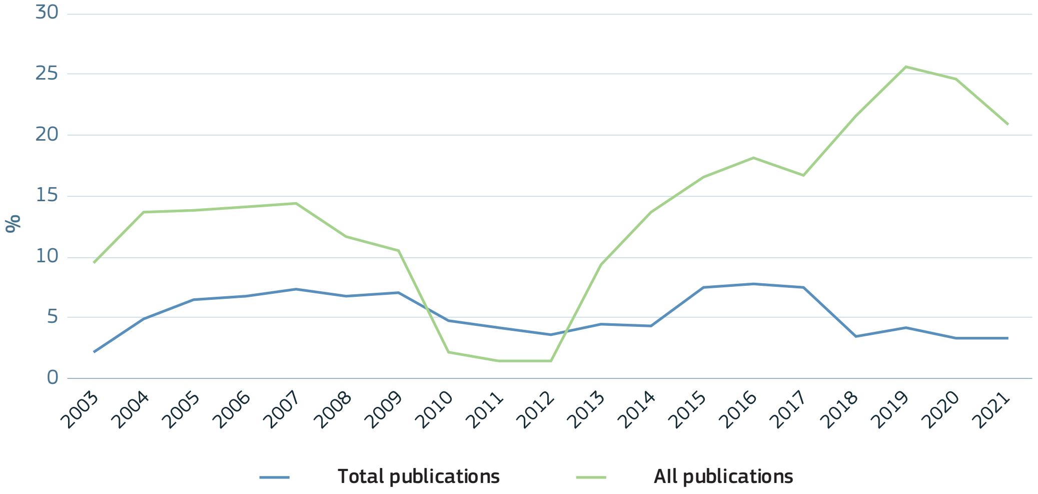
2. An increasing diffusion of AI in science and its potential to accelerate scientific and technological progress

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.

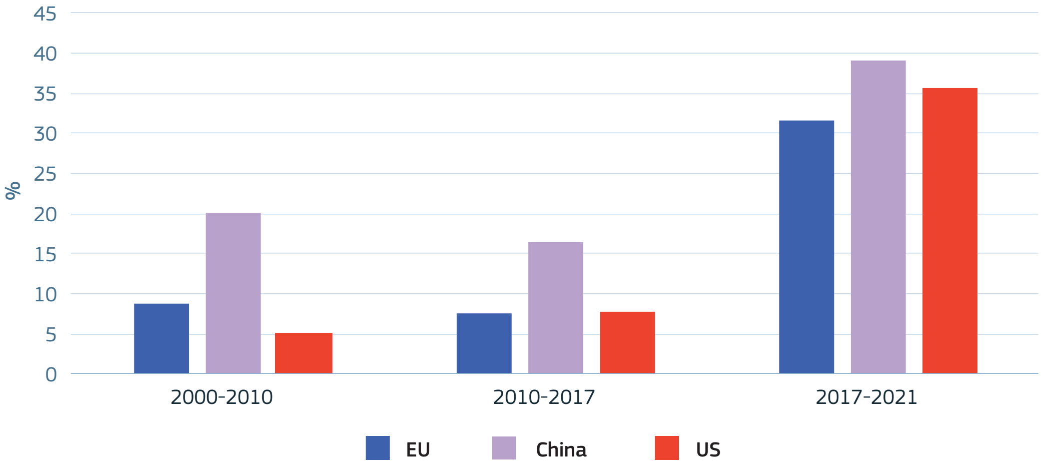
Figure 3.3-1 Growth in scientific activity (3-year rolling average)



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

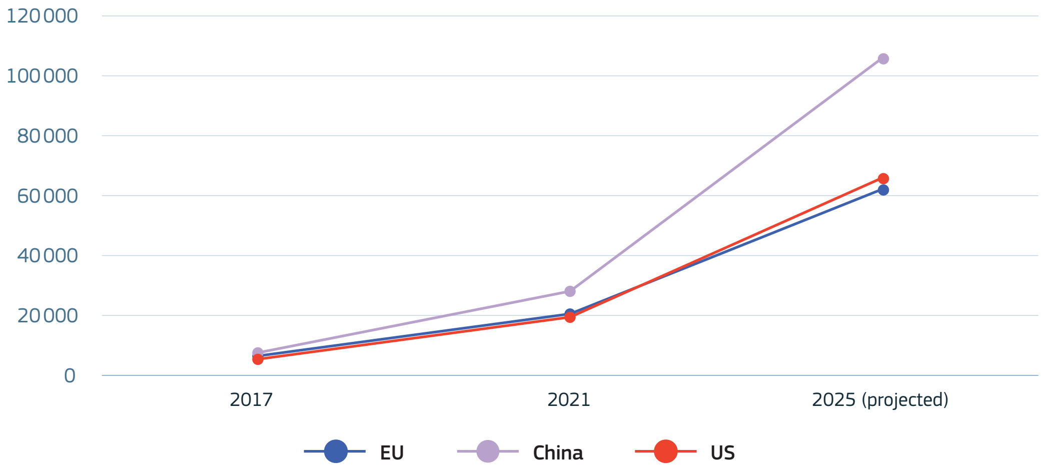


Source: Arranz et al. (2023).

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



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]

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[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).

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[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

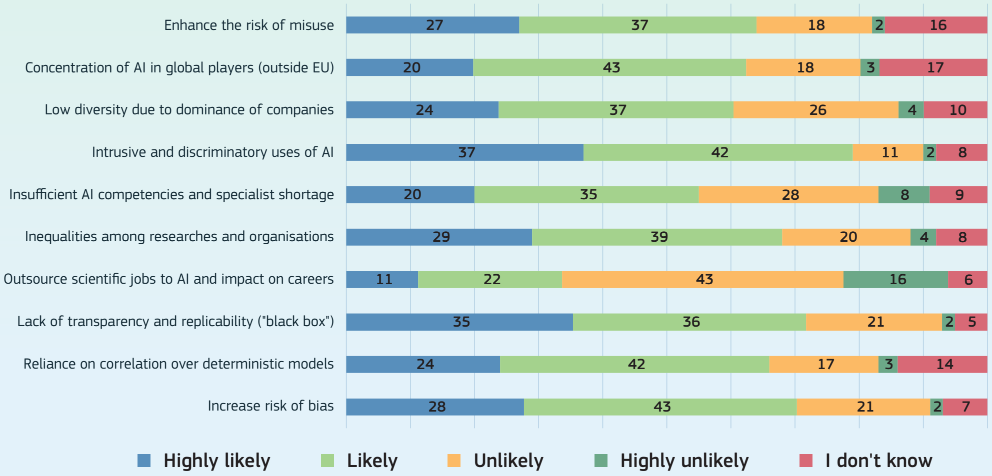
The European Research Council (ERC) is the premier European funding organisation for excellent frontier research. Since its establishment in 2007, the ERC has played a pivotal role within the EU's funding programmes for research and innovation. The ERC funds a rich and diverse portfolio of projects spanning 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)



Science, research and innovation performance of the EU 2024

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.

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[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.

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[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/