CHAPTER 6.1

SCIENTIFIC PERFORMANCE

KEY FIGURES

21 %
EU's share of global scientific publications

21 %
EU's share of the top 1% highly cited scientific publications

60 000
EU publications contributing to or using machine-based learning activities

27 %
EU's share of highly cited scientific publications on food and bioeconomy

What can we learn?

- The **EU and China are the global leaders in terms of scientific output**, while the United States retains its lead in terms of scientific quality. **Output from Chinese researchers has risen exponentially** in the last two decades to almost match the EU.
- Within the EU, there is a **diversity of research intensities** and a **positive correlation between scientific quality and investments** in most countries.
- **Digitalisation is transforming science**. All areas of research are becoming data-intensive, increasingly relying upon and generating big data.
- **Science is key in addressing societal challenges**. The EU is leading in high-quality scientific publications in the food/bioeconomy and climate/environment sectors, while China is increasing exponentially across sectors, and the United States is losing its overall leadership.

What does it mean for policy?

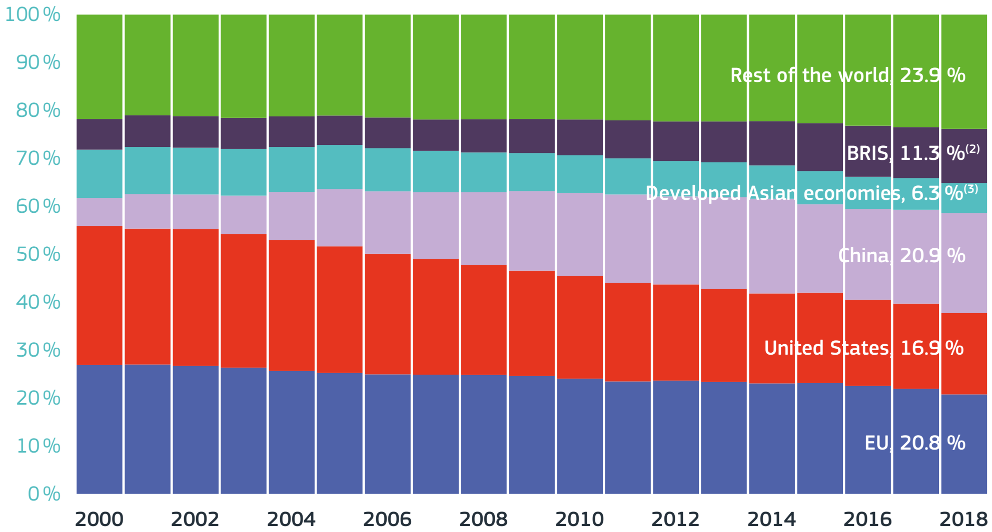
- To remain a leading global scientific player, the EU and its Member States must **strengthen their efforts to increase the effectiveness and performance of their public research systems** through stronger R&I investments and policy reforms.
- To **exploit the full potential of science digitalisation**, policies must be adapted to reinforce researchers' digital skills, promote open science as well as to ensure the necessary investment in high-quality data infrastructures.
- As science is key in addressing societal challenges, the EU must not only ensure scientific leadership in key areas but must also **foster interdisciplinarity research** that is necessary to successfully deliver on the SDGs.

1. The EU and China are global leaders in terms of scientific output, while the United States retains the lead in scientific quality

Jointly with China, the EU remains in the leading position in terms of the share of scientific output worldwide, while the US' share has continued to shrink. With 7% of the world population, the EU is responsible for 20% of global R&D expenditure and 21% of scientific publications worldwide. However, with the United Kingdom leaving the EU, the EU's share declined from 30 % in 2000 to 21 % in 2018 (see Figure 6.1-1)[1].

China has established itself as a major scientific player and a competitor in high-tech sectors. The country's world share of scientific publications rose exponentially from 5.8 % in 2000 to 20.9% in 2018 (see Figure 6.1.2), showing China's leadership in the global ranking, jointly with the EU (without the UK). Moreover, China's share of world R&D expenditure has increased from 5% in 2000 to more than 20% today, which means that its R&D intensity has already overtaken that of the EU (European Commission, 2019a: 59).

Figure 6.1-1 World share of scientific publications(1), 2000 and 2018



Science, research and innovation performance of the EU 2020

Source: DG Research and Innovation, Chief Economist - R&I Strategy & Foresight Unit

Notes: (1)Data produced by Science-Metrix based on Scopus database. Fractional counting method used. (2)BRIS includes Brazil, Russian Federation, India and South Africa. (3)Developed Asia economies includes Japan and South Korea. (4)Figures correspond to the latest year, 2018.

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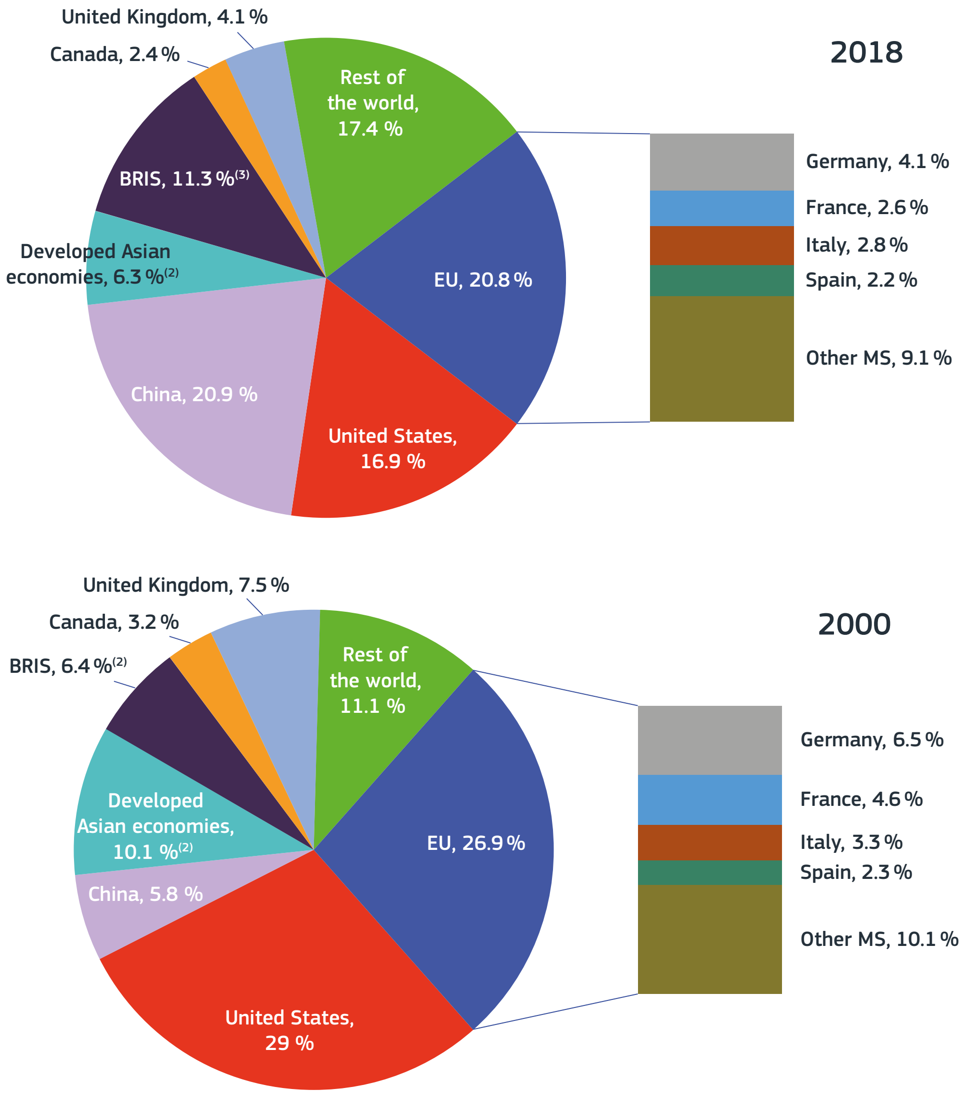
1 One way to analyse the scientific performance of countries and regions is to look at the number of scientific publications published by the researchers based there. However, the rise of international collaboration over the last 20 years needs to be taken into account as a high proportion of scientific publications now have authors in more than one country.

Figure 6.1-2 World share of scientific publications[1] %, 2000 and 2018



Source: DG Research and Innovation, Chief Economist - R&I Strategy & Foresight Unit

Notes: (1)Data produced by Science-Metrix based on Scopus database. Fractional counting method used. (2)Developed Asia economies includes Japan and South Korea. (3)BRIS includes Brazil, Russian Federation, India and South Africa.

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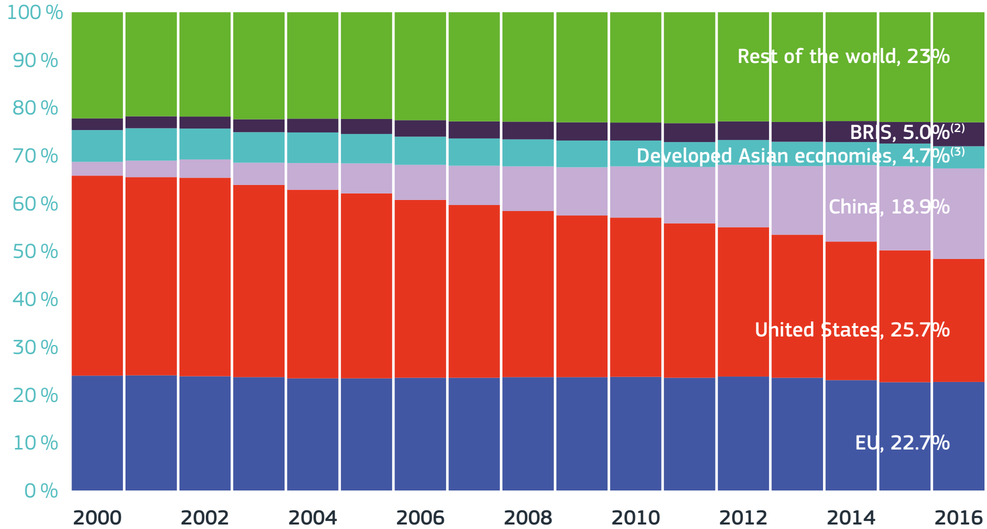
Simultaneously, the US' world share of scientific publications fell from 29 % in 2000 to 16.9% in 2018. This decline positions the US behind the EU, whose share fell from 26.9% in 2000 to 20.8 % in 2018 (both figures calculated without the UK). During the same period, BRIS countries[2] were able to increase their share from 6.4% to 11.3%.

2 Brazil, Russia, India and South Africa.

Within the EU, all of the countries with the highest number of scientific publications have seen their world share shrink. From 2000 to 2018, Germany dropped from 6.5 % to 4.1 %, France from 4.6 % to 2.6 %, Italy from 3.3 % to 2.8 %, and Spain from 2.3 % to 2.2 %. The UK's share dropped from 7.5 % to 4.1 %.

The United States maintains its global leadership in terms of highly cited scientific publications, although it has seen a dramatic decline in its share. Europe remains in second place, while China continues its sharp rise. At 22.7 %, the EU has also maintained its high global share in terms of the top 10 % highly cited publications[3] (Figure 6.1-3). However, the respective output from the Chinese science system has grown exponentially – from 2.9 % in 2000 to 18.9 % in 2016 – and is coming closer to the output from the EU and US systems. In the latter, the share of the top 10 % highly cited publications fell dramatically from 41.8 % in 2000 to 25.7 % in 2016, significantly closing the gap between the United States and the EU. Moreover, the average quality of China's publications is improving (European Commission, 2019a: 60).

Figure 6.1-3 World share of top 10 % highly cited scientific publications[(1)], 2000 (citation window: 2000-2002) and 2016 (citation window: 2016-2018)



Science, research and innovation performance of the EU 2020

Source: DG Research and Innovation, Chief Economist - R&I Strategy & Foresight Unit

Note: [(1)]Data produced by Science-Metrix based on Scopus database. Scientific publications within the 10 % most-cited scientific publications worldwide as % of total scientific publications of the country; fractional counting method. [(2)]BRIS includes Brazil, Russian Federation, India and South Africa. [(3)]Developed Asia economies includes Japan and South Korea. [(4)]Figures correspond to the latest year, 2018.

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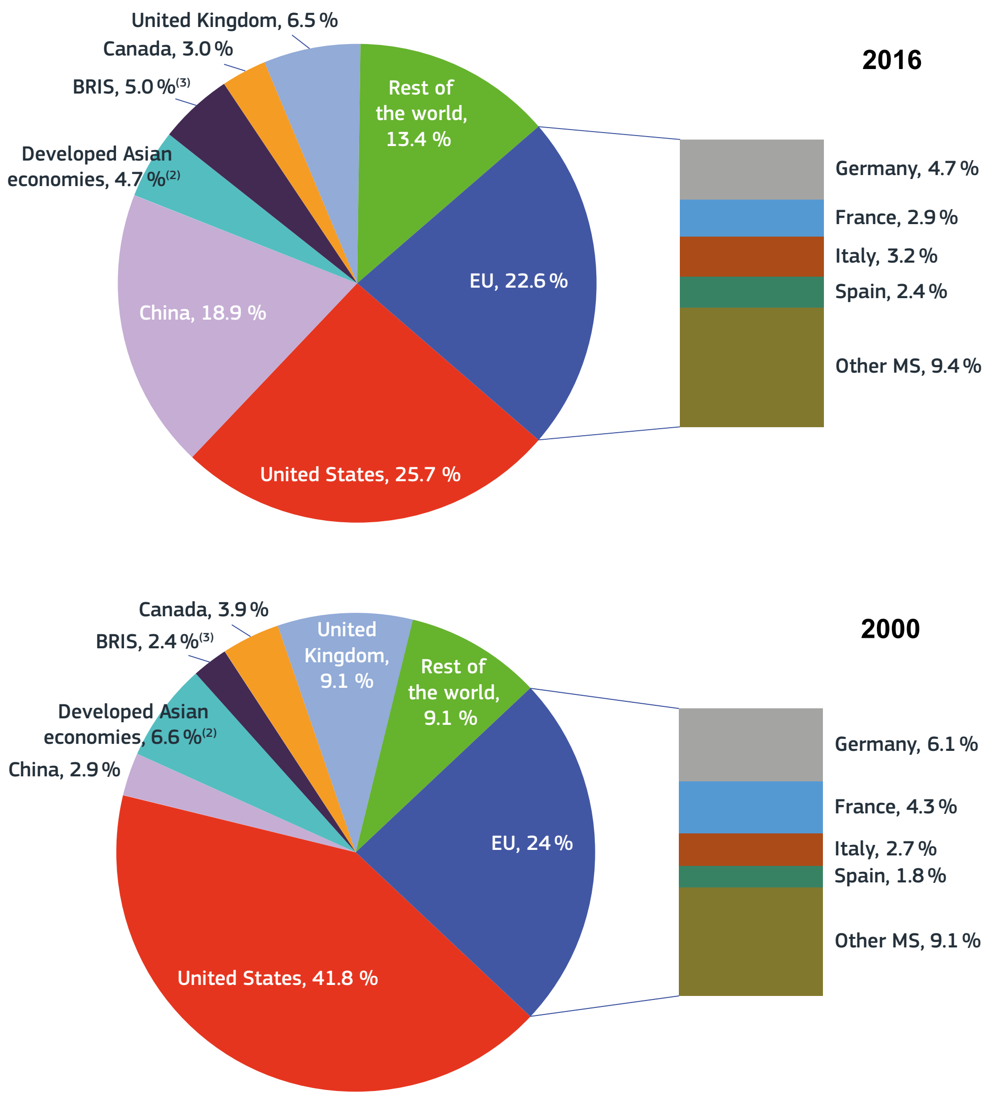
3 In terms of quality, the number of times a publication is cited by other publications is seen as a useful proxy for the impact of that publication. The number of citations publications receive leans very heavily towards the most important or interesting findings. The top 1 % of highly cited papers receive around 25 % of all citations while a significant proportion of papers are not cited at all. International co-publications also tend to be more highly cited.

While the world share of 10% highly cited scientific publications dropped in most EU countries between 2000 and 2016, Spain saw an increase from 1.8% to 2.4% (Figure 6.1-4).

Figure 6.1-4 World share of top 10% highly cited scientific publications[1], 2000 (citation window: 2000-2002) and 2016 (citation window: 2016-2018)



Source: DG Research and Innovation, Chief Economist - R&I Strategy & Foresight Unit

Notes: [1]Data produced by Science-Metrix based on Scopus database. Scientific publications within the 10 % most-cited scientific publications worldwide as % of total scientific publications of the country; fractional counting method. [2]Developed Asia economies includes Japan and South Korea. [3]BRIS includes Brazil, Russian Federation, India and South Africa.

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With 21.2 % in 2000 and 20.9 % in 2016, the EU is maintaining its world share of the top 1 % highly cited scientific publications at an almost constant rate. Once again, as with the other indicators, China's increase in this category is exponential, rising from 1.9 % in 2000 to 17.5 % in 2016. On the other hand, while still the leading country, the US's share is in decline, falling from 48.8 % in 2000 to 31.3 % in 2016. During this period, there was no significant change in the share of BRIS countries and developed Asian economies.

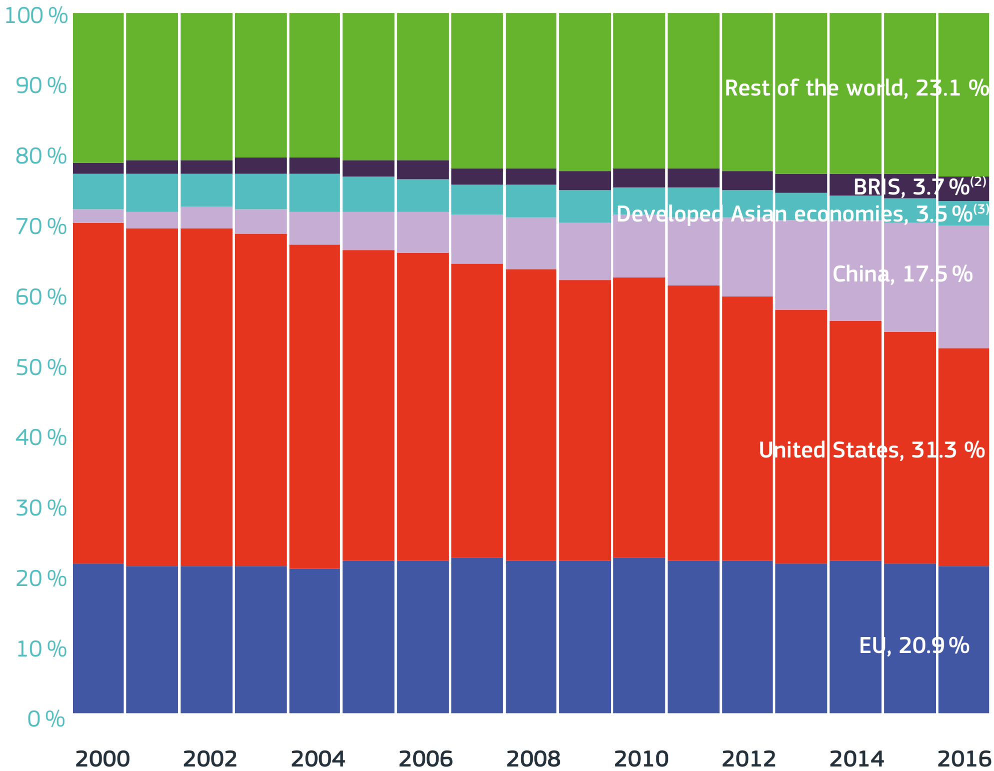
BOX 6.1-1 The European Research Council – facts and figures

The European Research Council (ERC) – the first pan-European funding body for frontier research – was set up in 2007 under the EU's Seventh Framework Programme for Research (FP7, 2007-2013). The total budget allocated to the ERC for the period 2014-2020 is EUR 13.1 billion.

- The ERC represents **17 % of the overall Horizon 2020 budget** (EUR 13.1 billion of EUR 77 billion).
- Since 2007, some **9 000 projects** have been selected for funding from more than **65 000 applications**.
- ERC grantees have won prestigious prizes, including **six Nobel Prizes**, four Fields Medals, and five Wolf Prizes.
- At the end of 2015, there were over **40 000 articles** acknowledging ERC support in international, peer-reviewed journals.
- Each ERC grantee employs on average **six team members**, thereby contributing to train **a new generation of excellent researchers**. Currently, over 50 000 postdocs, PhD students and other staff are working in their research teams.
- More than 70 % of projects assessed by an independent study made **scientific breakthroughs or major advances**, whilst around 25 % of them made incremental contributions.

Source: https://erc.europa.eu/projects-figures/facts-and-figures, accessed: 30 October 2019

Figure 6.1-5 World share of top 1% highly cited scientific publications[1], 2000 (citation window: 2000-2002) and 2016 (citation window: 2016-2018)



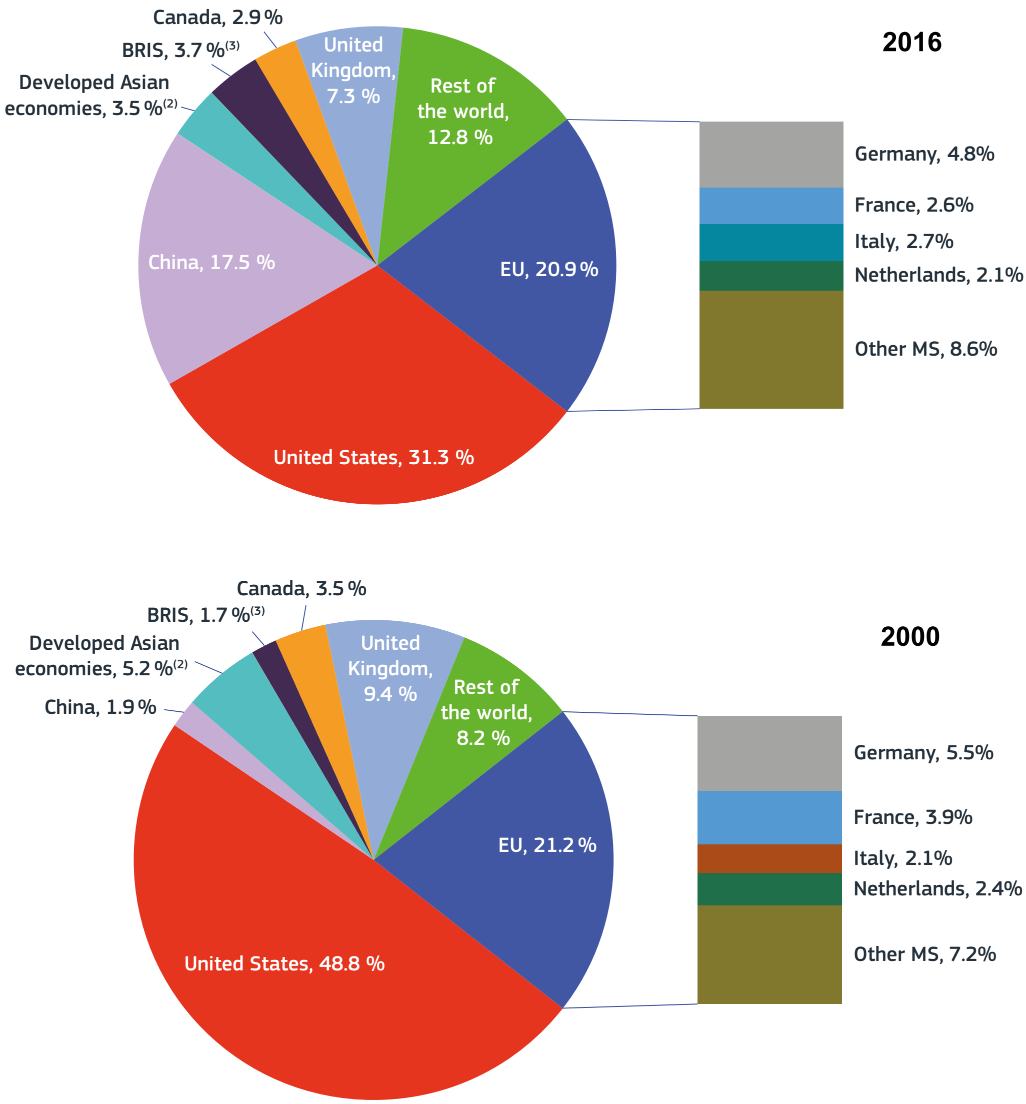
Source: DG Research and Innovation, Chief Economist - R&I Strategy & Foresight Unit

Note: [1]Data produced by Science-Metrix based on Scopus database. Scientific publications within the 1 % most-cited scientific publications worldwide as % of total scientific publications of the country; fractional counting method. [2]BRIS includes Brazil, Russian Federation, India and South Africa. [3]Developed Asia economies includes Japan and South Korea. [4]Figures correspond to the latest year, 2018.

Stat. link: https://ec.europa.eu/info/sites/info/files/srip/2020/parti/chapter61/figure-61-5.xlsx

Whilst the world share of the 1 % of highly cited scientific publications dropped in most EU countries between 2000 and 2016, Spain saw an increase from 1.4 % to 2.0 %, as did Italy from 2.1 % to 2.7 %.

Figure 6.1-6 World share of top 1% highly cited scientific publications[1], 2000 (citation window: 2000-2002) and 2016 (citation window: 2016-2018)



Source: DG Research and Innovation, Chief Economist - R&I Strategy & Foresight Unit

Notes: [1]Data produced by Science-Metrix based on Scopus database. Scientific publications within the 1 % most-cited scientific publications worldwide as % of total scientific publications of the country; fractional counting method. [2]Developed Asia economies includes Japan and South Korea. [3]BRIS includes Brazil, Russian Federation, India and South Africa.

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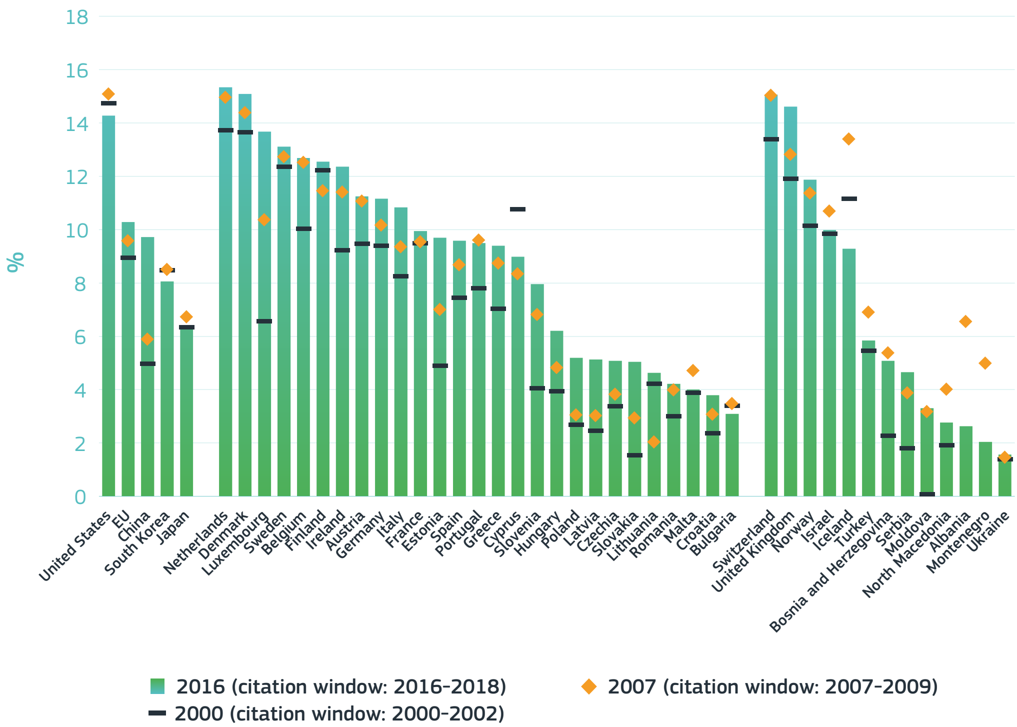
In terms of the share of the top 10% and top 1% most-cited publications as a percentage of the total scientific publications, Europe has stabilised its position behind the United States, while China is quickly catching up. Although Europe has made some progress in raising the quality of its science, differences across Member States persist. Despite a slight fall in the share of total publications among the 10% most-cited worldwide since 2000 (Figure 6.1-7), the United States still outperforms the EU. In other words, the EU has more publications than the United States but with a lower impact in terms of citations. China is quickly bridging the gap with the EU as its top 10% most-cited publications have almost doubled since 2000.

Strong differences persist between European countries' performances. Switzerland confirms its leading global position, followed by numerous western European and Scandinavian countries, which have continued to raise their scientific performance since 2000 (e.g. Belgium, Ireland, Germany, Austria and Luxembourg). While several Mediterranean and eastern European countries like Estonia, Greece, Hungary, Italy, Slovenia and Spain have managed to raise their scientific output compared to 2000, a decline has been noted for Iceland, Israel, Malta and Turkey since 2007.

Figure 6.1-7 Top 10% highly cited scientific publications[1], 2000, 2007 and 2016



Source: DG Research and Innovation, Chief Economist - R&I Strategy & Foresight Unit

Notes: [1]Data produced by Science-Metrix based on Scopus database. Scientific publications within the 10 % most-cited scientific publications worldwide as % of total scientific publications of the country; fractional counting method. [2]AL: 2008. ME: 2005.

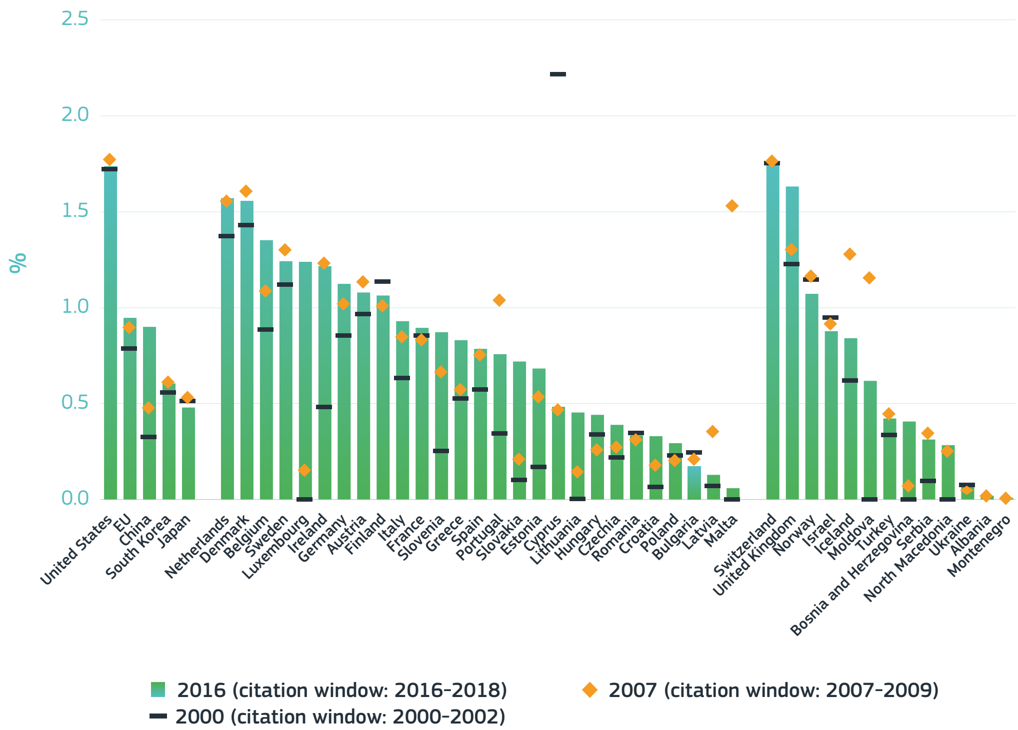
Stat. link: https://ec.europa.eu/info/sites/info/files/srip/2020/parti/chapter61/figure-61-7.xlsx

The share of the top 1% of highly cited scientific publications as a percentage of the total scientific publications (Figure 6.1-8) **is often used as a proxy for scientific excellence**. On this measure, the EU has remained at the same level since 2007. This trend is similar for the United States, South Korea and Japan, while China's performance continues to increase steadily.

Within Europe, although differences between the Member States persist, the majority of EU13 countries have managed to increase the proportion of their publications in the top 1% highly cited. Switzerland is the world's top performer in science as regards the top 1% articles, ahead of the United States and followed by the UK, the Netherlands, Denmark, Belgium, Sweden, Luxembourg, Ireland, Germany, Austria and Finland, all of which score above the EU average.

The citation impact of scientific publications demonstrates the importance of international science collaboration to reach high scientific quality. This is confirmed by the fact that the citation impact of international co-publications for all countries is greater than that of single-country publications for all countries (Figure 6.1-9). China's scientific quality benefits most as a result of international scientific collaboration.

Figure 6.1-8 Top 1% highly cited scientific publications[1], 2000, 2007 and 2016



Source: DG Research and Innovation, Chief Economist - R&I Strategy & Foresight Unit

Notes: [1]Data produced by Science-Metrix based on Scopus database. Scientific publications within the 1 % most-cited scientific publications worldwide as % of total scientific publications of the country; fractional counting method. [2]AL: 2008. ME: 2005.

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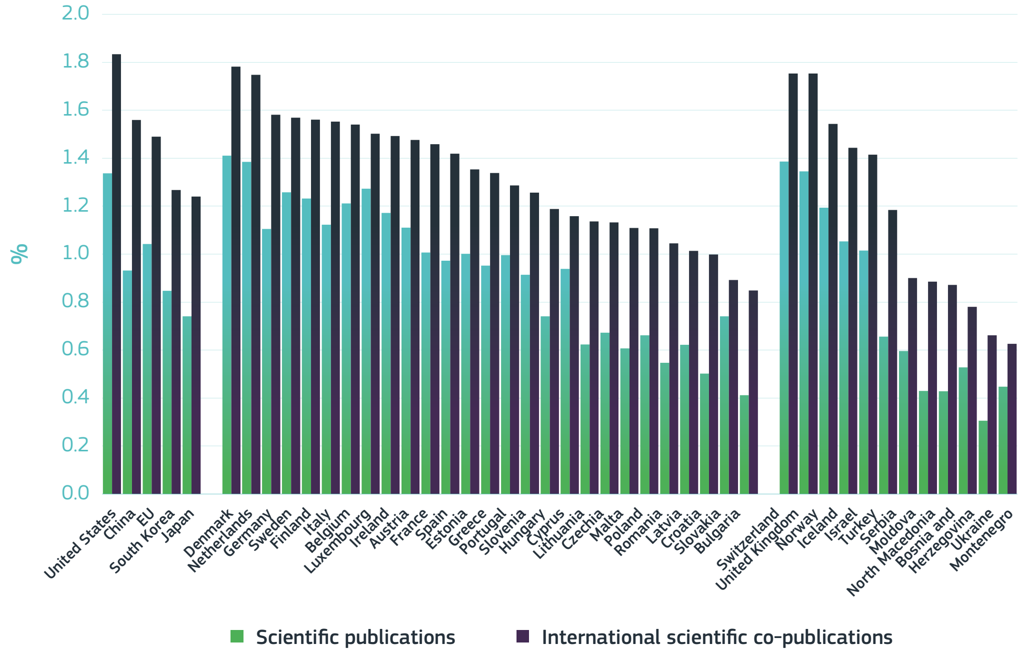
Figure 6.1-9 Citation impact[(1)] of scientific publications, 2016 (citation window: 2016-2018)



Science, research and innovation performance of the EU 2020

Source: DG Research and Innovation, Chief Economist - R&I Strategy & Foresight Unit

Note: [(1)]Data produced by Science-Metrix based on Scopus database. Citation impact normalised by field and publication year (ratio of the average number of citations received by the papers considered and the average number of citations received by all papers in the main field, or 'expected' number of citations), citation window publication year plus two years.

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Within the EU, this positive correlation is stronger for most of the countries exhibiting lower scientific performance.

The international rankings (the Shanghai and Leiden Rankings[4]) position the EU as a leader in 'world-class' universities among the top 500 institutions, while the United States still heads the top 100.

Although all innovation leader countries[5] outperform the United States, some have seen their position deteriorate over the last decade. According to the Academic Ranking of World Universities (ARWU)[6], the EU has more universities (179) among the top 500 institutions than the United States (139), while the United States still leads in the top 100 (46, compared to 27 in the EU). The same holds true for the

4 Global international higher education rankings are perceived as a measure of quality, although the approaches vary according to the different rankings.

5 As defined by the European Innovation Scoreboard 2019, these are Sweden, Finland, Denmark and the Netherlands (see https://ec.europa.eu/growth/industry/innovation/facts-figures/scoreboards_en, accessed: 30 October 2019).

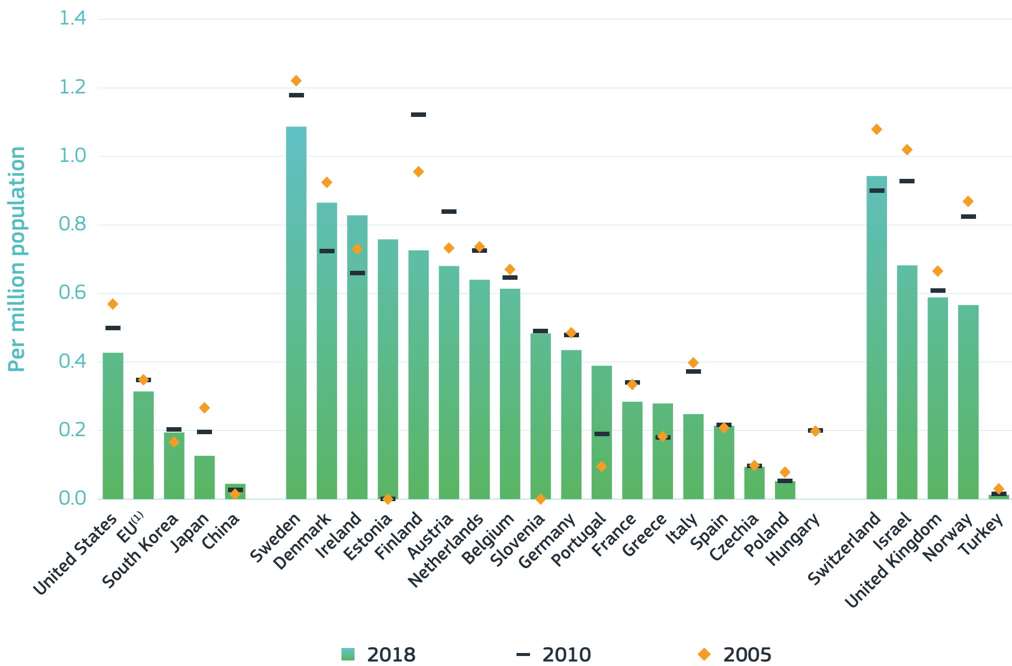
6 Also called Shanghai Ranking, which is based on six indicators mainly related to an institution's scientific output (number of Nobel Prizes and Fields Medals, highly cited researchers, papers published).

Leiden Ranking[7], which shows a total of 211 EU universities and 146 US universities in the top 500 list of institutions, and 33 EU universities and 52 US universities in the top 100 list[8].

Overall, the United States still slightly outperforms the EU in terms of the number of top 500 universities per million population. However, all EU countries classed as 'innovation leaders' and 'strong innovators' outperform the United States on this indicator when using the Shanghai Ranking. The EU also outperforms South Korea, Japan and China[9] in terms of top institutions per million population (see Figure 6.1-10).

According to the Leiden Ranking, some of the best-performing countries in terms of the number of top 500 universities per million population (Sweden, Belgium, Finland and Switzerland) have seen their position drop since 2011. Yet, countries such as Ireland, Austria, Denmark and Norway have experienced a strong improvement in their performance compared to 2011 (Figure 6.1-11).

Figure 6.1-10 Number of top 500 universities in the Shanghai Ranking per million population, 2005, 2010 and 2018



Science, research and innovation performance of the EU 2020

Source: DG Research and Innovation, Chief Economist - R&I Strategy & Foresight Unit based on Shanghai ranking (http://www.shanghairanking.com/)

Note: (1)EU was estimated by DG Research and Innovation based on the data available for the Member States.

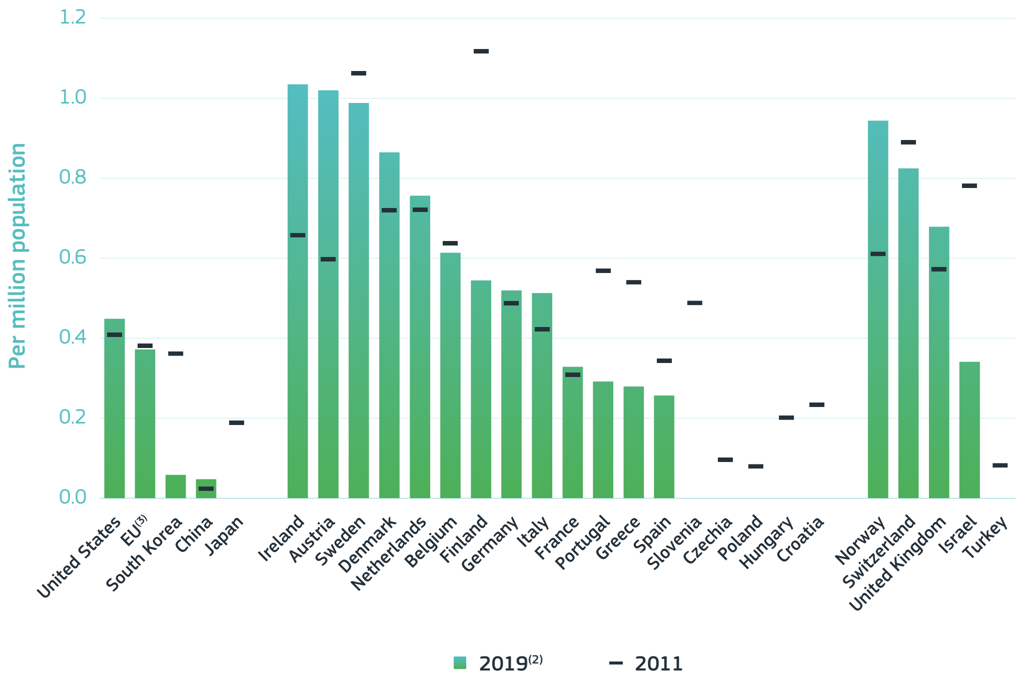
Stat. link: https://ec.europa.eu/info/sites/info/files/srip/2020/parti/chapter61/figure-61-10.xlsx

7 The Leiden Ranking 2019 is based on a set of bibliometric indicators that provide statistics at the level of universities on scientific impact, collaboration, open access publishing, and gender diversity (for further details see https://www.leidenranking.com/information/indicators, accessed: 30 October 2019.

8 Please note that university rankings do not take into account research efforts made by publicly funded research performing organisations.

9 In the ARWU, this includes Hong Kong, Macao and Taiwan.

Figure 6.1-11 Number of top 500 universities in the Leiden Ranking per million population[1], 2011 and 2019



Science, research and innovation performance of the EU 2020

Source: DG Research and Innovation, Chief Economist - R&I Strategy & Foresight Unit based on Leiden ranking (http://www.leidenranking.com/)

Notes: [1]All publications included. Fractional counting used. Universities ranked by proportion of top 10 % publications. [2]Population refers to 2018 for all countries except US, JP, CN, and KR in respect of which population refers to 2017. [3]EU was estimated by DG Research and Innovation based on the data available for the Member States.

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2. Within the EU, there is a diversity of research intensities and a positive correlation between scientific quality and investments

In Europe, a positive correlation between R&D intensity and scientific quality is evident in most countries. The Netherlands, Switzerland, Denmark, Sweden, Belgium, Finland, Austria, Norway and Germany enjoy higher levels of public investment in R&D than the EU average, as well as better scientific results (Figure 6.1-12). All Mediterranean (except Italy) and central and eastern European countries show below-EU-average R&D investment levels matched with below-EU-average levels of scientific excellence.

At the global level, the United States has a higher scientific impact than the EU despite lower public R&D intensity. Japan and South Korea show lower levels of scientific quality in relation to public investments. At the same time, China's scientific quality is approaching the EU level, despite a slightly lower R&D-intensity (Figure 6.1-12).

Figure 6.1-12 Public R&D intensity, 2016 and top 10 % highly cited scientific publications(1) 2016 (citation window: 2016-2018)

Science, research and innovation performance of the EU 2020

Source: Eurostat (online data code: rd_e_gerdtot), OECD and Science-Metrix using data from the Scopus database

Notes: (1)Scientific publications within the 10 % most-cited scientific publications worldwide as % of total scientific publications of the country; fractional counting method. (2)CH: 2015.

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Although several EU Member States are making numerous efforts to increase the effectiveness and performance of their public-sector research systems, further efforts are needed to introduce the necessary policy reforms. Between 2013 and 2016, research excellence in the EU28 increased at an annual growth rate of 3.2 %[10]. However, further efforts are needed to ensure well-functioning, efficient and impactful national R&I systems. The European Research Area (ERA) Priority 1 recognises this by calling for more effective national research systems and richer R&I policy mixes geared towards making a stronger impact by science and innovation in society.

10 Headline indicator composed of: share of top 10 % most highly cited publications per total publications (data source: CWTS); PCT patent applications per population (OECD); European Research Council (ERC) grants per public R&D (DG RTD, Eurostat, OECD); and participation in Marie Skłodowska-Curie fellowships (DG EAC); see European Commission (2019c: 11).

The European Semester 2019 also shows that further progress must be made, and it has demanded, for the first time, that all EU Member States make greater investments in R&I. A number of countries received additional country-specific recommendations (CSRs) for policy action to promote the quality and efficiency of their national R&I systems (quality of R&I policies and systems, stronger science-business links, support for breakthrough innovations and scale-up of high-growth firms, and sound framework conditions for business R&D).

The European Structural and Investment Funds (ESIF) and smart specialisation strategies are also prioritising investments in R&I in support of these reforms. Other reform-supporting tools include the Structural Support Reform Programme and the Horizon 2020 Policy Support Facility (PSF), which give advice to those Member States willing to improve the design, implementation or evaluation of their national R&I policies.

To ensure the effective use of public R&I funds, competitive funding is widely applied in EU Member States. However, the 2018 ERA Progress Report found that 'the balance between competitive funding and block funding still varies greatly between countries. In some countries with less-developed R&I systems, less competitive research-performing organisations rely mainly on block funding; this often affects their ability to attract the best talent and to develop and maintain research infrastructures' (European Commission, 2019b: 3). The Horizon 2020 PSF Mutual Learning Exercise on Performance-Based Funding[11] recommended Member States to carefully consider the proportion of institutional funding governed by performance-based criteria as a means of enhancing the effectiveness and performance of their public-sector research systems.

3. Digitalisation is transforming science. All areas of research are becoming data-intensive, increasingly relying upon and generating big data

Digitalisation has the potential to increase the productivity of science, enable novel forms of discovery and enhance reproducibility. Deep learning has become an increasingly popular method in most scientific disciplines. Digitalisation is a game-changer for science. The development and use of big data, for example, and the application of artificial intelligence (AI) is becoming increasingly relevant across all scientific domains (see Chapter 7 - R&I enabling artificial intelligence).

Digitalisation has the potential to promote collaboration as well as improve the efficiency of scientific research (OECD, 2019b: 57). The most noted potential – one that applies across all disciplines, including the humanities – concerns exploiting data and machine-learning techniques to support the research process (OECD, 2019c: 69ff).

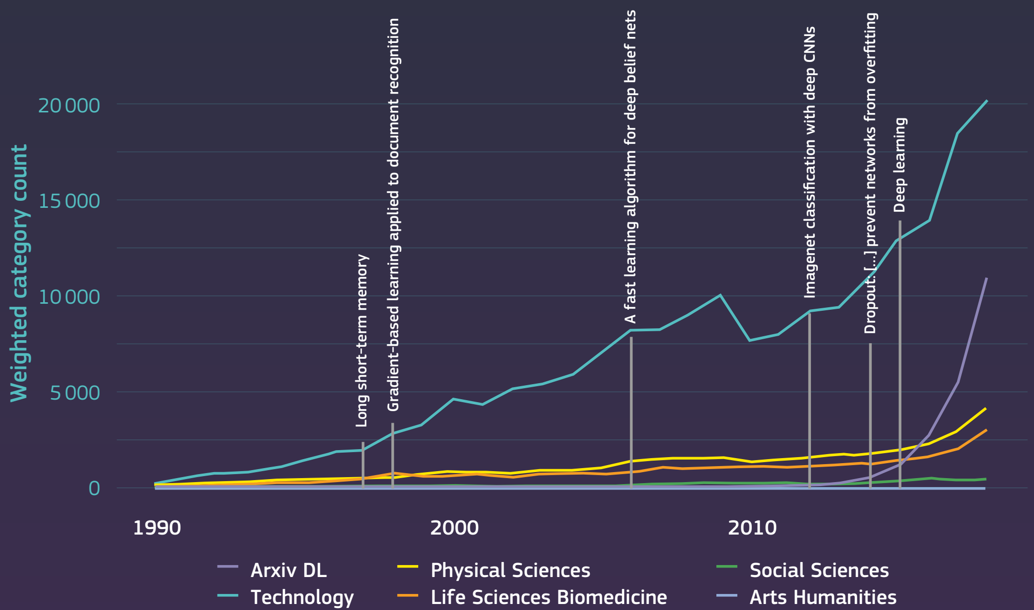
11 See https://rio.jrc.ec.europa.eu/en/policy-support-facility/mle-performance-based-funding-systems, accessed 22 October 2019.

BOX 6.1-2 The rise of deep learning and its impact on global science[12]

Based on a contribution by Stefano Bianchini, Moritz Muller and Pierre Pelletier, BETA – University of Strasbourg

Much of the recent success of AI has been spurred by impressive achievements within a broader family of machine-learning methods, commonly referred to as deep learning. Deep learning enables computational models to learn representations of data with multiple levels of abstraction. Deep learning can be viewed as an 'invention in the methods of invention' – i.e. A technology that transforms the process of knowledge creation and improves the potential for discoveries in combinatorial-type research problems.

Figure 6.1-13 Publication activity related to deep learning



Science, research and innovation performance of the EU 2020

Source: Stefano Bianchini, Moritz Muller and Pierre Pelletier, BETA – Université de Strasbourg

Note: This figure represents the annual trends in deep-learning documents divided into five WoS subject categories. It also shows the yearly trend in deep-learning research published in arXiv, an open archive of academic preprints widely used by the computer-science community. The vertical grey lines indicate important methodological achievements in the field of deep learning. These breakthroughs (especially those in recent years) precede a strong upward trend in the application of the technology in various domains.

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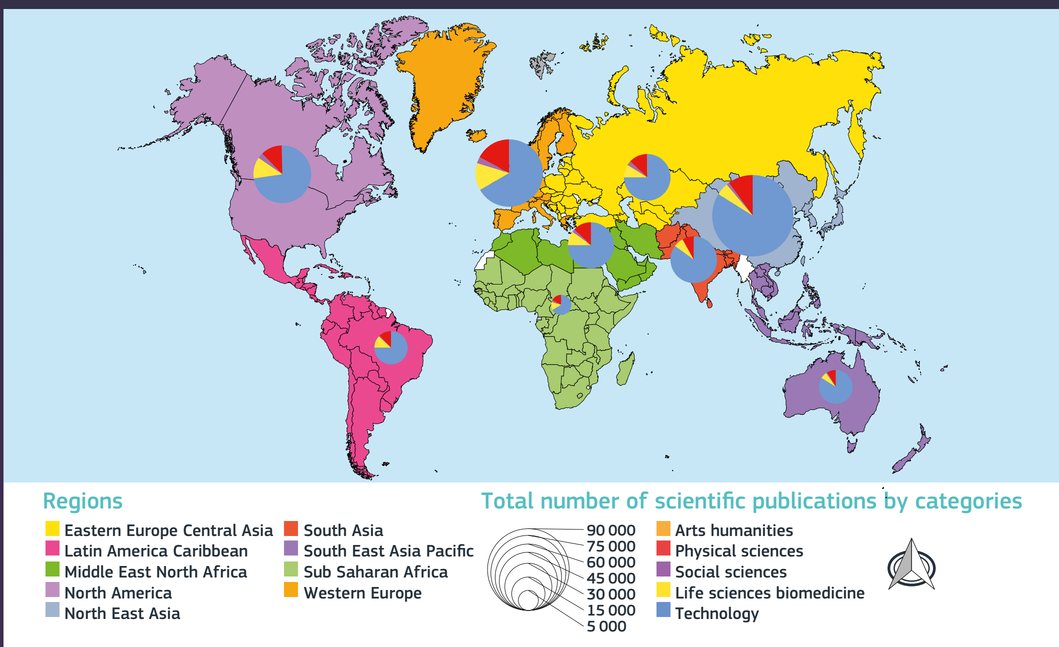
12 Methodology: Web of Science (WoS) publication statistics are used to document how deep learning is being spread in science. Natural language processing techniques are used on text corpus (i.e. abstracts of scientific documents) for the identification of deep-learning-related terms (e.g. deep neural networks). Then a selected list of terms is used to identify those WoS documents that involve deep learning. These documents can either contribute methodologically to deep learning or use deep-learning-based tools to address disparate research questions. The WoS subject categories assigned to each document and authors' affiliations are used to map the diffusion of deep learning across the scientific system.

Figure 6.1-14 presents the geography of deep-learning activity by regions. The map shows a high level of activity in a small number of regions ranked as follows: north-east Asia, western Europe and North America. The map also documents a substantial variation in the applications across regions. Regions such as north-east Asia and eastern Europe seem to deploy deep learning mainly in the field of technology, while western Europe and North America show a significantly larger proportion of applications in life sciences and biomedicine.

The evidence suggests that **deep learning is spreading rapidly in many areas in the scientific system**. However, the important geographical dimension inherent in the process of creating and disseminating deep-learning-related knowledge suggests that countries are likely to exhibit heterogeneous patterns of specialisation. The performance of any deep-learning system relies heavily on good data. As such, science and technology policies should **improve access to high-quality data infrastructures through a well-designed data strategy**, which includes ethical and legal considerations. In addition, to achieve the full potential of deep learning, complementary resources are necessary. Among these assets, human resources (i.e. talented AI researchers) are the most important. **Deep learning also implies organisational changes in the scientific system**, such as team structure, public-private interaction, data sharing, etc.

Figure 6.1-14 Geography of deep-learning activity



Science, research and innovation performance of the EU 2020

Source: Stefano Bianchini, Moritz Muller and Pierre Pelletier, BETA – Université de Strasbourg

Note: This figure represents the geography of deep-learning activity by regions in the period 1990-2018. It also shows the share of WoS subject categories for each region.

Stat. link: https://ec.europa.eu/info/sites/info/files/srip/2020/parti/chapter61/figure-61-14.xlsx

Moreover, the use of AI in science could enable novel forms of discovery and enhance reproducibility (OECD, 2018).

Avenues to promote the digitalisation of public research include strengthening researchers' digital skills, promoting open science (access to publications and data), ensuring appropriate investments in digital infrastructures for research, and creating incentives for interdisciplinary research. Promoting digitalisation of public research has become a priority for almost all EU Member States. In addition to open science[13], Member States are supporting various other measures, including strengthening researchers' digital skills by reinforcing interdisciplinarity (i.e. combining computer science with traditional disciplines) or offering specific trainings to master digital tools.

Moreover, Member States are investing in digital infrastructures that are critical for research (for example, platforms for sharing data and supercomputing facilities for AI). In 2018, the EU launched the European High-Performance Computing Joint Undertaking (EuroHPC JU) with a budget of around EUR 1 billion to develop top-of-the-range exascale supercomputers for processing big data, based on competitive European technology (see Chapter 7 - R&I enabling artificial intelligence)[14].

The digital transformation is also likely to change the accessibility of publications and data which has been limited to date[15]. While immediate open access is steadily increasing, the traditional subscription model remains the most prevalent, 'representing over 80% of the total number of articles published globally last year' (OECD, 2019a: 73). Access to data must consider legal and ethical constraints as well as normative attitudes and the availability of infrastructures (OECD, 2019a: 73).

4. Science is key in addressing societal challenges. The EU is a leader in high-quality scientific publications in the food/bioeconomy and climate/environment sectors

European Member States dominate the analysis targeting the UN SDGs. Figure 6.1-15 shows that Europe dominates the analysis targeted on the UN SDGs, indicating primarily the commitment of researchers to better understanding the goals, interactions between each of them, and potential trade-offs when addressing them. The figure is based on papers directly pertaining to SDGs, i.e. research articles with a title, abstract or keywords that explicitly contain the phrase 'sustainable development goal(s)'. North America and the Asia and Pacific region contribute less. Notably, the highest level of collaboration within the SDG papers surveyed was among European countries (see the 'dark purple cell'). Moreover, Europe

13 See Chapter 6.2 - Knowledge flows.

14 https://ec.europa.eu/digital-single-market/en/eurohpc-joint-undertaking#Budget, accessed 9 October 2019.

15 See Chapter 6.2 - Knowledge flows.

Figure 6.1-15 Regional collaboration matrix for SDG core and citing papers(1)

	Latin America	North America	Africa	Europe	Asia & Pacific	Arab States
Latin America	275	408	179	434	237	63
North America	408	1329	656	1446	1089	114
Africa	179	656	262	863	432	90
Europe	434	1446	863	**2602**	1300	169
Asia & Pacific	217	1089	432	1300	1623	108
Arab States	63	114	90	169	108	41

Source: Institute for Scientific Information (2019: 10)
Note: (1)The figure is a pair-wise matrix showing the number of SDG papers authored by researchers in countries within each regional pair represented by the intersection of the row and column.
Stat. link: https://ec.europa.eu/info/sites/info/files/srip/2020/parti/chapter61/figure-61-15.xlsx

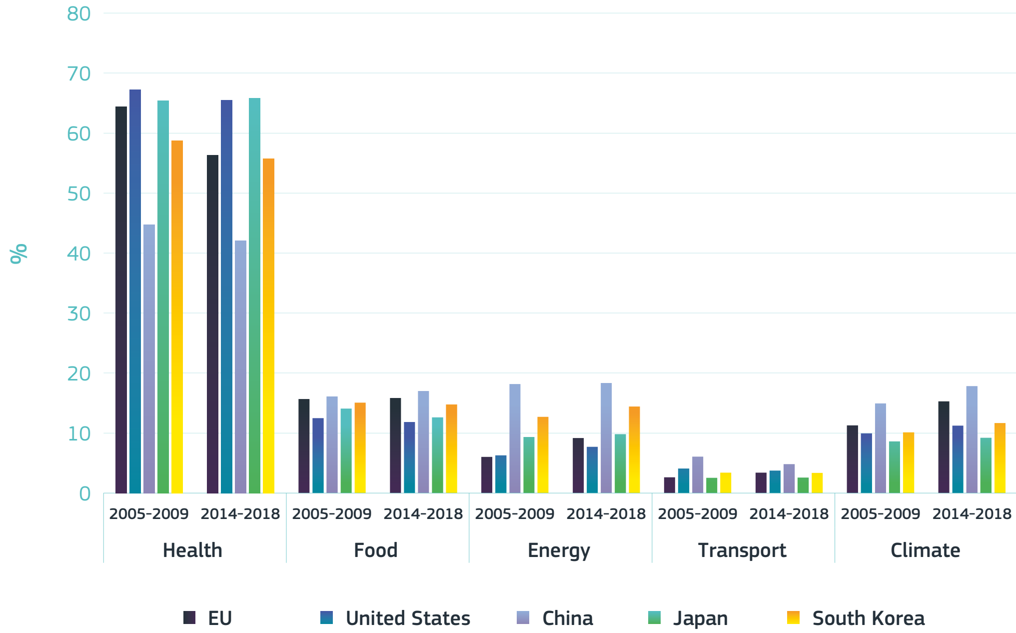
is the largest collaborator with North America (even larger than the intra-North American collaboration) and the largest collaborator with the Asia and Pacific region (while intra-Asia and Pacific region collaboration is slightly higher). Africa, the Arab States and Latin America have more frequent co-authorships with Europe than with North America.

The share of scientific publications remains the highest in 'health, demographic change and well-being' field. For all major science producers, the shares of scientific publications are highest for the societal challenge 'health, demographic change and well-being', although the EU saw a decrease from 64.4% to 56.3% between the periods of 2005-2009 and 2014-2018. Yet, for all other challenges, EU shares increased over the same periods. The same trend can be observed for China.

Scientific publications on 'food security, sustainable agriculture and forestry, marine, maritime and inland water research, and the bioeconomy' have the second highest share for all countries except China, for which both 'secure, clean and efficient energy' and 'climate action, environment, resource efficiency and raw materials' rank second (Figure 6.1-16).

16 Figure 6.1-15 is a pair-wise matrix showing the number of SDG papers authored by researchers in countries within each regional pair represented by the intersection of the row and column.

Figure 6.1-16 Share of scientific publications by societal challenge[(1)], 2005-2009 and 2014-2018)



Science, research and innovation performance of the EU 2020

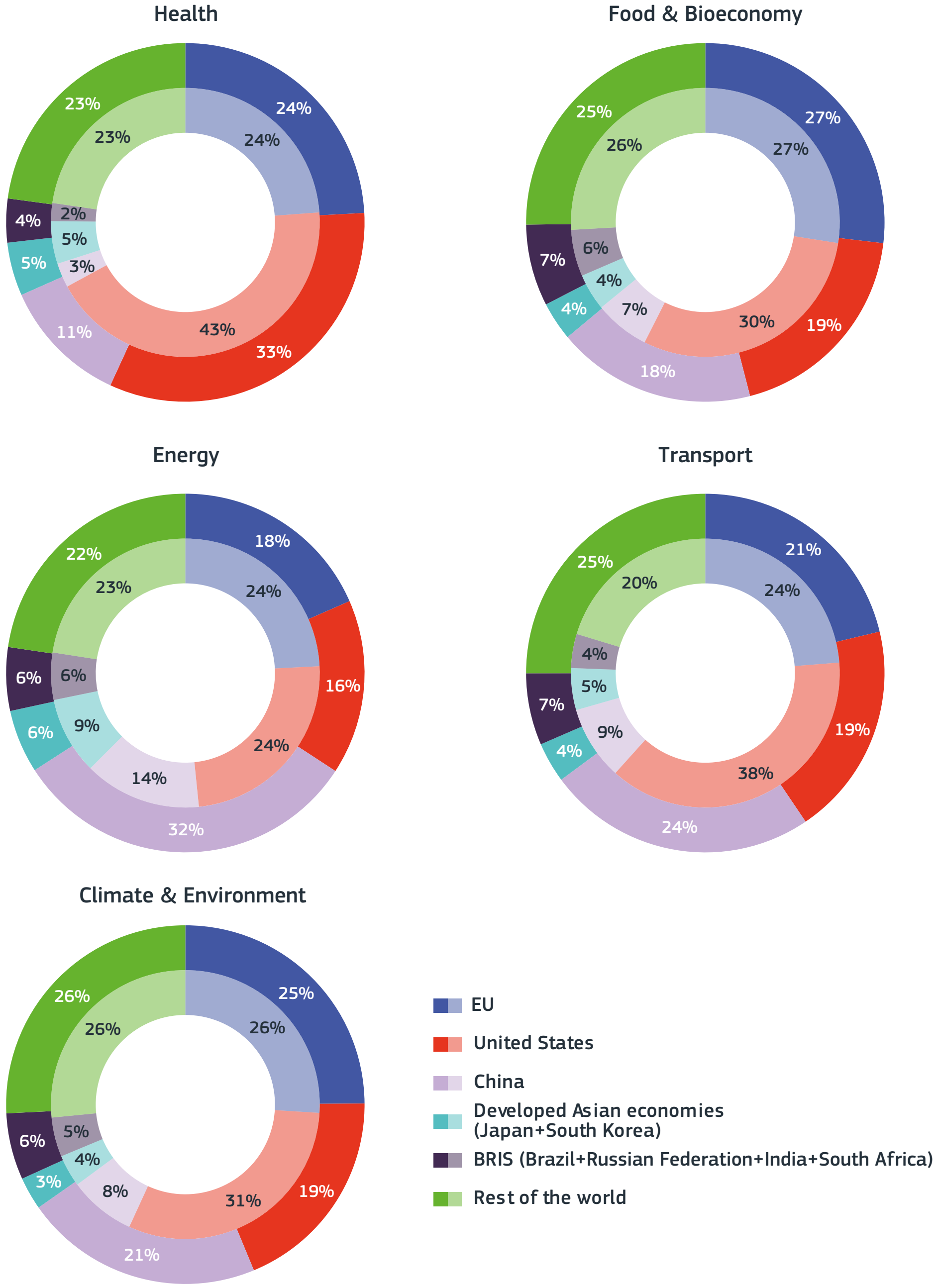
Source: DG Research and Innovation, Chief Economist - R&I Strategy & Foresight Unit

Note: [(1)]Data produced by Science-Metrix based on Scopus database. This presents the overall % of publications by area. The specialisation indices below are just dividing the % of EU by the % of other countries.

Stat. link: https://ec.europa.eu/info/sites/info/files/srip/2020/parti/chapter61/figure-61-16.xlsx

The EU leads in high-quality scientific publications in the food and bioeconomy and climate and environment sectors when compared to its major competitors. While China increased its shares exponentially across all societal challenges, the United States lost its leadership in all of them. When comparing the EU to its major competitors (the US, China, and Japan), the EU leads in scientific publications related to food and bioeconomy and climate and environment (Figure 6.1-17). In all fields, the EU's share remained stable between 2006 and 2016, with the exception of energy where its share dropped from 24% to 18%. During the same period, China increased its shares exponentially across all societal challenges, taking top position in the areas of energy (from 14% in 2006 to 32% in 2016) and transport (from 9% in 2006 to 25% in 2016). At the same time, it reached second place in climate and environment (with 22% in 2016) behind the EU (with 25% in 2016). In contrast to the rise of China, the United States lost its leadership in all fields.

Figure 6.1-17 Shares (%) of top 10 % of scientific publications by Societal Grand Challenges, 2006 (interior) and 2016 (exterior)



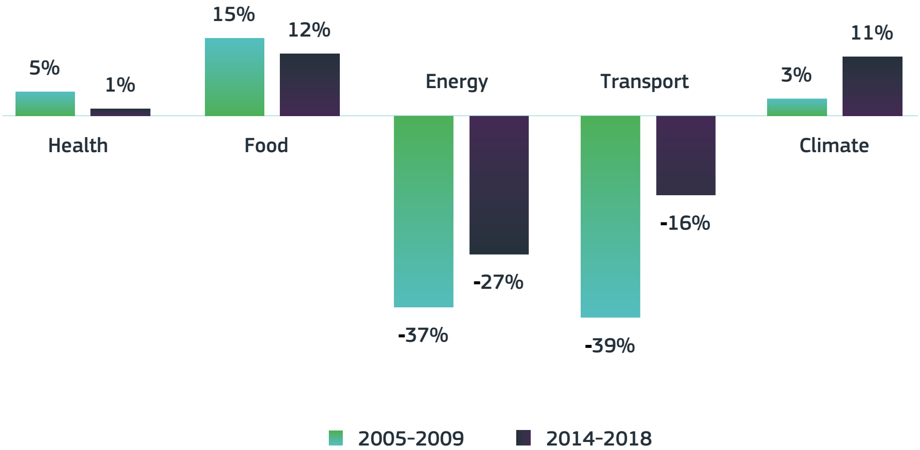
Source: DG Research and Innovation, Chief Economist - R&I Strategy & Foresight Unit

Note: [(1)]Data produced by Science-Metrix based on Scopus database.

Stat. link: https://ec.europa.eu/info/sites/info/files/srip/2020/parti/chapter61/figure-61-17.xlsx

Compared to its main competitors, the EU is particularly specialised in food- and climate-related scientific publications. In comparison to its major competitors (the United States, China, Japan and South Korea), Europe shows a particular specialisation in food and climate change challenges (Figure 6.1-18). During the period 2014-2018, the share of EU publications in food-related challenge was 12% higher than for its competitors (falling from 15% during the period 2005-2009). In the climate-change challenge, it was 11% higher (increasing from 3% during the period 2005-2009). On the other hand, the EU lags behind in the energy and transport challenges.

Figure 6.1-18 Percentage difference in EU specialisation index (vs. US, China, Japan and South Korea), 2005-2009 and 2014-2018



Science, research and innovation performance of the EU 2020

Source: DG Research and Innovation, Chief Economist - R&I Strategy & Foresight Unit

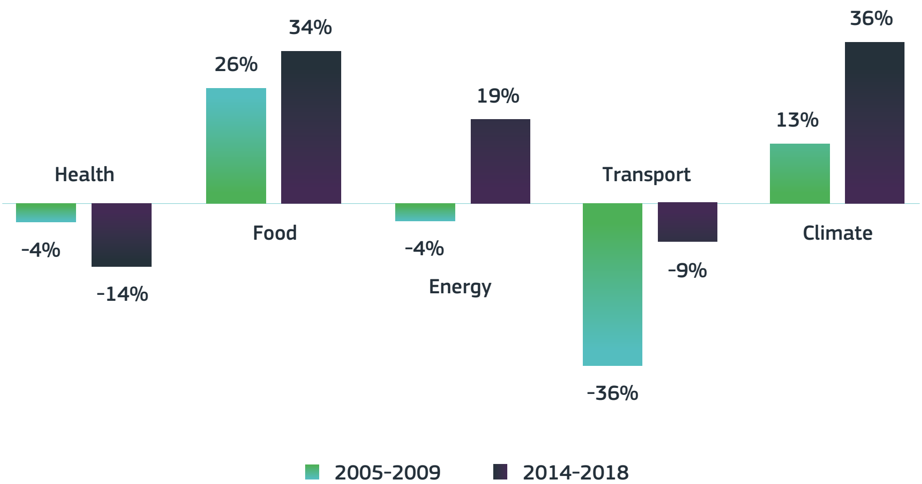
Note: [1]Data produced by Science-Metrix based on Scopus database. These figures compare the percentage of publications in the EU in one area (% of all EU publications) with the percentage of publications in the US, China, Japan and South Korea in the same area (% of all publications in these countries).

Stat. link: https://ec.europa.eu/info/sites/info/files/srip/2020/parti/chapter61/figure-61-18.xlsx

When compared only to the United States, the EU is stronger in the areas of food, energy and climate change, but lags behind it in health and transport-related publications. From 2005 to 2018, the EU increased its advance in the climate change area vis-à-vis the United States by almost three times (Figure 6.1-19).

Compared to China, the EU only appears stronger in health challenge, where its share of scientific publications is 34% higher (2014-2018). In all other areas, the EU appears weaker than China, especially in the energy challenge where the former produced 50% (2014-2018) fewer scientific publications than the latter (Figure 6.1-20).

Figure 6.1-19 Percentage difference in EU specialisation index (vs. US), 2005-2009 and 2014-2018



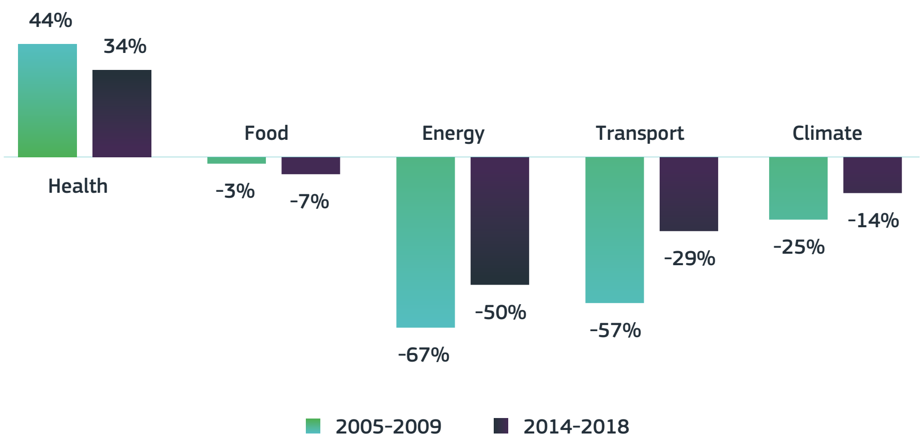
Science, research and innovation performance of the EU 2020

Source: DG Research and Innovation, Chief Economist - R&I Strategy & Foresight Unit

Note: (1)Data produced by Science-Metrix based on Scopus database. These figures compare the percentage of publications in the EU in one area (% of all EU publications) with the percentage of publications in the US in the same area (% of all publications in these countries).

Stat. link: https://ec.europa.eu/info/sites/info/files/srip/2020/parti/chapter61/figure-61-19.xlsx

Figure 6.1-20 Percentage difference in EU specialisation index (vs. China), 2005-2009 and 2014-2018



Science, research and innovation performance of the EU 2020

Source: DG Research and Innovation, Chief Economist - R&I Strategy & Foresight Unit

Note: (1)Data produced by Science-Metrix based on Scopus database. These figures compare the percentage of publications in the EU in one area (% of all EU publications) with the percentage of publications in China in the same area (% of all publications in these countries).

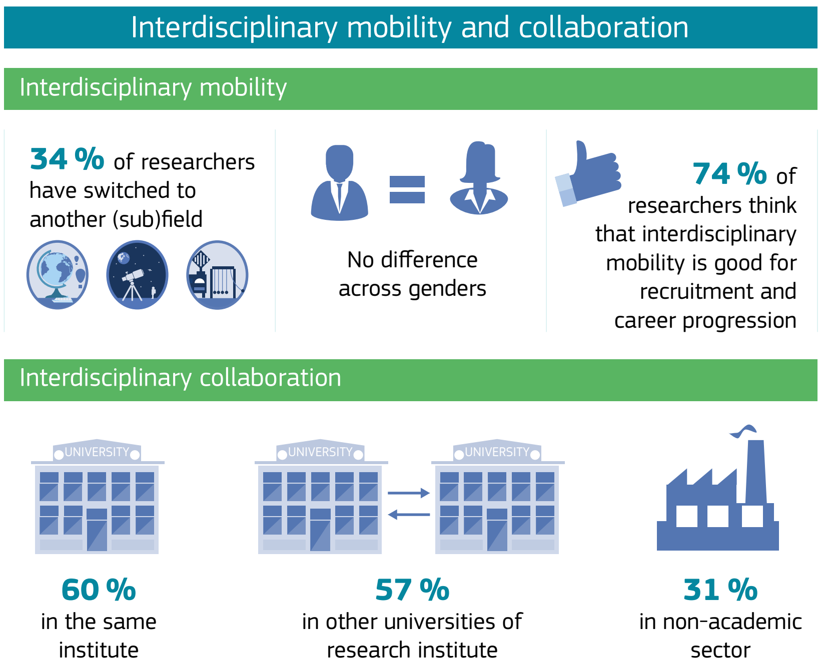
Stat. link: https://ec.europa.eu/info/sites/info/files/srip/2020/parti/chapter61/figure-61-20.xlsx

Research addressing SDGs requires interdisciplinarity. One third of all researchers in the EU have switched to another field or sub-field during their academic career. As all SDGs are interconnected, interdisciplinary and transdisciplinary research will be key to identifying positive complimentary interactions between the SDGs, as well as trade-offs that can constrain or stop progress on certain SDGs (International Council for Science, 2017).

A wide range of research approaches are needed to address the breadth and nature of the challenges reflected by the SDGs (SDSN Australia Pacific 2017). This goes beyond research between disciplines and demands the creation of new ones, such as 'sustainability science'. As a unique trans-, inter-, and multidisciplinary endeavour, sustainability science (Kates et al., 2001) aims to identify problems, opportunities and trade-offs between human, environmental and engineered systems. According to this concept, scientific, lay, practical and indigenous knowledge, as well as varying world views, are brought together (UN, 2019).

The MORE3 Final Report[17] provides evidence that one third of all researchers switch to another field or sub-field during their academic career. Below average shares of interdisciplinary collaboration are observed in the social sciences and humanities (Figure 6.1-21).

Figure 6.1-21 Interdisciplinary mobility and collaboration



Source: Based on MORE EU HE report
Stat. link: https://ec.europa.eu/info/sites/info/files/srip/2020/parti/chapter61/figure-61-21.xlsx

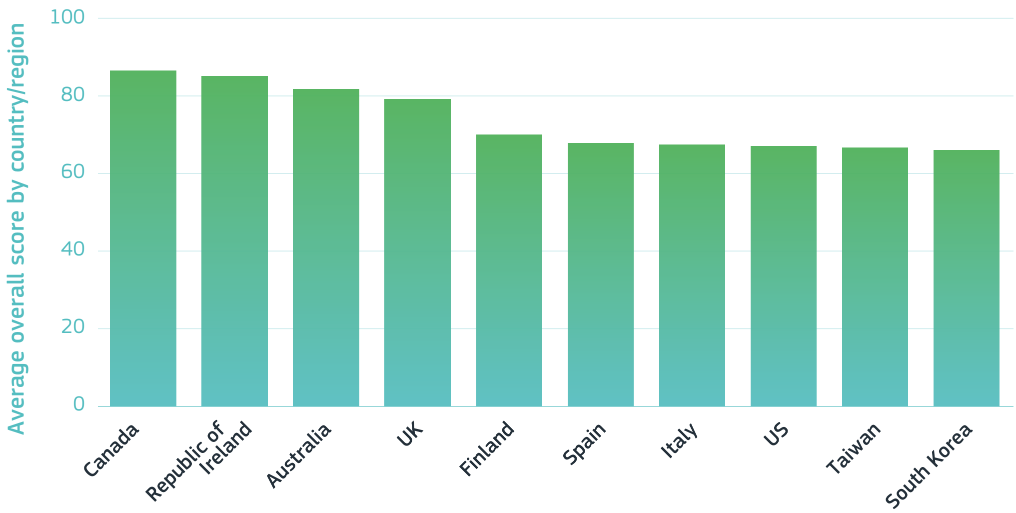
17 See XXXX

Although interdisciplinarity may be well suited to addressing complex societal challenges while fostering academic excellence and innovation, the development of policies pursuing interdisciplinary careers is hampered by the absence of a clear-cut definition of interdisciplinarity.

Universities play a critical role in providing the necessary knowledge to support social, environmental and economic transitions. Canada, Ireland and Australia are the top countries where universities are leading the way in supporting just and responsible social change. The Times Higher Education University Impact Rankings 2019 is the first attempt to measure global universities' success in delivering the SDGs[18]. It uses calibrated indicators to provide comparisons across three broad areas: research, outreach, and stewardship. Metrics are based on 11 of the 17 UN SDGs.

Results from the first edition reveal a new hierarchy of global institutions compared to research-focused rankings, with New Zealand's Auckland and two Canadian institutions – McMaster University and the University of British Columbia – comprising the top three overall, alongside the UK's University of Manchester. On average, universities in Canada are the highest performing, with Ireland and Australia coming next[19] (Figure 6.1-22). When it comes to overall representation, Japan tops the list of the 76 countries represented with 41 ranked institutions, while the United States has 31 and Russia 30. Twenty-six EU universities feature among the top 100 performing universities, followed by 17 from the UK.

Figure 6.1-22 Average overall score by country/region in the Times Higher Education University Impact Rankings 2019



Source: THE Impact Rankings

Note: Excludes territories with fewer than five institutions in ranking.

Stat. link: https://ec.europa.eu/info/sites/info/files/srip/2020/parti/chapter61/figure-61-22.xlsx

18 For the ranking, see: https://www.timeshighereducation.com/rankings/impact/2019/overall#!/page/0/length/25/ sort_by/rank/sort_order/asc/cols/undefined; for the methodology, see: https://www.timeshighereducation.com/ world-university-rankings/ methodology-impact-rankings-2019, accessed 4 September 2019.

19 https://www.timeshighereducation.com/news/university-impact-rankings-2019-canada-leads-way, accessed 16 October 2019.

Figure 6.1-23 Global performance of EU universities against UN SDGs in the Times Higher Education University Impact Rankings 2019

Global performance of EU universities against UN SDGs (Top 100)		
Position in THE ranking	**Name**	**Country**
6	University of Gothenburg	Sweden
7	KTH Royal Institute of Technology	Sweden
9	University of Bologna	Italy
15	University of Helsinki	Finland
16	University of Padua	Italy
16	Vrije Universiteit Amsterdam	The Netherlands
19	Aalto University	Finland
21	University College Cork	Ireland
28	Trinity College Dublin	Ireland
29	Pompeu Fabra University	Spain
34	Autonomous University of Barcelona	Spain
35	University of Limerick	Ireland
43	Aix-Marseille University	France
58	University College Dublin	Ireland
60	University of Hamburg	Germany
65	University of Amsterdam	The Netherlands
75	University of Eastern Finland	Finland
76	Comenius University in Bratislava	Slovakia
78	University of L'Aquila	Italy
83	University of Minho	Portugal
86	Comillas Pontifical University	Spain
92	University of Latvia	Latvia
94	University of Girona	Spain
97	Aalborg University	Denmark
98	Dublin City University	Ireland

Science, research and innovation performance of the EU 2020

Source: DG Research and Innovation, Chief Economist - R&I Strategy & Foresight Unit based on Times Higher Education ranking (https://www.timeshighereducation.com/rankings/impact/2019)

Stat. link: https://ec.europa.eu/info/sites/info/files/srip/2020/parti/chapter61/figure-61-23.xlsx

5. Conclusions

The EU's scientific performance is framed by several grave developments, including the UK's exit from the EU, the rise of China, digitalisation, and a new focus on the SDGs. This chapter has shown that the **EU and China are the global leaders in terms of scientific output, while the United States retains the lead in scientific quality**. Notably, output by Chinese researchers has risen exponentially over the last two decades to nearly match the EU.

Within the EU, there is a diversity of research intensities among the Member States and a positive correlation between scientific quality and R&I investments in most countries. Although several EU Member States are making numerous efforts to enhance the effectiveness and performance of their public-sector research systems, further efforts are needed to introduce the necessary policy reforms.

Digitalisation has the potential to increase science productivity, enable novel forms of discovery and enhance reproducibility. It is transforming science. This chapter has illustrated that all areas of research are becoming data-intensive, increasingly relying upon and generating big data.

Last but not least, this chapter points out that science is key in addressing societal challenges. The EU leads high-quality scientific publications in the food/bioeconomy and climate/environment sectors, while China's output is increasing exponentially across sectors and the United States has lost its overall leadership.

These findings trigger certain policy implications. First, to remain a leading global scientific player, the EU and its Member States must **strengthen their efforts to enhance the effectiveness and performance of their public research systems through stronger R&I investments and policy reforms**. Second, to exploit the full potential science digitalisation, policies must be adapted to reinforce researcher's digital skills, promote open science as well as ensure the necessary investments in high-quality data infrastructures. And third, as science is key to addressing societal challenges, the **EU must not only ensure scientific leadership in key areas but must also foster interdisciplinarity research which is necessary to successfully deliver on the SDGs**.

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