STUDY

Requested by the ITRE committee

Europe – the Global Centre for Excellent Research

Policy Department for Economic, Scientific and Quality of Life Policies
Directorate-General for Internal Policies
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Europe – the Global Centre for Excellent Research

Abstract

The world of research and innovation is becoming increasingly multipolar with China joining the ranks of science and technology leaders. For the EU, increased global research capacities offer a larger global talent pool and opportunities for specialisation, but also increased competition for investment, talent and the position as world-leader in critical technological fields. To be a global centre for excellent research, the EU and its Framework Programme must support the further integration of the intra-EU excellent research pole and at the same time being open for foreign talent and internationally connected with strong extra-EU partners.

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LIST OF ABBREVIATIONS

AC	Associated Countries to the FP
AI	Artificial Intelligence
ERA	European research area
ERC	European Research Council
EU13	The 13 countries that joined the European Union since 2004.
EU15	The 15 countries that were members of the European Union in 2003.
FP	Framework Programmes
FP7	Seventh Framework Programme
FWCI	Field-weighted citation impact
GDP	Gross domestic product
H2020	Horizon 2020
ICT	Information and Communications Technology
IP	Intellectual property
MSCA	Marie Skłodowska-Curie Actions
PCT	Patent Cooperation Treaty
R&D	Research and development
R&I	Research and innovation
S&E	Science and engineering
KPI	Key Performance Indicator

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EXECUTIVE SUMMARY

Investment in science, technology, innovation and education correlates strongly with economic growth, and with the development of a safe, healthy and green society. Nations understand the economic and social benefits of such investments and commit substantial parts of their public expenditures to research and development (R&D) and education, taking into account that knowledge is a global public good that can be used by others, and that it will inevitably cross borders.

In the European Union, research and innovation (R&I) has been firmly embedded as an engine for growth. The rising share of research spending in the EU budget demonstrates the European Commission's commitment to boosting R&I.

But the EU must also face an increasingly multipolar world. After many decades of leadership by the United States, the EU and Japan, other economies have increased their R&D and education spending, with China the most significant case. This trend towards more multipolar global science and technology (S&T) capacity and capability presents the EU with both opportunities and challenges. While competition for resources will intensify at the global scale, increased global S&T capacity offers opportunities for faster S&T advancement: it offers the possibility of mobilising a large pool of global talent and of building deep research strengths through specialisation and collaboration.

This report analyses the EU's potential to be a global centre of excellence for research as a driver of its future growth in a complex global S&T landscape, and how EU public resources, most notably its research and innovation Framework Programmes, can contribute to this.

We start with an assessment of global research trends and the EU's position in the global context, and illustrate in particular the very fast rise of China, in terms of total scientific output and of top-cited research, though the US and the EU retain for now the leading positions in terms of research excellence. While the vast majority of the world's top universities are American, EU universities have improved their positions, but Chinese universities are increasingly appearing in the rankings.

International collaborative research produces higher-quality publications. While EU researchers are most likely to collaborate with foreign colleagues, China remains quite closed to international cooperation. Private-sector R&D expenditure is highly concentrated among a few large corporations, with US firms in leading positions, followed by EU firms. Chinese companies are however making their way up the list of the top 2,500 R&D spenders, especially in digital technologies. A similar trend can be seen for patents, with the number of Chinese patent filings rising rapidly, though China is still lagging behind the US, the EU and Japan when it comes to patent quality.

We then look at the EU's R&D spending through an assessment of the Seventh Framework Programme (FP7) and Horizon 2020 (H2020). We find that FP7-funded projects are of significantly higher quality than the world average, as measured by field-weighted citation impact. FP7-funded projects are also more likely to be result in publications that enter the top 1 percent of most-cited publications; this is even more so for publications funded by the European Research Council, the most excellence-oriented of FP instruments. These publications, when involving cross-border collaboration, were overwhelmingly the result of intra-EU partnerships. However, evidence shows that publications co-written by EU and non-EU researchers achieved an even greater citation impact than EU-only partnerships.

Based on our assessment we make a number of recommendations for the design of the 2021-27 Framework Programme, Horizon Europe.

First, a long-term commitment should be made to increase the EU budget for research and innovation. The evidence from past Framework Programmes shows that the EU budget has contributed to supporting the EU's improvement in research excellence, most importantly by improving internal integration by improving intra-EU collaboration and the intra-EU mobility of researchers.

The evidence is supportive of the European Parliament's call for a Horizon Europe budget of €120 billion, exceeding the €100 billion proposed by the European Commission.

Second, the potential for extra-EU connectedness and extra-EU talent should be better exploited, something previous Framework Programmes fell short of achieving. Horizon Europe should be open to the rest of the world and able to benefit from this openness. This double objective requires three underpinnings:

- A sustained and preferably reinforced effort to build excellence in S&T capacity; S&T excellence is crucial for attracting the best talent, for building networks and cooperation and for absorbing external knowledge.
- Benefitting from openness requires continued commitment and support for open circulation within an integrated single European market for research through the freedom for researchers to move across borders and to work together across borders.
- Further internal integration of EU countries and with associated partners should however not crowd out extra-EU openness. The EU needs to become more open to the rest of the world, with much more support than in the past for collaboration with the best non-EU partners and mobility of research talent into and out of the EU.

Third, as research excellence is critical in terms of openness and benefitting from it, research excellence should be the major criteria for selecting and evaluating the impact of Framework Programme projects under all of its pillars. This holds a fortiori for the Excellent Science pillar, for which scientific research excellence is the sole criteria. But this should also apply to the other pillars (Global Challenges and Missions and Open Innovation). The cohesion criteria should not be mixed with the excellence criteria for selection and impact assessment under the main pillars. It should be addressed through dedicated instruments such as the Sharing Excellence programme in Horizon Europe and other EU funds, such as the Structural Funds.

Fourth, targeting specific areas in which Europe could become a global centre of research excellence, if done, should be embedded in an overall balanced allocation of funding to bottom-up and top-down programmes. The Excellent Science and Open Innovation pillars should be investigator driven. Targeting is the hallmark of the pillar on Global Challenges and Missions. Targeting should focus on impact while being sufficiently neutral on how impact is achieved.

Finally, Horizon Europe should be systematically monitored and evaluated to assess the impact of the programme overall and that of its individual instruments. The evaluation should be done one the basis of three criteria: a) contribution to research excellence; b) contribution to pathways leading to research excellence (i.e. international research collaboration and mobility); and c) improvements in research excellence stemming from development of these pathways. Additionally, the impact of Framework Programme-induced research excellence on development, innovation capacity, EU growth and competitiveness and societal challenges should be assessed. Key performance indicators should be defined to ensure the relevance of the evaluation process. Excellence should be evaluated in terms of high-impact frontier research output, rather than by counting total publications and patents. To ensure an accurate assessment of the results of international research collaboration and mobility, the Framework Programme should be more systematically documented and monitored with respect to these aspects.

1. GLOBAL SCIENCE AND TECHNOLOGY TRENDS

1.1. Investment in R&D

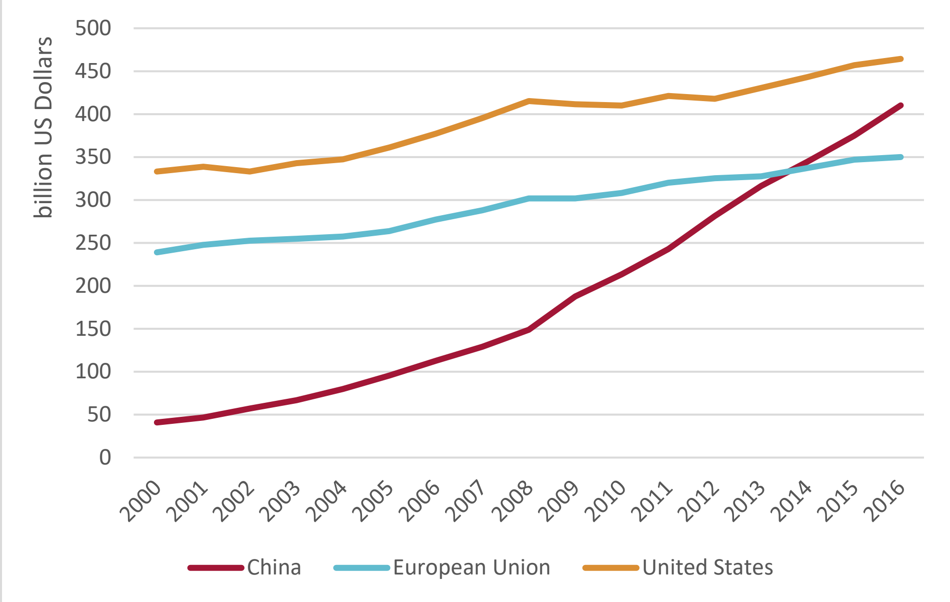
The creation of knowledge and its use in technology and economic and societal development has become increasingly global and multipolar. Europe and the United States have traditionally led in science and technology (S&T) development, but new S&T powerhouses have emerged. Investment in research and development (R&D) is increasing globally, and is growing more rapidly outside the centres that previously dominated global R&D. An increasingly larger group of governments is focusing on S&T as a national priority, drafting strategic plans and investing public funding in S&T infrastructure.

The most notable new power in the world S&T landscape is China. China's rise in science and technology is not an accident. Successive Chinese leaderships have viewed S&T as integral to economic growth and consequently have taken steps to develop China's S&T infrastructures (see for example China's *National Medium-and Long-Term Programme for Science and Technology Development (2006-2020)*). China has a goal for the country's reliance on foreign technology to decline, emphasising "*indigenous innovation*".

The following figures and tables show trends in EU R&D expenditure compared to US and Chinese R&D expenditure, in absolute terms and relative to GDP. Figure 1 shows how in the EU and US, R&D expenditure has increased in absolute terms. Relative to GDP, R&D expenditure has increased more rapidly in the EU (Table 1). The EU has thus managed to close somewhat the R&D-to-GDP gap relative to the US. But the EU is still far from its 3 % target. In terms of R&D expenditure growth rates, China is the best performer. The growth rate of Chinese R&D expenditure has even outpaced its substantial GDP growth rates. In 2015, China already managed to reach an R&D-to-GDP ratio similar to the EU's (i.e. 1.9).

In all three economies, both public and private sector R&D expenditure have increased. In China, the increase is not only due to the public sector; the private sector has also increased substantially its R&D expenditure. The private sector's share of total R&D expenditure is even higher in China than in the EU and the US, though of course the boundaries between private and public entities are blurred in China. Figure 3 shows the trends in employment of researchers. The EU, compared to the US and China, reports the highest numbers and a substantial increase since 2008. But compared to the US and China, a much smaller share of the EU's researchers is employed in the business sector.

Figure 1: Gross Domestic Expenditure on R&D



Source: Bruegel based on data from OECD (2018a).

Note: European Union as composed in 2018. GERD at constant 2010 prices and PPP US Dollars.

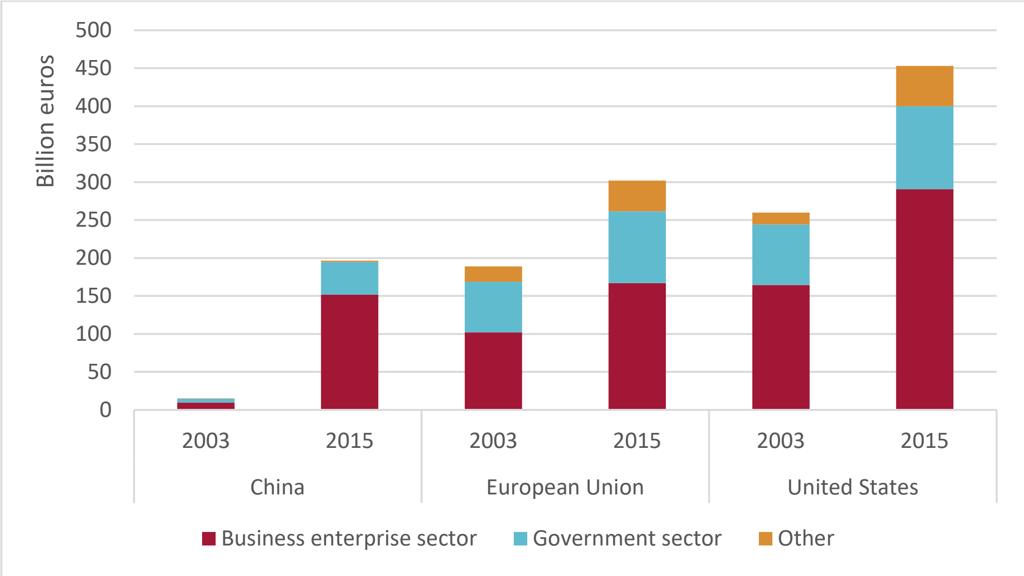
Table 1: R&D and GDP trends in the EU compared to the US and China

	US	EU	China
Annual growth of R&D expenditures			
CAGR 2000–10	2.1	3.1	18.0
CAGR 2010–15	2.3	2.9	12.0
Annual growth of GDP			
CAGR 2000–10	1.6	2.2	10.6
CAGR 2010–15	2.2	1.6	7.8
R&D-to-GDP ratio			
2000-10	2.6	1.7	1.3
2010-15	2.7	1.9	1.9

Source: National Science Foundation (2018).

Note: CAGR are compound annual growth rates.

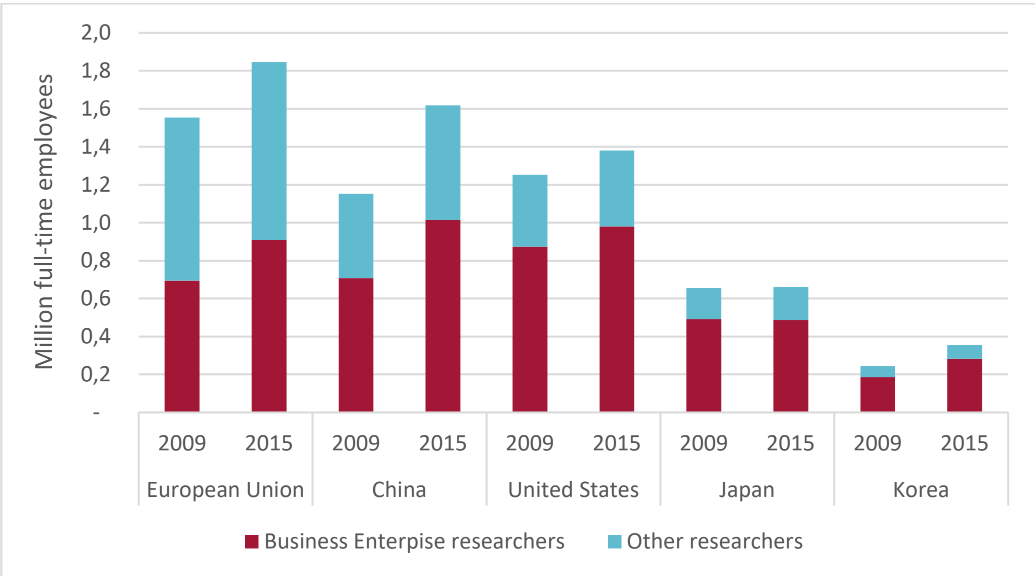
Figure 2: Intramural R&D expenditure by source of funds (million euro)



Source: Bruegel based on data from Eurostat (2018a).

Note: China excluding Hong Kong, European Union as composed in 2018.

Figure 3: Number of researchers



Source: Bruegel based on data from OECD (2018a).

Note: Full-time-equivalents of employed researchers.

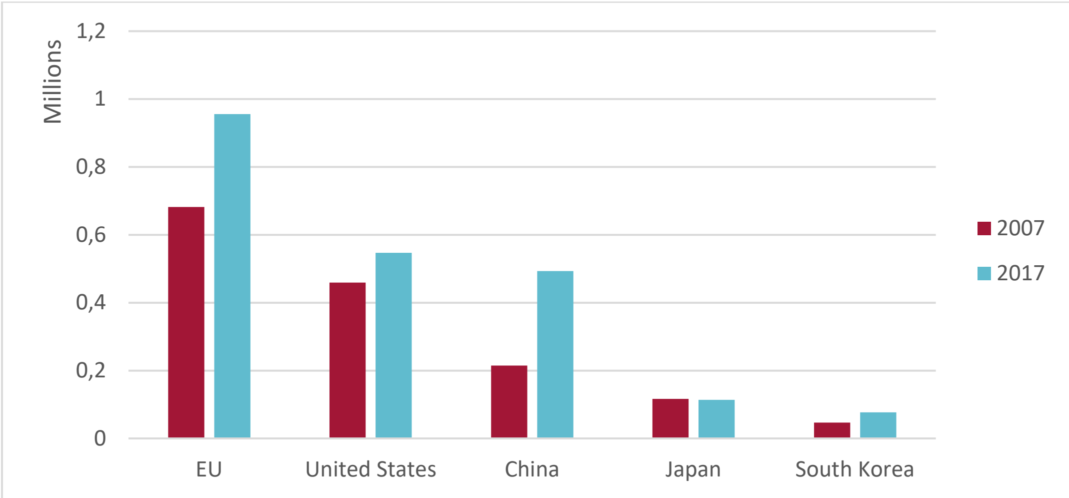
1.2. Towards a multipolar science world

1.2.1. Volume of scientific production

In terms of individual countries, the US has long led the world in the production of scientific knowledge. However, in recent decades, the EU considered as a bloc has managed to outperform the US in terms of volume of scientific output – and increasingly so (Figure 4).

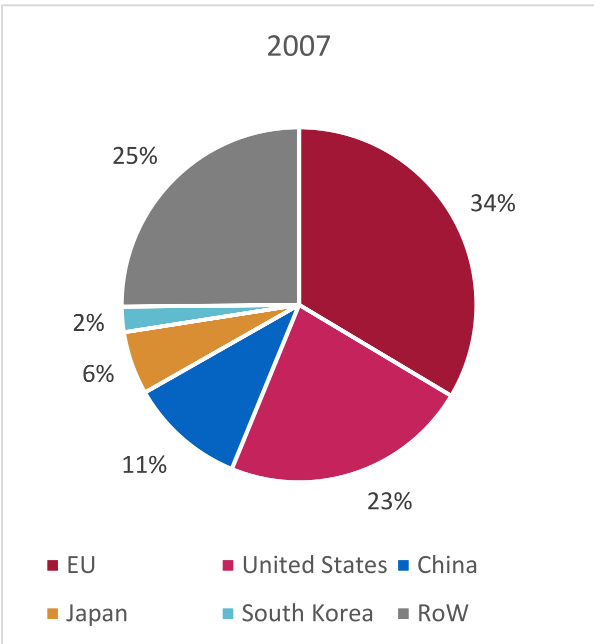
But the biggest change more recently has come from outside the traditional science powerhouses (Figure 5). The growing share of scientific output of the rest of the world (RoW) category illustrates this rise. However, on an individual country basis, China is the most illustrative case. China now publishes more than any other country apart from the US. China and the US are now about equal in terms of number of scientific publications. *However, if China maintains its scientific output growth rate, it will very quickly overtake the US, and even the EU as a bloc, in terms of volume of scientific output.*

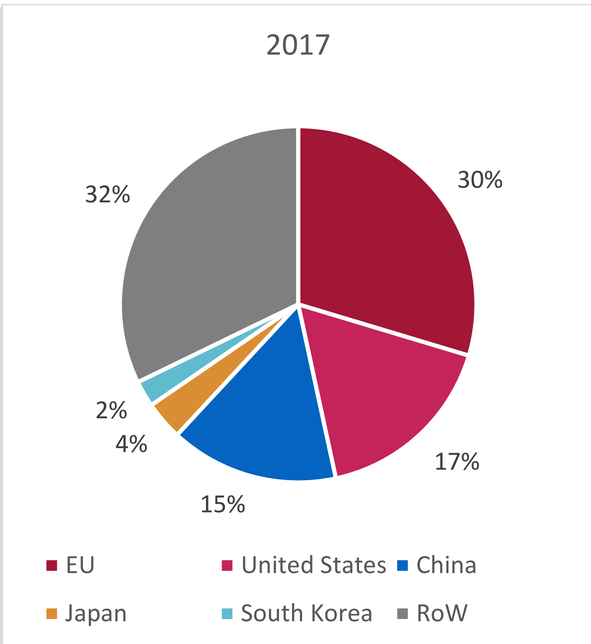
Figure 4: Number of citable documents published



Source: Bruegel based on data from SCImago (2019).

Figure 5: Share of citable documents published





Source: Bruegel based on data from SCImago (2019).

1.2.2. Specialisation in scientific fields

Table 2: Country/region's share of world publications by scientific field

		EU	US	China
Engineering	2007	27	19	20
	2017	24	13	24
Material Sciences	2007	29	26	18
	2017	23	11	26
Chem Engineering	2007	30	20	15
	2017	23	12	26
Computer Sciences	2007	32	20	15
	2017	27	14	18
Mathematics	2007	35	19	15
	2017	30	13	19
Mol. Bio-Genetics	2007	34	27	7
	2017	30	19	16
Medicine	2007	37	26	5
	2017	32	21	11

Source: SCImago (2019).

Note: A full list of all fields can be found in Appendix.

China's rise as a science powerhouse is not evenly distributed. China's scientific priorities are shown by the big and increasing share of published papers in particular fields. In *engineering, chemical engineering* and *material sciences*, China has become the country that produces the most scientific output, far ahead of the US. For the EU, these fields used to be strongholds relative to the US. China has managed to challenge the EU's leadership in these fields, and is currently at par or even already ahead of the EU as a bloc, in terms of share of published papers. Another critical field is *computer sciences,* where the EU for the moment still holds a strong lead, currently representing 27 % of world scientific output. But China is also making significant progress in this field, and has already surpassed the US, which has seen its share declining, to a current share of about 14 % of world scientific output in *computer sciences*. A similar pattern holds for *mathematics*, where the EU still has a strong position, though it is gradually eroding.

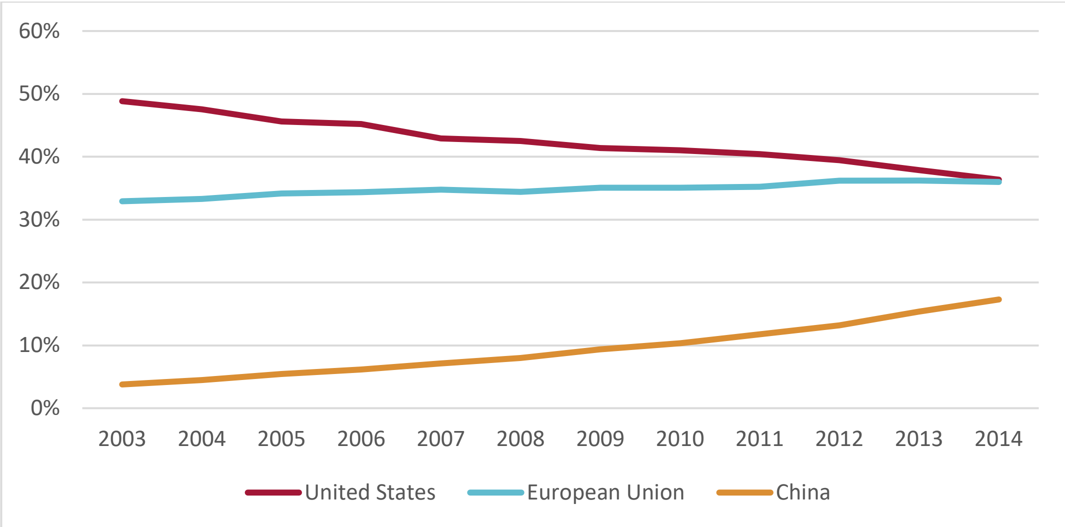
In *life sciences* (biological and medical sciences), China is also on the rise, though to a much less pronounced degree. The EU and the US retain for the moment their traditional dominant roles in these areas. While the EU's share of all world publications in *medical sciences* is 32 %, and the US share is 21 %, China's share is only 11 % (for the moment).

1.2.3. Scientific excellence

When looking at research excellence, the major focus of this report, the most commonly used indicators to measure research excellence is by looking at the impact of the scientific output within the scientific community, as measured by citations received.[1] Although it is a measure of impact and visibility of research and not necessarily of research quality, it is a commonly used indicator of research excellence.

The US has long been in the lead as the country with the largest share of scientific articles within the top 1 % most cited articles in their field (Figure 6). However, along its growth in the number of its scientific publications (cf Figure 4), the EU has gradually caught up with the US share of most-cited articles. The EU and US now have similar shares of most-cited articles. Despite the impressive growth in the volume of its scientific output, China remains far behind the EU and US in terms of most-cited articles, though it is rapidly catching up.

Figure 6: Share of country/region in world Top 1 % most-cited science and engineering articles



Source: Bruegel calculations based on National Science Foundation (2018).

Notes: Article counts refer to publications from a selection of journals, books, and conference proceedings in S&E from Scopus. EU refers to only major publishing countries: Austria, Belgium, Czechia, Denmark, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Netherlands, Poland, Portugal, Spain, Sweden and United Kingdom.

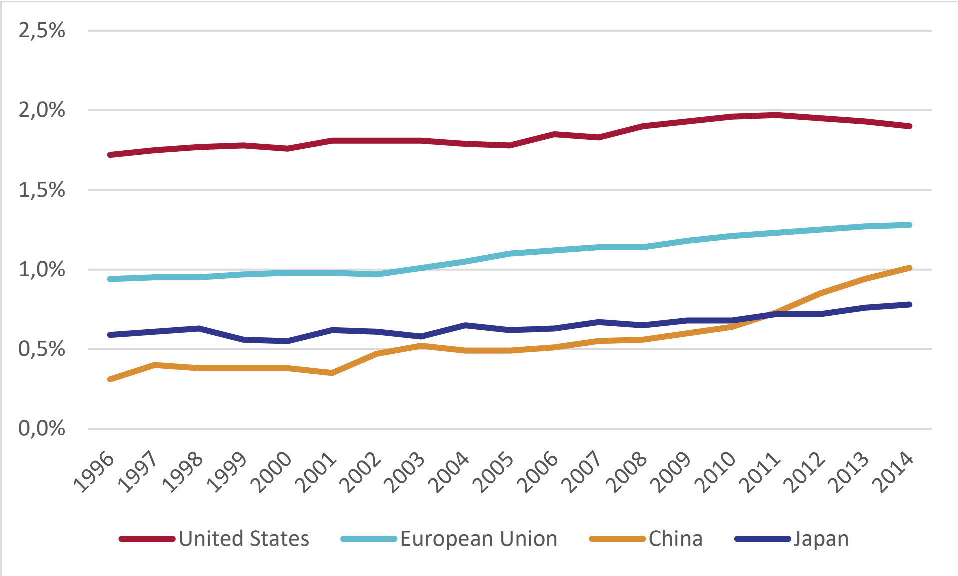
Figure 7 shows trends in the quality of the body of scientific output produced by the main economies, as measured by the share of each economy's total publications that are among the top 1 % most-cited scientific articles in the world (with a share greater than 1 % reflecting a higher-than-world-average number of highly cited papers in the total number of publications produced by that economy). Though the quality of its scientific output remains high and even has increased, the US lead relative to the EU and China is eroding, not only in terms of quantity (cf supra), but also in terms of quality of scientific publications. Importantly for the EU, the growth of its scientific output has been accompanied by an increase in the quality of the scientific output it produces.

While before 2005, a smaller share of EU publications than the world average made it into the top-quality segment, the share of top-quality articles among all the articles the EU produces is now ahead

[1] As citations received are very much field and time specific, indicators need to correct for this. The indicators used in this report: Top x% highly cited and the field-weighted citation impact (FWCI) do this.

of the world average, though still behind the US, a gap that is very slowly shrinking. The quality of China's growing scientific output is still below the EU and far below the US, but the gap is shrinking fast.

Figure 7: Share of S&E publications in the top 1 citation percentile



Source: Bruegel based on National Science Foundation (2018).

Looking more closely at the quality of scientific publications, the strong position of the US is most evident at the frontier, when looking at the top 1 %. The US's lead is less pronounced further down the quality ladder (Table 3). The EU's relative improvement in quality is consistent for all the different segments of the quality ladder, but it is stronger further up the quality ladder. The EU's improvement in quality has been greatest for the top 1 % segment. China is catching in every quality segment, and has made the biggest leap in the top 1 % segment. China has improved more rapidly than the EU in all quality segments, but this is most pronounced in the top 1 % segment.

Table 3: Share of an economy's total publications in the world most cited publications

	US		EU		China	
	2004	**2014**	**2004**	**2014**	**2004**	**2014**
Share of top 1 %	**1.79**	**1.90**	**1.05**	**1.28**	0.49	**1.01**
Share of top 5 %	**8.04**	**8.27**	**5.33**	**6.15**	2.75	4.96
Share of top 10 %	**15.01**	**15.36**	**10.79**	**12.14**	5.76	9.72
Share of top 25 %	**33.59**	**33.90**	**27.10**	**29.20**	15.69	23.64
Share of top 50 %	**59.74**	**59.72**	**53.01**	**55.18**	36.44	47.23
Share of bottom 50 %	40.26	40.28	46.99	44.82	**63.56**	**52.77**

Source: Bruegel based on National Science Foundation (2018).

Note: Numbers in bold are above world average.

1.2.4. Scientific excellence by field

We further examine the trends in research quality by scientific field.

Table 4: Share of S&E articles, by field, citation percentile and economy

	US		EU		China	
	2004	**2014**	**2004**	**2014**	**2004**	**2014**
Engineering						
99th (top 1 %)	**1.93**	**1.79**	**1.26**	**1.15**	0.42	**1.09**
90th (top 10 %)	**14.50**	**14.03**	**12.57**	**11.49**	5.44	**10.17**
Chemistry						
99th (top 1 %)	**1.87**	**1.47**	**1.03**	0.97	0.69	**1.36**
90th (top 10 %)	**15.22**	**13.98**	**10.76**	**10.12**	8.28	**12.76**
Physics						
99th (top 1 %)	**1.89**	**2.07**	**1.10**	**1.41**	0.67	0.88
90th (top 10 %)	**15.01**	**14.69**	**11.57**	**12.55**	7.48	9.95
Mathematics						
99th (top 1 %)	**1.78**	**1.40**	**1.01**	**1.25**	**1.28**	**1.30**
90th (top 10 %)	**15.08**	**13.15**	**10.27**	**12.01**	**12.44**	**10.90**
Computer sciences						
99th (top 1 %)	**2.10**	**2.21**	0.77	0.96	0.46	**1.45**
90th (top 10 %)	**16.53**	**18.50**	9.40	**11.35**	4.86	9.95
Biological sciences						
99th (top 1 %)	**1.67**	**2.00**	**1.09**	**1.38**	0.21	0.63
90th (top 10 %)	**14.90**	**15.97**	**11.02**	**13.10**	3.43	7.62
Medical sciences						
99th (top 1 %)	**1.93**	**2.10**	0.97	**1.44**	0.33	0.56
90th (top 10 %)	**16.35**	**16.51**	9.91	**12.58**	3.57	7.14

Source: Bruegel based on National Science Foundation (2018).

Note: The citation percentile is the share of an economy's publications that are in the top 1 % of the world's citations, relative to all the country's or economy's publications in that period and field. In bold are an economy's position which is higher than expected. Appendix A.3 shows the trends for top 10 % for all scientific fields

In *engineering*, China's progress in terms of the volume of its scientific output has made it the biggest producing country of scientific output in this field. But what about the quality of this scientific output? Table 4 shows that the quality of the scientific output from the EU and the US is still above that of China in this field. But China is catching up very quickly in terms of quality, particularly in terms of the top 1 % of cited articles, where both the EU and the US are losing ground. Nevertheless, the quality of the US science base in this area is still substantially higher.

In *computer sciences*, which as we have noted is a field of specialisation for the EU, the EU lags in quality terms seriously behind the US. The EU is catching up on quality, but slowly. China is making very fast progress in this area, not only in terms of quantity, but also in terms of quality. It already outperforms the EU in terms of the share of its relevant articles that are among the top 1 % most cited articles in *computer sciences*.

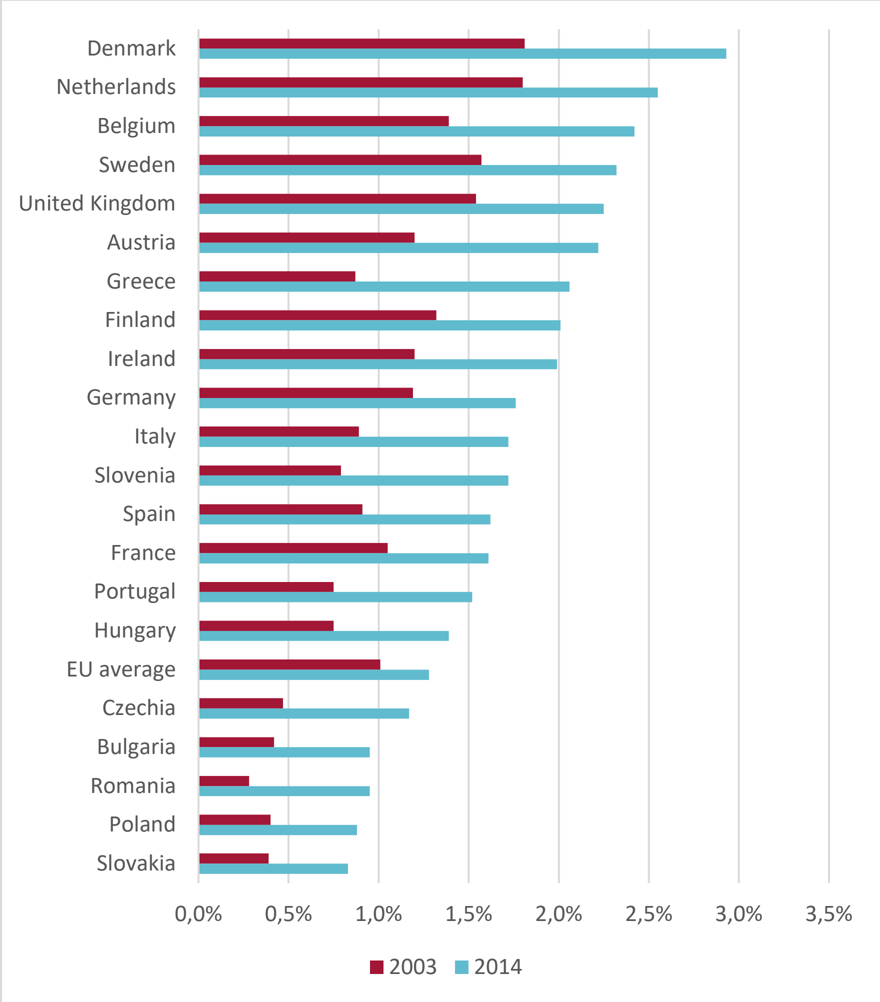
In *mathematics*, another specialisation area for the EU, the quality of its scientific output is improving, catching up with the US, but again China is forging ahead faster, particularly at the top end.

Life sciences shows different trends. In *medical sciences*, a field of specialisation for the EU and especially for the US, but not for China, the EU has managed to substantially improve the quality of its research, most pronouncedly at the top end. Nevertheless, the US is still the major producer of the highest-cited publications and is forging ahead. The quality of Chinese scientific output is improving in this area, but there is still a substantial gap between China and the US.

1.2.5. Scientific excellence by EU country

Figure 8 shows that the increase in the excellence of the EU's scientific knowledge base (as measured by the share of its publications in the top 1 % of cited publications) holds across all member states. The top countries – the UK, Sweden, the Netherlands, Denmark and Belgium – have increased their presence among the top 1 % and remain top countries. But all EU countries have improved, even those at the bottom.

Figure 8: Share of publications in global top 1 % of cited publications

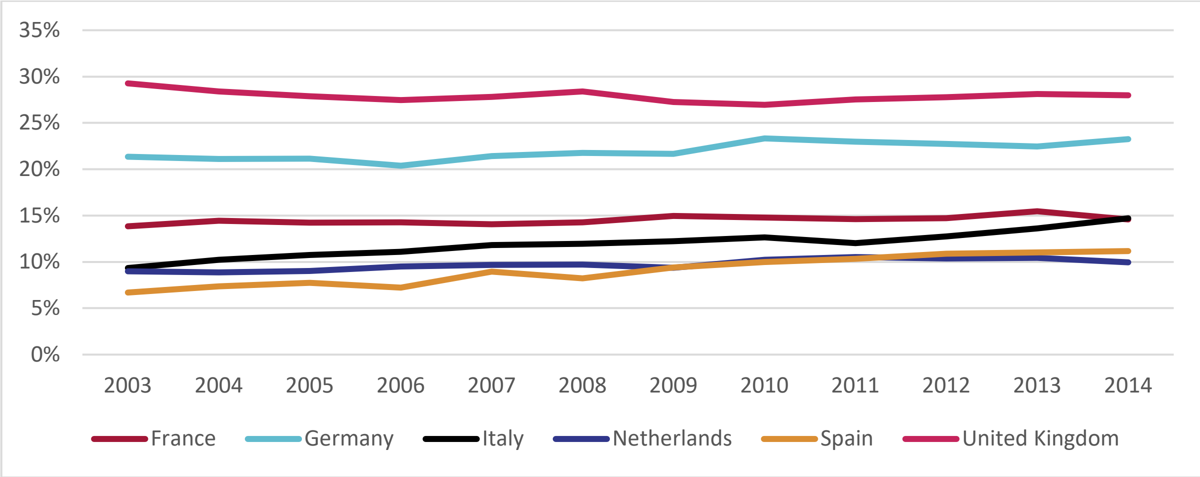


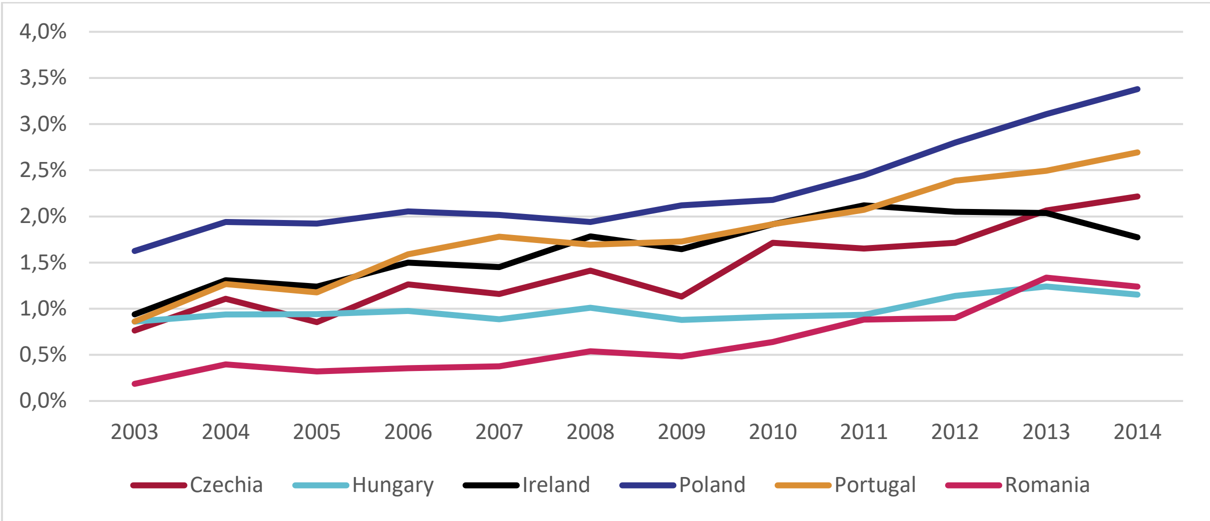
Source: Bruegel calculations based on National Science Foundation (2018)

Note: only EU countries with a sufficient number of publications are reported (at least 1000 publications per year).

Figure 9 shows which member states the top 1 % of cited EU publications come from. The UK is the major contributor to the EU's top 1 % of articles, followed by Germany, France and Italy. Over time, the UK's share has diminished somewhat. Although the current and former Cohesion countries are still minor contributors to the EU's top 1 % of articles, their rising research excellence has made them into more important contributors to the EU's top 1 % of articles. This is particularly the case for Poland and Portugal.

Figure 9: Origin of EU top 1 % cited publications





Source: Bruegel calculations based on National Science Foundation (2018).

Note: Figures show contribution by EU member states

1.2.6. Rankings of universities

Another indicator of research excellence is the position of universities in global rankings focusing on research excellence. One of the most famous such rankings is the Academic Ranking of World Universities (ARWU, or better known as the Shanghai Ranking). ARWU uses six indicators to rank universities on their research performance: the number of alumni and staff winning Nobel Prizes and Fields Medals; the number of highly-cited researchers; the number of articles published in the journals Nature and Science; the number of articles indexed in the Science Citation Index Expanded and the Social Sciences Citation Index; and a *per-capita* performance indicator, which is the scores of the previous five indicators divided by the number of academic staff.

The following tables show trends in the performance of the EU+[2] relative to the US and China in the ARWU. It should be noted that ARWU only ranks universities. It does not include other (public) research organisations.

[2] EU+ refers to all 28 member states of the EU and Switzerland, Israel and Norway.

For continental Europe, this excludes a significant part of the research landscape, particularly in Germany (Fraunhofer Society, Max Planck Institutes, Helmholtz Association, Leibniz Association), France (CNRS) and Italy (CNR).

Table 5 shows how US universities dominate the top of the ARWU, occupying 16 out of the top 20 places. In line with the evidence on improvements to its research quality, the EU has improved its ARWU position, including at the top. It doubled the number of its institutions in the top 20 from 2 (both from the UK), to 4 (3 from the UK, 1 from Switzerland). China is not yet in the top 20, but is slowly making its way to the top, taking three positions in the top 100: Tsinghua University, Peking University and Zhejiang University.

While overall neither the EU+ nor China has been able to substantially challenge the US universities for top positions, there is more turbulence lower down in the ranking, particularly when in specific fields (Table 6). While US universities still have the lead in all fields (most strongly in medical sciences and social sciences, least strongly in engineering), EU+ universities have been able to take top 100 places from the US in all fields, most notably in life sciences, medical sciences and the social sciences. The weaker position of the EU+ in engineering should be considered in the context of the exclusion from the ranking of German public research organisations, which are engineering strongholds.

In line with the trends for scientific publications, the rise of Chinese universities is most pronounced for engineering, for which Chinese universities occupy 27 of the top 100 places (and five places in the top 20).

Table 5: Country/region's share of universities in Shanghai ranking

		EU+	US	China
Share in top 20	2012	10	85	0
	2018	20	80	0
Share in top 100	2012	33	53	0
	2018	35	46	3
Share in top 200	2012	39	42.5	3.5
	2018	41.5	34.5	7.5
Share in top 500	2012	41	30	8
	2018	39.2	27.8	12.4

Source: Bruegel based on ShanghaiRanking Consultancy (2018).

Note: EU+ refers to all 28 member states of the EU and Switzerland, Israel and Norway.

Table 6: Country/region's share of universities in Shanghai Top 100 ranking; by scientific field

		EU+	US	China
Sciences	2011	35	52	1
	2016	35	44	7
Engineering	2011	22	46	13
	2016	24	29	27
Life Sciences	2011	32	57	0
	2016	38	49	0
Medical Sciences	2011	34	54	0
	2016	44	44	0
Social Sciences	2011	19	71	1
	2016	31	57	1

Source: Bruegel based on ShanghaiRanking Consultancy (2018).

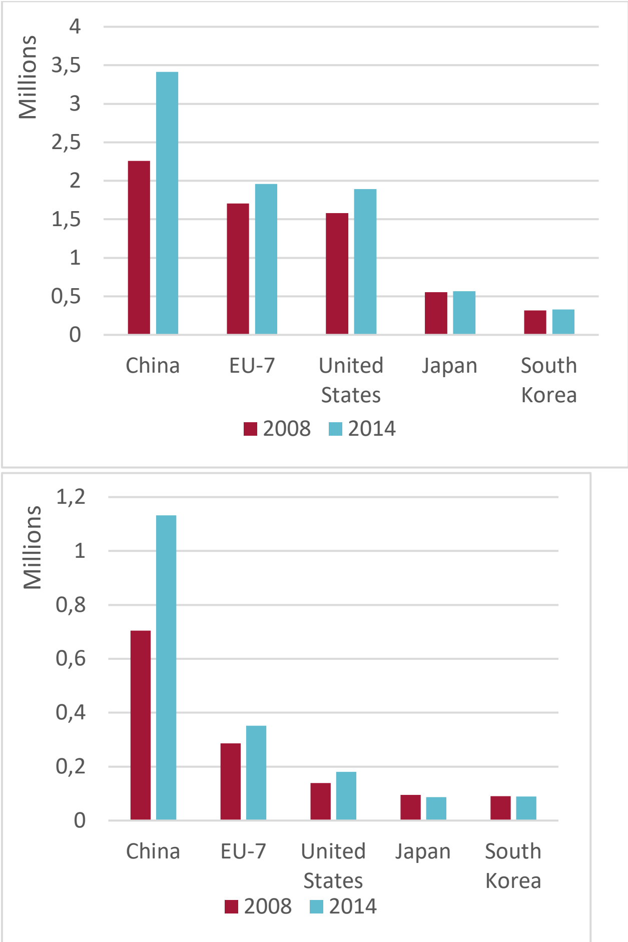
Note: EU+ refers to all 28 member states of the EU and Switzerland, Israel and Norway.

1.2.7. Training the next generation of researchers: students and PhDs

Investing and building capacity in science and in knowledge- and technology-intensive industries requires a growing R&D workforce. Educating the next generation of researchers is thus also a policy priority. Figure 10 and Figure 11 show the trends in the numbers of students and PhDs graduating.

While the numbers of first university degrees and PhD degrees have increased in the EU and the US (while stagnating in Japan), China has massively increased the number of degrees it awards. This is particularly the case for first university degrees in *engineering* (which includes *computer sciences*), consistent with China's improving scientific performance in this field. While Western governments are concerned about lagging student interest in this area, which is considered vital for knowledge-intensive economies, the number of university degrees awarded in this field in China has risen very rapidly.

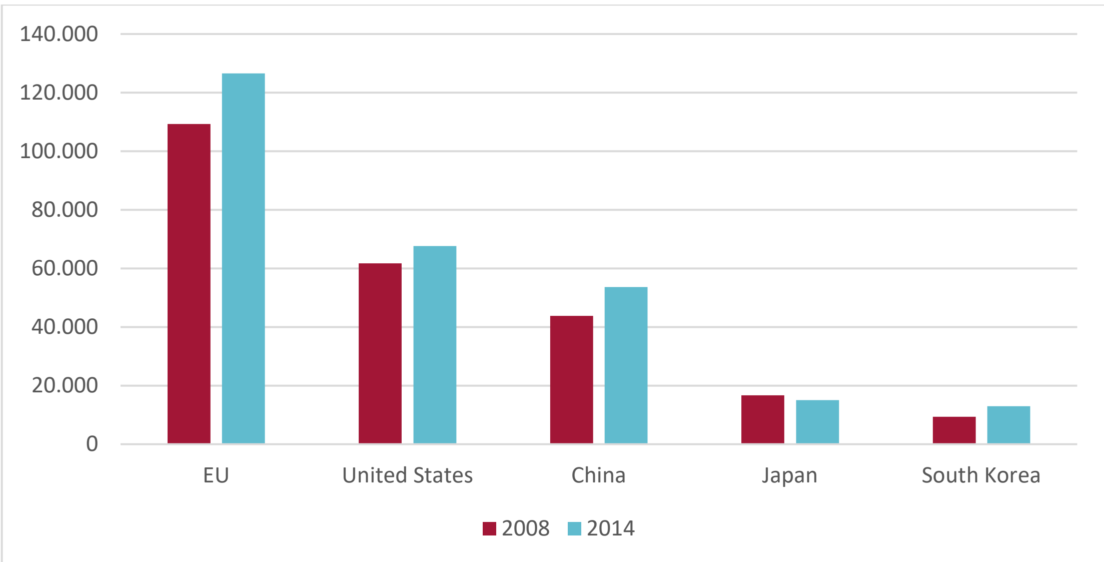
Figure 10: First University Degrees by country/region; all fields (left) and Engineering & Computer Sciences (right)



Source: Bruegel based on National Science Foundation (2018).

Note: EU-7 are France, Germany, Italy, Spain, Netherlands, Poland and the United Kingdom.

Figure 11: S&E PhD degrees by country/region (all fields)



Source: Bruegel based on National Science Foundation (2018).

Note: Data for doctoral degrees use ISCED 2011 level 8. Data do not include health fields.

1.3. Pathways to research excellence in a multipolar global S&T landscape

The trend towards a more multipolar global science landscape could present opportunities for faster advancements in scientific knowledge and greater opportunities from specialisation and from building research excellence. These opportunities arise from being able to source from a large pool of global talents when building scientific capacity, and from a wider range of possibilities for international collaboration and utilisation of major foreign research facilities. But for these opportunities to materialise, countries need to be open to be both host and home for global knowledge flows. In this section, we examine how open different countries are in terms of attracting and sending out students and researchers, and in terms of international collaboration in science.

1.3.1. International collaboration in science

Table 7 shows how international scientific collaboration, as measured by the number of internationally co-authored scientific publications, has been on the rise worldwide and in every major country considered. The size of a county is a factor that can explain variation in international cooperation. It is easier for researchers in large countries with a large scientific sector (e.g. the US) to find suitable co-authors domestically. Nonetheless, variation in internationally co-authored publications between countries of similar size is informative about the extent of scientific openness. Although collaboration has increased in China, it remains one of the least open science systems in the world. But Japan is also among the least internationally open.

Compared to Asia and also to the US, most EU countries are much more inclined towards international collaboration, and increasingly so. This is most pronounced for Switzerland and smaller EU countries including Sweden and the Netherlands. But even the larger EU countries, including France, Germany, Spain and Italy, count on international collaboration for about half of their scientific output. The UK stands out as among the large European countries as the most inclined to collaborate internationally. We will examine in section 3 how the EU's framework programmes have helped to stimulate collaboration among EU countries.

Table 7: Internationally co-authored publications as a share of a country's total publications

	2006	2016
World	17 %	22 %
France	42 %	55 %
Germany	42 %	51 %
Italy	36 %	47 %
Netherlands	47 %	62 %
Poland	29 %	31 %
Spain	36 %	51 %
Sweden	48 %	64 %
United Kingdom	41 %	57 %
Switzerland	57 %	69 %
China	13 %	20 %
Japan	20 %	28 %
United States	25 %	37 %

Source: Bruegel based on National Science Foundation (2018).

Whether international collaboration in science is a lever for building research excellence will depend on whom one collaborates with and the extent to which partners offer access to complementary research excellence.

Table 8Table 8 examines the extent to which selected countries are open to collaborate with each other. The numbers in the table show the expected intensity of collaborative ties between two countries, taking into account the attractiveness (scientific size) of both countries as partners for international collaboration. Numbers above 1 reflect stronger than expected ties; numbers below 1 reflect weaker than expected ties.

The table shows that although all the large EU countries have strengthened their ties to the US, they are still under-represented in research collaboration with the US. The US-China tie has also grown in importance and is now above par. For China, only the collaborative tie with US has strengthened and is now above par. Also above par, though not strengthening, are the ties the US has with South Korea and Singapore (not shown in Table 8). For the large EU countries, ties with China, although becoming more important, are only slowly becoming stronger but remain below par (for Germany, there has even been a decrease in China's relative importance as a research partner). The UK is the large European country most connected to China, although also still below par.

Table 8: Indexes of internationally co-authored S&E publications, worldwide

	US	France	Germany	UK	China	Japan
France						
2006	0.58					
2016	0.66					
Germany						
2006	0.69	0.87				
2016	0.74	1.16				
UK						
2006	0.71	0.82	0.83			
2016	0.77	1.01	1.07			
China						
2006	0.88	0.35	0.46	0.58		
2016	1.19	0.38	0.44	0.62		
Japan						
2006	0.89	0.48	0.51	0.49	1.51	
2016	0.85	0.78	0.78	0.65	1.09	
S. Korea						
2006	1.23	0.27	0.32	0.32	0.95	1.88
2016	1.23	0.44	0.56	0.45	0.90	1.83

Source: Bruegel based on National Science Foundation (2018).

Note: The index of collaboration is calculated as follows: ICxy = (Cxy/Cx)/(Cy/Cw), where ICxy = index of collaboration between country x and country y, Cxy = number of papers co-authored between country x and country y, Cx = total number of international co-authorships by country x, Cy = total number of international co-authorships by country y, and Cw = total number of international co-authorships in the database.

Table 9 focuses on a selection of the collaborative ties among the EU+ countries with sufficient numbers of publications. (Appendix A.4 contains a full list of bilateral intra-EU+ ties). It shows how virtually all bilateral ties among EU+ countries have become stronger over time and are now all above par, often very substantially. These results are therefore supportive for the increasing integration and gradual building of a European Research Area.

Table 9: A selection of Indexes of internationally co-authored S&E publications, Intra-ERA

Country dyad	2006	2016
Denmark - Norway	4.31	4.94
Sweden - Norway	3.86	4.42
Finland - Sweden	3.97	4.15
Finland - Norway	3.31	3.79
Denmark - Sweden	3.62	3.65
Denmark - Finland	2.73	3.16
Hungary - Poland	1.84	4.95
Austria - Hungary	2.47	4.93
Austria - Czech Republic	2.36	3.64
Austria - Germany	2.09	2.63
Austria - Switzerland	1.87	2.51
Germany - Switzerland	1.66	2.04
Ireland-UK	2.04	2.16
Netherlands-UK	1.21	1.50
Germany - Spain	0.87	1.19
France - Germany	0.87	1.16
Spain - United Kingdom	0.99	1.16
Germany - United Kingdom	0.83	1.07
France - United Kingdom	0.82	1.01

Source: Bruegel based on National Science Foundation (2018).

Finally, we look at whether international co-publications are of higher research quality as measured by how often they are cited compared to other scientific publications. This will allow us to evaluate whether international collaboration is a lever for building research excellence. We report on the evidence for EU researchers and their extra-EU collaborations. An examination of publications registered on Scopus (Elsevier 2017) shows that EU28 publications written with extra-EU collaborators had a larger impact as measured by the Field-Weighted Citation Index (FWCI)[3] than EU28 publications in general.

[3] The FWCI *"compares the actual number of citations received with the average number of citations for a publication of the same subject, document type, and publication year. It therefore accounts for differences in citation practices between subjects, and is benchmarked against*

On average, a national publication written by EU28 authors is 20 % more cited than the world average. But a publication written by an EU28 author with extra-EU partners is more impactful: it is on average 75 % more often cited than the world average. This evidence suggests that international collaboration is indeed a pathway towards research excellence for the EU.[4]

For the EU13[5], collaboration with external partners (both other-EU and extra-EU) provides an even more important pathway to excellence While their national publications measured by FWCI are significantly below world average (with an FWCI around 0.6), their publications in collaboration with external partners are 50 % more likely to be cited.

1.3.2. Attracting international talent: the international mobility of researchers

Another aspect of openness in building excellence is the ability to attract international research talent. The right panel of Table 10 illustrates the importance of inward and outward flows of active researchers (i.e. publishing authors), while the left panel assesses the quality of the different mobility profiles of authors. The left panel allows us to check the quality increments associated with mobility and how important the mobility of active researchers is in building research excellence.

the world average, set at 1.00. For instance, an FWCI of 1.24 means that a publication in this subject is cited 24% more often than expected compared to the world, while a value of 0.90 would mean the publication is cited 10% less than the global average" (Elsevier 2017, p. 8).

4 It is also plausible that the best researchers tend to collaborate the most internationally. In that case, excellence also drives international cooperation. Hence, causality might run both ways: excellent researchers cooperate internationally and cooperation improves the quality of researchers (through learning) and research (through optimal inputs).

5 The 13 countries that have joined the European Union since 2004: Bulgaria, Croatia, Cyprus, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Malta, Poland, Romania, Slovakia and Slovenia.

Table 10: International mobility of researchers and their quality impact

	Expected citation impact of scientific authors, by mobility profile in 2016				International mobility of scientific authors, as share of all authors, 2016			
	New inflows	Returnees	Stayers	Outflows	New inflows	Returnees	Stayers	Net flow
Switzerland	2.38	2.30	2.11	2.27	11.14	2.86	86.01	0.83
United Kingdom	2.25	1.92	1.98	1.96	7.28	2.78	89.94	0.15
Germany	2.26	2.07	1.70	2.11	4.57	2.29	93.13	-0.54
France	1.80	1.88	1.65	1.93	3.78	2.43	93.79	-0.98
Spain	1.85	1.68	1.36	1.98	2.11	2.28	95.61	-1.56
Italy	1.60	1.55	1.33	1.95	1.37	1.64	96.99	-1.23
Netherlands	2.13	2.15	1.91	2.16	4.70	2.41	92.89	-0.61
Denmark	2.19	2.15	1.82	2.23	6.32	2.17	91.51	0.73
Sweden	2.37	2.04	1.70	1.96	6.21	2.45	91.35	0.45
USA	2.35	2.10	2.09	1.86	3.85	1.55	94.59	-0.02
Japan	1.79	1.69	1.18	1.83	1.25	1.10	97.65	-0.40
China	1.60	1.39	1.00	1.92	1.54	1.25	97.21	0.35
Korea	1.61	1.47	1.16	1.72	1.91	1.26	96.84	-0.11

Note: The left panel shows the citation impact of scholars that enter, return, remain or leave a specific country. The right panel shows modes of mobility among the total population of scholars.

Source: Bruegel based on OECD (2018); OECD calculations based on Scopus Custom Data, Elsevier, Version 4.2017; and 2015 Scimago Journal Rank, July 2017.

China, like other Asian economies (Japan and South Korea), has a relatively closed science system with respect to the mobility of its scientific authors, confirming the evidence on international scientific collaboration. These countries have the highest shares of 'stayers' among their authors. Those stayers are however low in quality, barely at the world average and definitely much weaker than those who leave to pursue opportunities elsewhere and those that enter China, Japan or South Korea. Researchers returning to these countries also outdo the stayers, suggesting their experience in other countries improves their research quality. Overall, for these countries, becoming more open would be a major step in improving their research standards.

Compared to Asia, the US is much more open in terms of the mobility of its scientific authors, and in particular has a higher share of new inflows. As the US has traditionally been more open, it includes among its stayers a substantial share of former inflows. Most pronounced for the US is the high quality of its new inflows: the US manages not only to attract the most talented authors compared to other countries, but these new recruits are also even better than its already high level of stayers or returnees. And although outflows of researchers from the US exceed inflows, the outflow is of lower quality.

So overall, the US's high score in terms of research quality seems strongly related to its openness in a virtuous circle: because of the high quality of its stock of active researchers, it is able to attract the best talents, and these talents help to further reinforce the quality of the stock of active researchers, further contributing to the attractiveness of the US as a location for foreign talent.

European countries differ substantially in the mobility patterns of their active researchers. The most open science system is Switzerland, which has the highest share of 'movers'. Although the quality of its outflow is very high, the quality of its inflow is even higher, contributing to overall very high Swiss research quality. Switzerland is therefore a strong (if not stronger than the US) example of a virtuous circle in terms of the benefits of openness for excellence. A second tier of open European countries includes the UK and Northern Europe (the Netherlands, Sweden, Denmark), which also exhibit substantial mobility and high quality of inflows.

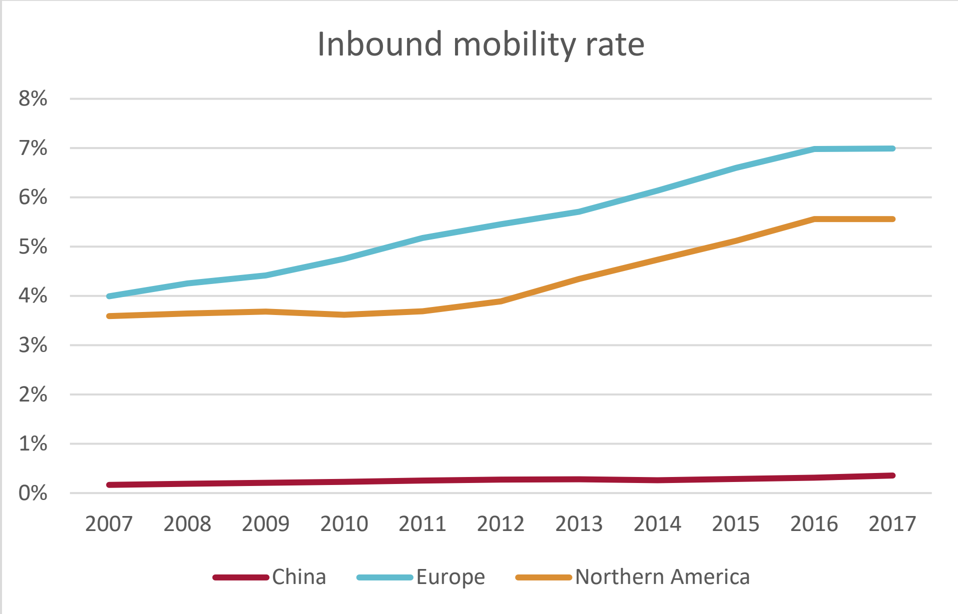
Compared to this tier of open European countries, Germany and France are less open with smaller shares of movers. Although their inflows are of higher quality than their stayers, their outflows are of high quality. This high quality of outflow is even more the case for Spain and Italy. Not only do they have a higher share of stayers, their stayers are of lower quality. And although the influx of new and returning talents is greater, the quality of these inward talents is lower than for other countries and definitely less than the talents moving out.

1.3.3. Attracting international students

Further evidence on openness to research excellence comes from the mobility of students, particularly graduate and PhD students, which are the next generation of researchers. Graduate and doctoral education generates new knowledge by linking specialised education and hands-on research experience. Such experience prepares each new generation of researchers and highly skilled workers for academia and for other sectors of the economy, including industry, government and non-profit organisations. Being able to attract the best of these students from abroad might be an important channel for getting the best research talent, particularly if these foreign students also stay on after graduating.

The share of students that is internationally mobile has been on the rise (OECD, 2016) with the proportion of internationally-mobile students higher at graduate than at undergraduate level (OECD, 2016). The share of foreign students is highest in Europe (Figure 12). Top destinations in Europe for international students include the UK, France and Germany. China is not a destination for foreign students.

Figure 12: Shares of foreign students in tertiary enrolments (percentage)



Note: Number of students from abroad studying in a given country, expressed as a percentage of total tertiary enrolment in that country.

Source: Bruegel based on UNESCO Education Statistics (2018).

In view of the importance of attracting foreign students, the US keeps track of the enrolment of foreign students. Science and engineering (S&E) graduate students with temporary visas have become an increasingly important part of US graduate enrolment. In 2015, about 240,000 international students on temporary visas were enrolled in US S&E graduate programmes, representing 36 % of total US graduate enrolment (up from 26 % in 2008). In some fields, including computer sciences, engineering, mathematics and statistics, and economics, a majority of enrolment is foreign (National Science Foundation, 2018).

International students on temporary visas earned more than 15,000 S&E doctorates in the US in 2015, up from about 8,000 in 2000, with a share of 34 %, up from 30 % in 2000. In engineering, mathematics, computer sciences and economics, these students earned more than half of the degrees.

Table 11: Share of PhDs awarded in the US to non-US citizens

	2000	2008	2015
All S&E fields	30 %	34 %	34 %
Engineering	51 %	61 %	56 %
Mathematics and Computer Sciences	47 %	56 %	53 %
Physical Sciences	38 %	45 %	40 %
Social and Behavioural Sciences	15 %	20 %	18 %
Biology & Medicine	24 %	19 %	22 %
Economics	53 %	67 %	56 %

Source: Bruegel based on National Science Foundation (2018).

Chinese students obtained more than a quarter of all the international S&E doctorates obtained in the US. The number of S&E doctorates earned in the US by students from China has increased more than sevenfold in the last 20 years. This growth coincides with the growth in the number of undergraduate, graduate and PhD students trained in China. Larger numbers of students trained in China therefore does not seem to have crowded out the flow into the US, on the contrary.

More than one third of Chinese students in the US earn their S&E doctorates in engineering, a proportion substantially higher than for US citizens (for whom the share of engineering doctorates is less than 16 %).

Compared to Asian and Chinese students, European students earned far fewer US S&E doctorates and tended to focus less on engineering than their Asian counterparts. The largest numbers of European students who achieve S&E doctorates in the US come from Germany, Italy, Romania, Greece and France, in that order. The number of EU13 students earning S&E doctorates at US universities nearly doubled between 1995 and 2007, but has declined since then. The number of US doctorate recipients from other EU countries has been more stable overall.

Being able to attract the best student talents matters, particularly if these students stay after they graduate. The US keeps track of these stay rates. Table 12 shows that about 70 % of temporary visa holders earning a US S&E doctorate are still in the United States 5 years and 10 years later. Chinese graduates have the highest stay rate, with 90 % of those who graduated in 2005 still in the US 10 years later. In terms of their intentions to stay immediately after graduation (Table 12, left panel), a stable trend over time is evident, with Chinese students most likely to have firm plans to stay after graduation. This numbers are even somewhat higher in the field of *engineering*, the most frequently chosen field for Chinese students. The share of Chinese students with plans to stay has fallen somewhat over time but still remain high.

Table 12: Shares of doctoral students in the US from selected countries who plan to stay after graduation

	Plans to stay (%)			5-year stay rate	10-year stay rate
	2004–07	2008–11	2012–15		
All countries	**76.7**	**75.5**	**75.4**	**70**	**70**
China	91	85.6	83.4	85	90
India	89.1	86.6	86.5	83	85
South Korea	69.5	68.1	65.7	66	56
Germany	69.2	66.8	61.6	64	65

Source: Left panel: National Science Foundation (2018) based on SED (Survey of Earned Doctorates). Right panel: Bruegel based on National Science Foundation (2018).

Note: Left panel: Plans of foreign recipients of U.S. doctorates to stay in the United States as share of all recipients in base year. Right panel: Temporary visa holders receiving S&E doctorates in 2010 and 2005 who were in the United States in 2015, by country of citizenship at time of degree.

1.4. Towards a multipolar technology and corporate R&D world

1.4.1. Corporate R&D

Before we look at corporate R&D trends, it is important to stress how concentrated private sector R&D is in few large firms. The 2500 top global corporations listed in the European Commission Joint Research Centre's R&D Scoreboard represent more than 80 % of total worldwide R&D in the private sector (Hernández *et al*, 2018). Among these 2500 top R&D spenders, there is further concentration among a handful of leading firms that dominate the R&D landscape (see Veugelers (2018) for more evidence and analysis on this concentration, trends and impact). With this high degree of concentration, we can concentrate on who the large corporate R&D spenders are and examine trends in their expenditures to learn about the aggregate trends in corporate R&D.

US firms are well-positioned in the Scoreboard of the world's largest R&D spenders, representing about one third of all 2500 Scoreboard firms, and representing about 40 % of all Scoreboard R&D spending (table 13). Over time, US firms have not lost their dominant position. On the contrary, they seem to have further consolidated their position. EU firms hold about a quarter of all Scoreboard places, representing somewhat more than a quarter of all scoreboard R&D spending. EU companies more than US companies ceded their positions in the Scoreboard in the face of the rise in numbers of Scoreboard firms from China. China's rise in the ranks of Scoreboard firms is impressive. In a short period, they increased their share of Scoreboard places to 18 %, surpassing Japan. But in terms of R&D expenditure, Chinese firms on average are still small.

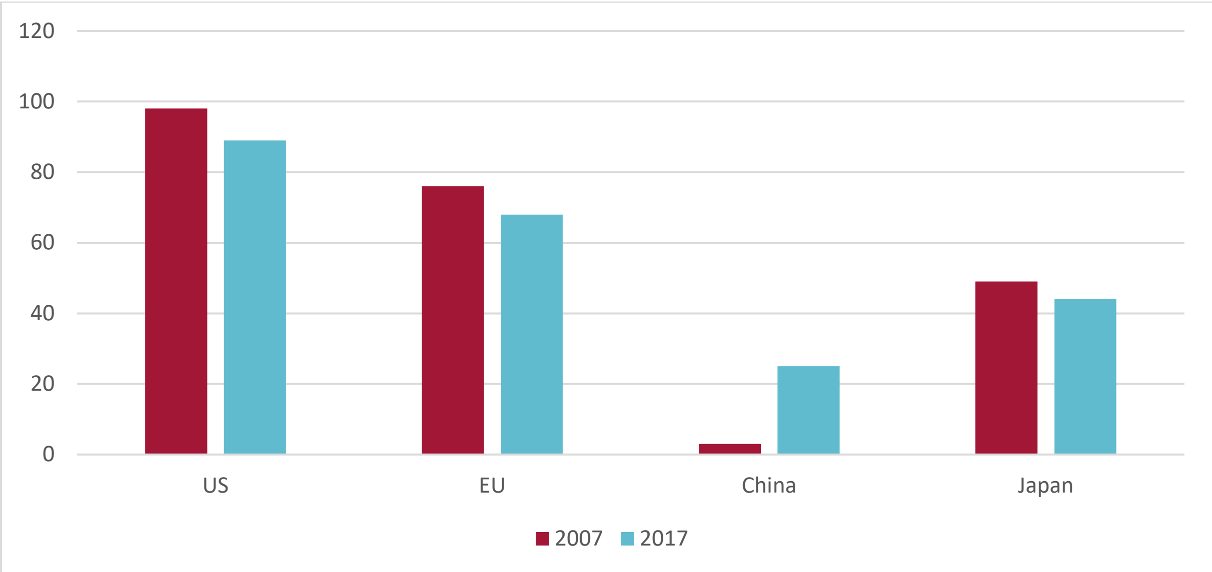
Table 13: The world largest R&D spending firms; by nationality

	China	EU	US	Japan
Number of Scoreboard companies in 2018	438	576	778	339
Number of Scoreboard companies in 2014	199	633	804	387
Share in World R&D expenditure in 2018	10 %	28 %	39 %	14 %
Share in World R&D expenditure in 2014	7 %	30 %	36 %	16 %
R&D-to-Sales Ratio 2018	2.8	3.4	6.3	3.4

Source: Bruegel calculations based on Hernández et al (2018).

As the distribution of Scoreboard firms' R&D expenditures is highly skewed (the top 10 % biggest spenders – i.e. the top 250 Scoreboard firms – accounted for 71 % of all Scoreboard R&D spending in 2015), it is interesting to look at the geographic shift in this top 10 %. Figure 13 shows that in 2017 the US dominated the top 10 % even more than the top 2500 list. The EU and Japan are also overrepresented at the top, while China is still underrepresented but improving its share within the top segment. Figure 14 differentiates the geographical distribution of top R&D spenders for specific industries. The rise and leading position of Chinese firms is most notable in digital sectors. The most notable Chinese firm in the Scoreboard is Huawei, which climbed in a very short time to fifth position in the 2018 Scoreboard, being the largest R&D spender in its sector (technology hardware).

Figure 13: Geographical distribution of the world's largest R&D spending firms



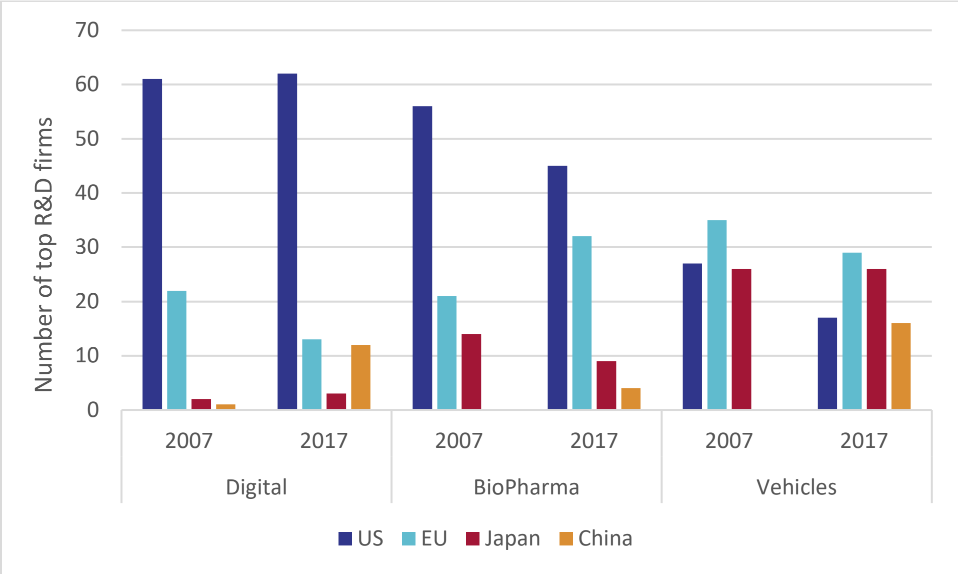
Source: Bruegel based on Hernández *et al* (2008) and Hernández *et al* (2018)

Note: Figure shows the geographical distribution of the firms that are among the 250 highest R&D spenders globally.

Huawei is an illustration of a more general phenomenon of Chinese corporate R&D being directed to digital (both hardware and software). China is much less present in the *BioPharma* sector, another big R&D sector in the Scoreboard.

The US and Europe specialise in *BioPharma*. For European corporate R&D, the most important sector is *Automotive*, while the digital sectors are not European strongholds. The corporate R&D specialisation patterns across sectors are strongly correlated with the specialisation patterns of the various regions and their positions at the scientific frontier.

Figure 14: Geographical distribution of the world's largest R&D spending firms in specific industries



Source: Bruegel based on Hernández *et al* (2018)

Note: Figure shows the geographical distribution of the firms that are among the 100 highest R&D spenders in a specific industry.

The specialisation patterns in sectors also reflect who dominates at the top of the distribution in these sectors. In digital sectors, US firms are clearly leading the pack while China is growing quickly and Europe is falling further behind. In *BioPharma*, the EU's position is increasing while the number of top US firms is declining. Similarly, the number of Chinese companies is growing while Japan is losing ground. In *Automotive*, the most important sector for the EU in terms of corporate R&D, a large number of Chinese companies have established themselves among the top R&D spenders within the last 10 years. This sector could have turbulent times ahead, with the advent of electric and autonomous driving, among others developments. It remains to be seen whether the automotive sector in Europe is able to maintain its leading position in this sector (see Tagliapietra and Veugelers, 2019, for an analysis of this).

1.4.2. Patenting

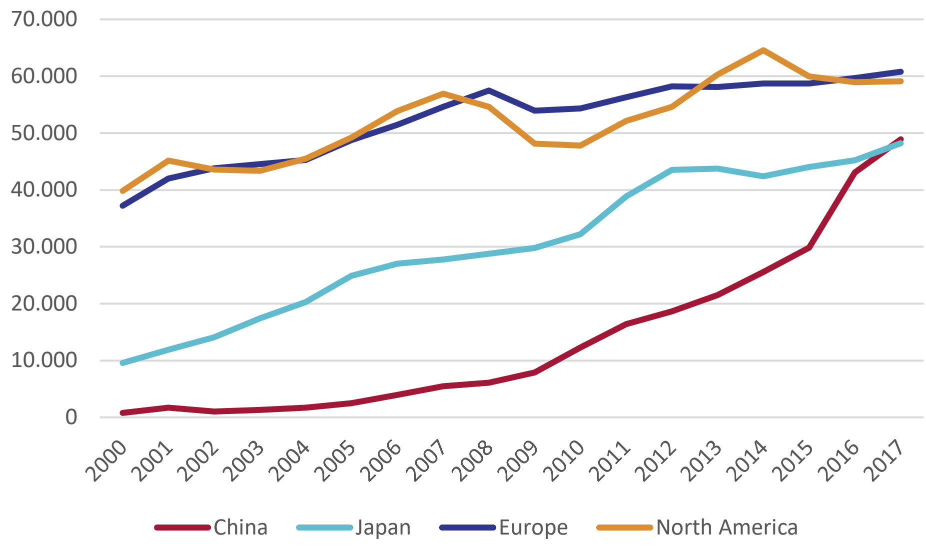
A last set of evidence to look at when examining research excellence is patent information. There is extensive publicly available administrative data on patents and their inventors. Patent data, despite its well-known limitations, provides unique and useful insights into the inventions deemed valuable enough to patent. We use this patent data to trace shifts in where inventive activities take place. For international comparability, we use PCT applications[6] (Figure 15). Europe and North America have roughly equal shares and are in the lead with respect to patent applications. While PCT applications

[6] The Patent Cooperation Treaty (PCT) allows inventors to receive protection for their inventions through a single patent application procedure that covers all states that have signed the treaty.

have increased in almost all countries, the country with the largest increase in PCT applications is China, a phenomenon that is in line with its rise in scientific power and its increasing investment in R&D.

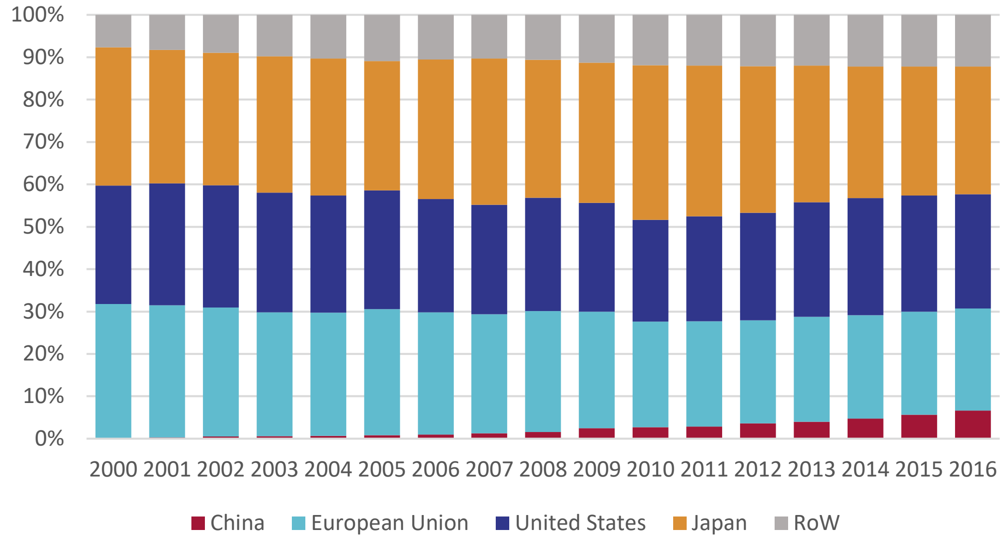
Beyond counting the number of patents, it is also important to look at the quality of patents. Many patent applications represent no or little commercial value, and there is only a handful truly important patents. There are not yet standard indicators for measuring the quality of patents. One way to measure the quality of patents is to look at those patents for which protection in all major markets is sought: US, Europe and Japan. These are the so-called 'triadic' patents. Figure 16 shows that on this indicator, US, Europe and Japan are in a clear lead, with China still trailing far behind, although it is starting to make inroads.

Figure 15: Patent Cooperation Treaty (PCT) applications by origin



Source: Bruegel based on WIPO (2019a).

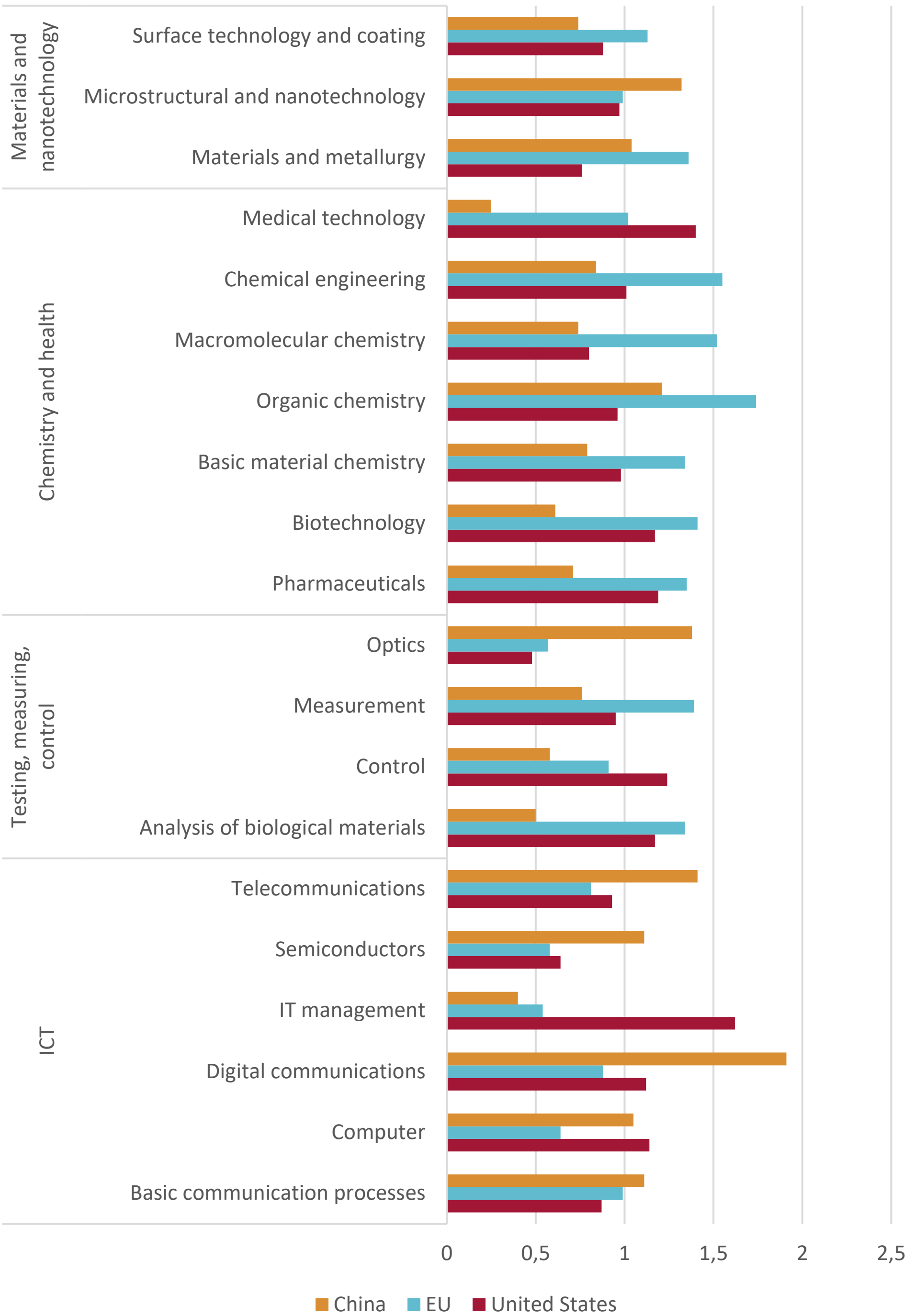
Figure 16: Share of applicant countries in triadic patent families



Source: OECD (2018a).

The patent data also allows us to look at which technology areas different countries specialise in. Figure 17 shows selected patent activity indexes, which indicate the extent to which a country's patents are concentrated in a particular technology. It is an output measure of specialisation, assessing the share of a country's patents produced in each technological area.

Figure 17: Patent activity indexes for selected technologies for selected economies: 2014–16



Source: Bruegel based on National Science Foundation (2018).

Note: Patents are categorised according to information about inventors. A patent activity index is the ratio of a country's share of a technology to its share of all patents. A patent activity index greater than 1.00 indicates that the country is relatively more concentrated in the technology area. An index less than 1.00 indicates that the economy is relatively less concentrated in the technology area.

Europe's specialises in nine technologies in terms of patenting, six in the chemistry and health category. Europe's relatively high concentration in pharmaceuticals and biotechnology coincides with the EU's strong science position in life sciences and the strong position of its corporates in pharmaceutical R&D. The EU is relatively less concentrated in all technologies in the ICT (information and communications technology) category.

US patenting activity is relatively highly concentrated in technologies in the ICT category, including in IT (information technology) management. The US is also strong in biotechnology, pharmaceuticals and medical equipment.

China is relatively highly concentrated in four technologies, including two technologies in the ICT category – telecommunications and digital communications.

Like the corporate R&D landscape, patents are highly concentrated. In 2014, the top 10 % of corporate R&D investors accounted for about 60 % of IP5 patent families (inventions patented in the five top IP offices) (OECD, 2018a). China's ZTE and Huawei are the two largest PCT applicants (WIPO, 2019b). The top corporate R&D investors in the computers and electronics industry are, by far, the most reliant on intellectual property (IP) rights and account for about one-third of total patent filings by top R&D investors. For the ICT technologies with the highest growth rates, five economies accounted for 69 % to 98 % of the top 20 (2012-2015). Japan and South Korea together account for 21 % to about 70 % of all patenting activities in these growing ICT fields. China also belongs to the top five economies that are developing technologies in most growing ICT fields. While the United States has led the development of ICT technologies in some of these fields, only a few European economies feature among the top five leaders of some growing ICT fields, confirming Europe's relatively weak position in digital technology development.

Artificial Intelligence (AI) is one such growing ICT technology: AI patenting in the five top IP offices (IP5), increased by 6 % per year on average between 2010 and 2015, which was twice the average annual growth rate observed for all patents.

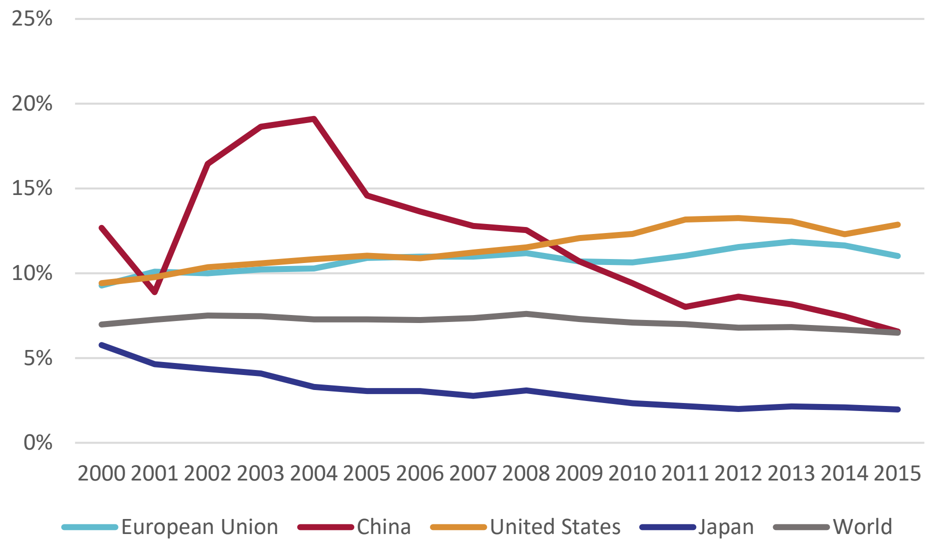
The top 2000 corporate R&D investors own 75 % of the IP5 patent families related to AI. Corporations based in Japan, South Korea, Chinese Taipei and China account for about 70 % of all these AI-related inventions. US-based companies account for 18 %, leaving only a marginal share for European corporations (3 % for German companies, 2 % for French) (OECD, 2018c).

1.5. Making the most of a multipolar technology and corporate R&D world

The emergence of a more multipolar technology and corporate R&D world poses both challenges and opportunities in terms of building research excellence. There are clear challenges in the context of building competitiveness in high-technology areas. Competition for market share, funding and S&T resources is becoming more intense at the global scale, but the increased global technology capacity offers opportunities for international collaboration and for sourcing foreign talents for inventive performance.

We can use the patent data to identify to what extent patented technology inventions were developed in collaboration between national and foreign co-inventors. Figure 18 shows the share of foreign co-inventions and Figure 19 shows the share of foreign-owned and foreign-invented patents. These charts show how China was initially when it started its growth path, the most open in terms of international technology co-invention and in terms of foreign ownership and foreign inventions. But gradually along its development path, it has become more 'closed', indiginous, over time. Japan and South Korea have traditionally been much more closed in their development of technology. Europe has been much more open in terms of co-inventions and foreign ownership and foreign invention, and the US even more so. And while China has become less open, Europe and the US have opened up even more.

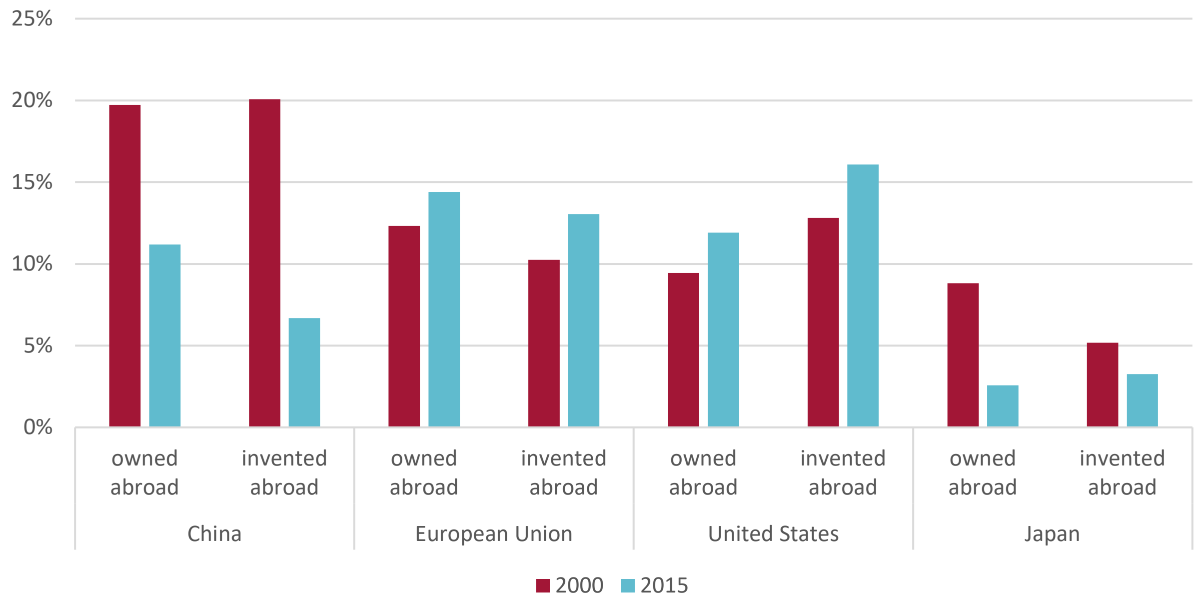
Figure 18: Share of patents filed under the PCT that have foreign co-inventors



Note: Patents with at least one foreign co-inventor as a share of total patents invented by resident(s) of country and filed under the Patent Cooperation Treaty.

Source: OECD (2018b).

Figure 19: Share of patent applications filed under PCT that are either invented abroad or owned by foreigners



Source: Bruegel based on data from OECD (2018b).

The EU's international co-inventions are accounted for partly by intra-EU activity, reflecting the power of the European Research Area. Nevertheless, most EU co-inventions involving foreign partners are collaborations with the US, which is the most important partner for EU co-inventions.

The US is also by far the most important partner for China for international technology cooperation, with more than twice as many China/US co-invented patent applications than China/EU co-inventions. Despite their geographical proximity, there is very little co-invention between Japan, South Korea and China. For Japan and South Korea, the US is by far the most important partner for international technology cooperation.

Table 14: Number of patent applications with foreign co-inventors

in 2015	China	EU	Japan	S. Korea
European Union	421	3,093		
Japan	119	234		
South Korea	41	82	49	
United States	1,032	3,337	346	167
in 2000	**China**	**EU**	**Japan**	**S. Korea**
European Union	23	1,625		
Japan	6	147		
South Korea	1	9	15	
United States	47	2,143	321	48

Note: Patent applications filed under the PCT between 2013 and 2015

Source: OECD Patents Statistics.

While the absolute number of foreign co-inventions has gone up over time, Table 15 reports that the share of foreign co-intentions in total patented inventions has not increased over the 2000-2015 period. For China, although in absolute terms the number of foreign co-inventions has increased (see Table 14), foreign co-inventions as a share of total Chinese PCT applications has decreased (from 12.7 % in 2000 to 6.6 % in 2015). The EU and the US have the highest shares of foreign co-inventions, and these shares have increased over time.

Table 15: Share of patent applications that have foreign co-inventors (percentages)

in 2015	China	EU	Japan	South Korea	US	World
China		1.6 %	0.4 %	0.2 %	3.9 %	6.6 %
European Union	0.8 %	5.8 %	0.4 %	0.2 %	6.2 %	11.0 %
Japan	0.3 %	0.6 %		0.1 %	0.8 %	2.0 %
South Korea	0.3 %	0.6 %	0.4 %		1.3 %	2.9 %
United States	1.8 %	6.0 %	0.6 %	0.3 %		12.9 %
World	0.9 %	4.1 %	0.4 %	0.2 %	3.5 %	6.5 %
in 2000	**China**	**EU**	**Japan**	**South Korea**	**US**	**World**
China		3.2 %	0.8 %	0.1 %	6.6 %	12.7 %
European Union	0.1 %	4.7 %	0.4 %	0.0 %	6.1 %	9.3 %
Japan	0.1 %	1.6 %		0.2 %	3.6 %	5.8 %
South Korea	0.1 %	0.6 %	1.0 %		3.3 %	5.7 %
United States	0.1 %	5.7 %	0.9 %	0.1 %		9.4 %
World	0.1 %	5.1 %	0.6 %	0.1 %	4.0 %	7.0 %

Note: Tables show how many patent applications have co-inventors from other countries, as a share of total patent applications by the row country. Only patents under the PCT are counted.

Source: OECD Patents Statistics.

A very similar pattern emerges when looking at foreign ownership of domestic inventions. A large number of foreign-owned patents may indicate that foreign investors are eager to participate in a country's S&T sector because that sector is attractive and that international S&T cooperation between two countries is high.

Table 16: Number of patent applications for domestically owned inventions made abroad

		inventor				
owner		China	EU	Japan	South Korea	United States
	China		763	240	62	1,619
	European Union	2,701	17,470	1,223	388	11,341
	Japan	690	1,556		130	1,633
	South Korea	208	347	200		691
	United States	3,884	12,167	1,620	576	

Note: Patent applications filed under the PCT between 2013 and 2015.

Source: OECD (2018b).

The owners of most foreign-owned EU invented patents reside in other EU countries, again testifying to the strength of the European Research Area. The US comes in a strong second position and Japan third, while China is still a minor owner of EU patents. Reciprocally, the EU is the most important foreign owner of patents invented in the US, while China and Japan are on an equal footing in second place. For patents invented in China, foreign owners are most likely to be from the US, with the EU in second position. Japan and South Korea are only minor foreign owners of patents invented elsewhere, reflecting their more closed natures.

While the EU and the US have the strongest link, it is also the most balanced link. The China-US and the China-EU links are much less balanced, with Chinese ownership of US and EU patents at a much lower level than US or EU ownership of Chinese inventions. One could interpret this as evidence of China being an attractive location for US and EU firms for locating R&D activities, being able to capitalise on the rise of China as an opportunity for S&T development, at least for the moment.

1.6. A summary of the main findings on trends at the global S&T frontier

After many decades of leadership by the United States, the EU and Japan, other economies have emerged as S&T powers, with China the most significant case. A multipolar global science and technology world has opportunities and challenges for the EU. Increased global S&T capacity offers opportunities for more rapid S&T advancement because of the possibility to mobilise a large pool of global talent, and for building-up research strengths from specialisation. Increased competition from other parts of the world makes it more difficult for Europe to attract investment and talent and to retain its position as a world leader in critical S&T fields.

- In the first half of the 2010s, the US spent 2.7 % of its GDP on R&D, while China and the EU each spent each 1.9 %.
- China is now the second largest producer of scientific publications, after the US. In the fields of engineering, chemical engineering and material sciences, China has become the producer of the most scientific output worldwide. These fields used to be strongholds of European research.
- The EU's share of top-cited publications has slightly increased in the last 15 years. The EU and the US have similar shares of top-cited articles for all research subjects. China remains far behind the EU and US in terms of top-cited research, though it is rapidly catching up, especially in engineering and computer sciences.

- Most research universities among the top 20 or top 100 worldwide are located in the US. In the last five years, European universities have improved their rankings, and Chinese universities are starting to appear in the top rankings, especially in engineering.
- International scientific collaboration is on the rise worldwide. While researchers in European countries are most likely to collaborate with international counterparts on scientific publications, China remains one of the least open science systems in terms of international collaboration. Within the EU, collaboration between member states has increased substantially in the last 10 years.
- International collaboration is a pathway for building research excellence, with international publications being, on average, of higher quality.
- The international mobility of researchers and students is on the rise. Mobility can be another factor in research excellence. However, while the UK and Northern Europe receive high-quality researchers, other countries such as Spain and Italy see outflows of high-quality researchers.
- Worldwide private-sector R&D expenditure is highly concentrated among a few large firms. US firms are leading R&D spenders, followed by EU firms. Chinese firms are making rapid inroads into the list of the 2,500 biggest R&D spenders worldwide, especially in digital technologies.
- While the number of patent filings at international patent offices from China has increased in the last 20 years, it is still lower than the number of filings from Europe, the US or Japan.
- The share of patent applications filed that involve foreign co-inventors is a useful measure of R&D internationalisation. While this share has declined in the last 10 years for East-Asian countries, it has increased slightly for the US and the EU. International co-inventions patented by inventors in the EU mostly involve partners in the US and/or in other EU countries. Chinese co-applications mostly involve co-inventors from the US, and to a lesser extent from the EU.

2. EU'S FRAMEWORK PROGRAMMES AND RESEARCH EXCELLENCE

In this section, we examine how the EU's Framework Programmes have performed and, more particularly, how they have contributed to the EU's global positioning on research excellence.

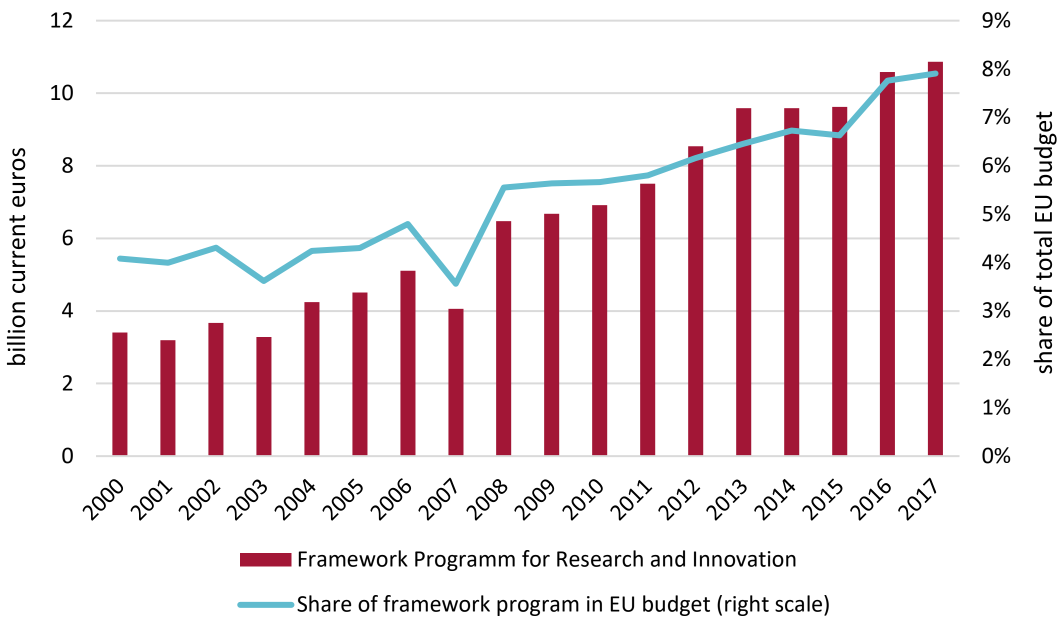
The elements of interest for this analysis include the impact of the Framework Programmes on the financial and human resources for research, their contribution to scientific publications and their contribution to building research excellence. We also look at how recent Framework Programmes (FP) have helped build international gateways to research excellence: international scientific and technological collaboration and the international mobility of scholars.

Our analysis is at the aggregate level of the FP, but also looks at particular instruments whenever most relevant. We use as inputs the final reviews of the Seventh Framework Programme (FP7) and mid-term reviews for Horizon 2020 (H2020) published by the European Commission.

Before looking at the impact in sections 2.2 and 2.3, we look at the size and composition of the FP budget.

2.1. The EU's budget for research excellence through its multi-annual Framework Programmes

Figure 20: EU Expenditure on Framework Programme for Research and Innovation



Source: Bruegel based on data from European Commission (2019a).

Figure 20 shows how the EU has committed an increasingly larger share of its total EU budget to its Framework Programmes for Research and Innovation, testifying to its commitment to research and innovation as drivers of the EU's growth. Nevertheless, the amount committed remains at less than 10 % of the overall EU budget.

The latest Framework Programme, H2020, covering 2014-2020, has the largest budget. The biggest pillar within H2020 is *Societal Challenges*, taking up 39 % of the H2020 budget. Spending on *Excellent Science* takes up another third. This pillar includes the European Research Council (ERC) and the Marie Skłodowska-Curie Action (MSCA) Fellowships.

Table 17: Distribution of Horizon 2020 resources by Pillar

	final amount in H2020 budget	
	million euro	Share of total
Pillar 1 - Excellent science	24,441	32 %
Pillar 2 - Industrial leadership	17,016	22 %
Pillar 3 - Societal challenges	29,679	39 %
Spreading excellence and widening participation	816	1 %
Science with and for society	462	0.60 %
Total	**72,414**	

Source: Bruegel based on data from European Commission (2018b) and European Commission (2013a).

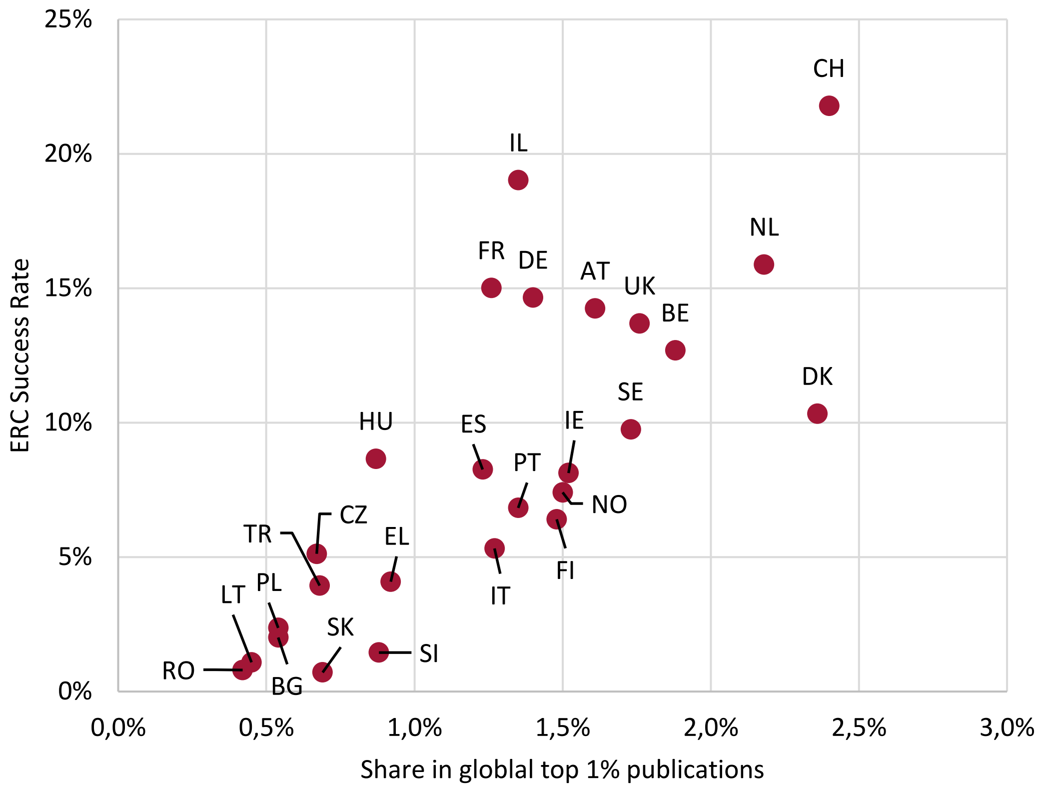
The EU FP instrument most geared towards research excellence is the ERC, which runs a bottom-up, individual-based pan-European competition, leading to the selection of 'high-gain/high-risk' projects that can push at the frontier of research. The ERC was introduced in FP7 with a budget of EUR 7.5 billion (or EUR 1.1 billion annually). In the next programme, H2020, it received EUR 13 billion (or EUR 1.9 billion annually), representing 17 % of the H2020 budget. The ERC has funded, since it started in 2007, more than 8,500 researchers, representing 76 nationalities working in more than 750 different institutions. The ERC's sizeable five-year grants (up to EUR 2.5 million) have employed more than 60,000 researchers.

Figure A.2 in the appendix shows the allocation of H2020 funding to each EU country and to Associated Countries. Not surprisingly, the largest EU countries are the biggest recipients. The UK is home to the coordinators for the largest number of H2020 projects (18 %). Spain comes in second place (12 %), Germany third (11 %) and France fourth (9 %). In terms of the different pillars, coordinators in the UK have the largest number of projects under Pillar 1 (*Excellence Science*), reminiscent of its largest contribution to the EU's research excellence as shown in section 2. Spain has the largest shares in terms of coordination under Pillar 2 and Pillar 3.

Pillar 1 (*Excellence Science*) is the most focused on research excellence. Consequently, we expect to see that the countries with more excellent research will be overrepresented under Pillar 1 of H2020. This is in fact the case: not only the UK, but also Denmark, Sweden and the Netherlands score highly on research excellence (see Figure 9). For these countries, about or close to half of their FP funding is allocated under Pillar 1.

The main instrument in Pillar 1 is the ERC. Figure 21 plots the success rate of EU and associated countries since the ERC's start in 2007 (y-axis) relative to the countries' research excellence (as measured by the shares of their total publications that make the world Top 1 %). Overall, the correlation is highly positive (with a correlation coefficient of 78.5 %). Countries with below world average research excellence also have below average ERC success rates and vice versa: countries with high research excellence also have above average ERC success rates. Examples of the latter include Switzerland and the Netherlands. An outlier is Denmark, a country with a high excellence score, but a relatively low success rate (and a relatively low share of ERC grants). Countries that in relative terms punch above their weights in their excellence scores are Israel, France, Germany and Hungary.

Figure 21: European Research Council success rate and excellence of research: by country



Note: Only countries with sufficient (>1000) annual publications and ERC applications are retained (ie excluded are CY, ES, LU, LV, MT, IC). Y-axis: Success rate in ERC applications (2007-2018) (average success rate: 10 %); X-axis: share of country's publication in Top 1 % measured in 2007.

Source: Bruegel based on ERC data downloaded 6/2018.

2.2. The impact of the EU's Framework Programmes on research excellence

Contributing to the EU's research excellence has been an explicit mission of the EU Framework Programmes: *"The added value comes through strengthening the EU's scientific excellence through competitive funding; the creation of cross-border, multidisciplinary networks; the pooling of resources to achieve critical mass for tackling global challenges, and developing the evidence-base to underpin policymaking. Overall, this increases EU's global attractiveness as a place to carry out R&I"* (European Commission 2019c, p. 1).

How did the EU's Framework Programmes (most recently FP7 and H2020) contribute to the strengthening of the EU's research excellence and, more generally, improve the EU's global position in S&T? To address this, we look at the direct effects on research output, as measured by publications associated with FP funding. To assess the impact on research excellence we focus in particular on the quality of FP-associated publications. In section 2.3, we examine how FP funding helped to build the EU position in research excellence in a multipolar global S&T landscape, by looking at international cooperation funded by FP and the international mobility of researchers.

2.2.1. Impact on the number of scientific publications

Because of the lengthy review, publication and indexing processes, the final number of publications that can be associated with FP funding only becomes available after a lag of 1-2 years. This limits the tracking of output from H2020, which started in 2014, which is why we concentrate mostly on FP7. According to Elsevier (2017) about 220,000 scientific publications were produced in the context of FP7[7] (2007-2013). This represents about 1.5 % of all scientific publications worldwide during the relevant period. The EUR 50 billion of FP7 funding therefore generated about 4.4 publications per million euros spent.

Table 18 looks at the FP-associated publications by geographic region. We differentiate between EU15 and EU13 countries because widening the participation and spreading excellence in the EU13 countries is part of H2020. The first column shows that FP-associated publications represented a smaller share of all publications for the EU13 countries, representing 1.5 % of that region's publications compared to 2.2 % for the EU15[8] and Associated Countries (AC)[9] . This correlates with the next columns, which show the regions' shares of total FP7-associated publications. About 62 % of all FP7-associated publications were from EU15 and 6.5 % were from EU13 countries. AC have been responsible for an increasing share of FP7-associated publications, representing 12 % in 2014.

Table 18: Geographical breakdown of Framework Programme publications

	FP-associated publications as a share of total publications	Regions' shares of total FP7-associated publications		
		ALL YEARS	2007-2010	2010-2014
EU15	2.27 %	62.90 %	66.07 %	62.20 %
EU13	1.5 %	6.48 %	7.07 %	6.34 %
AC	2.2 %	11.92 %	10.47 %	12.23 %

Source: Bruegel based on Elsevier (2017).[10]

2.2.2. Impact on scientific quality, reputation and scientific breakthroughs

To study the impact of research quality, we use two measures: the Field Weighted Citation Impact (FWCI)[11] and the Top 1 % most frequently cited publications.

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[7] In view of the lags in processing, while the FP7 ran from 2007-2013, its output occurs also after 2013.

[8] The 15 countries that were the member states of the European Union before 2004: Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, United Kingdom.

[9] As of January 1st 2017, 16 countries are associated to the FP: Albania, Armenia, Bosnia and Herzegovina, Faroe Islands, Georgia, Israel, Moldova, Montenegro, North Macedonia, Norway, Serbia, Switzerland, Tunisia, Turkey, Ukraine, Iceland. Legal entities from Associated Countries can participate under the same conditions as legal entities from the Member States.

[10] Elsevier's analyses make use of whole counting rather than fractional counting. For example, if a paper has been co-authored by one author from the EU 28 group and one author from the TC group, then that paper counts towards both the publication count of EU 28, as well as the publication count of the TC group.

[11] Field-weighted citation impact (FWCI) is an indicator of mean citation impact, and compares the actual number of citations received by an article with the expected number of citations for articles of the same document type, publication year and subject field. The indicator is always defined with reference to a global baseline of 1.0.

Table 19: Citation Impact of Framework Programme funded research by geographical region

	FWCI score, region's FP-associated publications (2007-2013) (1)	FWCI score, all region's publications (2007-2016) (2)	FWCI score, region's FP-associated publications relative to overall region's FWCI (2007-2016) (3)= (1)/(2)	Score of region's top 1 % FP-associated publications relative to top 1 % of all region's publications (2007-2016) (4)
EU28	2.5	1.19	2.1	3.3
EU15	2.6	1.30	2.0	3.2
EU13	2.3	0.82	2.8	4.4
AC	3.0	1.15	2.6	4.4

Source: Bruegel based on Elsevier (2017).

Note: Field-weighted citation impact (FWCI) is an indicator of mean citation impact, and compares the actual number of citations received by an article with the expected number of citations for articles of the same document type, publication year and subject field. The indicator is always defined with reference to a global baseline of 1.0.

Table 19 shows that the FWCI for each region's FP-associated publications is well above 1, indicating that FP-associated publications were of significantly higher quality than the world average. The scores are even well above 2, and for the AC even above 3, i.e. FP-associated publications were at least twice, even three times, more cited than world average. To assess whether the Framework Programmes have contributed to lifting research excellence in the EU, we compare the citation impact of FP-associated publications with the average impact of a region's overall publications (column 2 of Table 19). All numbers in the first column of Table 19 are at least twice as large as the numbers in column two. This indicates a substantial boost in quality from FP-associated publications relative to each region's overall quality of publications. This finding is consistent for all regions: EU15, EU13 and AC, but the relative increase in FWCI score is greatest for the EU13.

A similar result can be seen for each region's share of the top 1 % of cited publications (column 4 of Table 19). Of the world's top 1 % of cited research, FP7-funded output for all comparator groups was proportionally much higher than the groups' overall output included in the world's top 1 % of cited research. For the 2007 to 2013 period, the EU 28 group's FP7-funded output was 3.3 times more represented in the top 1 % category than the group's overall output. For the EU15 and EU13 regions, FP7-funded output was proportionally more present in the top 1 % category by factors of 3.2 and 4.4 respectively.

Box 1 shows how the ERC instrument has performed in terms of research excellence. The ERC's scores, based on a multitude of research excellence criteria, show how in a short time span since its start in 2007 it has managed to target and support research excellence in the EU, as specified in its mission.

Box 1: The ERC, an FP instrument specifically targeted at research excellence

- Over 90,000 articles from ERC projects have been published since its start in 2007.
- 7 % of ERC-related publications are among the world's top 1 % most-highly cited articles (adjusted for field, publication year and type).
- From 2008-2014, 650 publications that acknowledged ERC funding appeared in *Nature* and *Science*. In 2014, papers published in *Nature* and *Science* that acknowledged ERC funding represented 20 % of all *Nature* and *Science* papers written by authors based in the EU and Associated Countries.
- Qualitative evaluation of randomly-selected completed ERC-funded projects found that 71 % of the projects evaluated were considered to have made a scientific breakthrough or major scientific advance.
- As of December 2016, ERC beneficiaries were recipients of 526 major prizes, awards and other forms of recognition. These included 13 ERC beneficiaries who won Nobel prizes before, during or after receipt of their grant.

Source: European Commission 2017.

- Clarivate Analytics, on the tenth anniversary of the ERC, analysed more specifically the contribution of ERC to frontier research. The study identified clusters of high-impact papers (top 1 % cited) that are cited together. These clusters are called "Research Fronts" and have a large impact on scientific knowledge advancement. The study found that of the 9,214 identified Research Fronts, 7.4 % included at least one paper that acknowledged ERC funding. Of the Top 100 most cited of these Research Fronts, 43 % included at least one paper that acknowledged ERC funding. All this demonstrates the impact of ERC on high-impact frontier research.

Source: Clarivate Analytics (2017).

2.3. EU's FP for International collaboration and international mobility of researchers

2.3.1. Effects of the international mobility of researchers on research excellence

Beyond occasional mentions, there is little systematic evidence in the European Commission's reviews of how its FPs in general have attracted talent from outside the EU, involving researchers from outside the EU on EU funded projects or directly funding researchers from outside the EU to perform research in the EU. The Commission (2014b, p.9) did note that: *"it has been shown that FP participation helps the Higher Education Institutions to attract non-EU researchers to Europe, particularly through the Ideas and People programmes, but the magnitude is limited and the effect is not lasting (often confined to the duration of the project)."*

Furthermore, to assess whether the international mobility associated with FP funding helps to improve the EU's research excellence, we need to look at the quality of the researchers involved in FP-funded activities who are internationally mobile. Unfortunately, there is no tracing of the quality of mobile researchers within FPs.

We will look at the two major FP instruments for mobility: Marie Skłodowska-Curie Actions fellowships and ERC individual grants.

a. Marie Skłodowska-Curie Action Fellowships

Marie Skłodowska-Curie Actions (MSCA) fellowships are particularly aimed at encouraging international mobility, i.e; funding researchers who move to another host country to be research active. The H2020 programme has a target for 65,000 MSCA researchers to undertake international mobility, either between EU member states or between a member state and a non-EU state.

Data on MSCA Fellowships from H2020 (European Commission 2019b) from the eight major destination countries (UK, France, Germany, Italy, Poland, Switzerland, US and China) show that most MSCA Fellowships are intra-EU.

The UK is the major destination country for MSCA fellows (29 %). The most important source countries for MSCA fellows moving into the UK are intra-EU, with Italy in first place (22 % of MSCA fellows), followed by Spain (15 %). From outside the EU, 11 % of MSCA fellows moving in the UK are Chinese researchers and 7 % are Indian. Germany is the second main destination country (16 % of incoming MSCA fellows), with again Italian researchers leading (22 %). From outside the EU, 10 % of MSCA fellows in Germany are Indian and 6 % are Chinese researchers.

When looking at extra-EU destinations for MSCA fellows, the US is the destination for 12.6 % of all major destination fellows. One third of these are Italian nationals, another 17 % are Spanish, 11.5 % are German and 9.5 % from the UK. China is the destination for 5.7 % of which about 46 % are 'returnees', ie with Chinese nationality.

b. ERC grants

The ERC is also an instrument for host institutions in the EU and AC to attract foreign talent.

(i) Major destination countries for ERC applicants applying outside their country of nationality

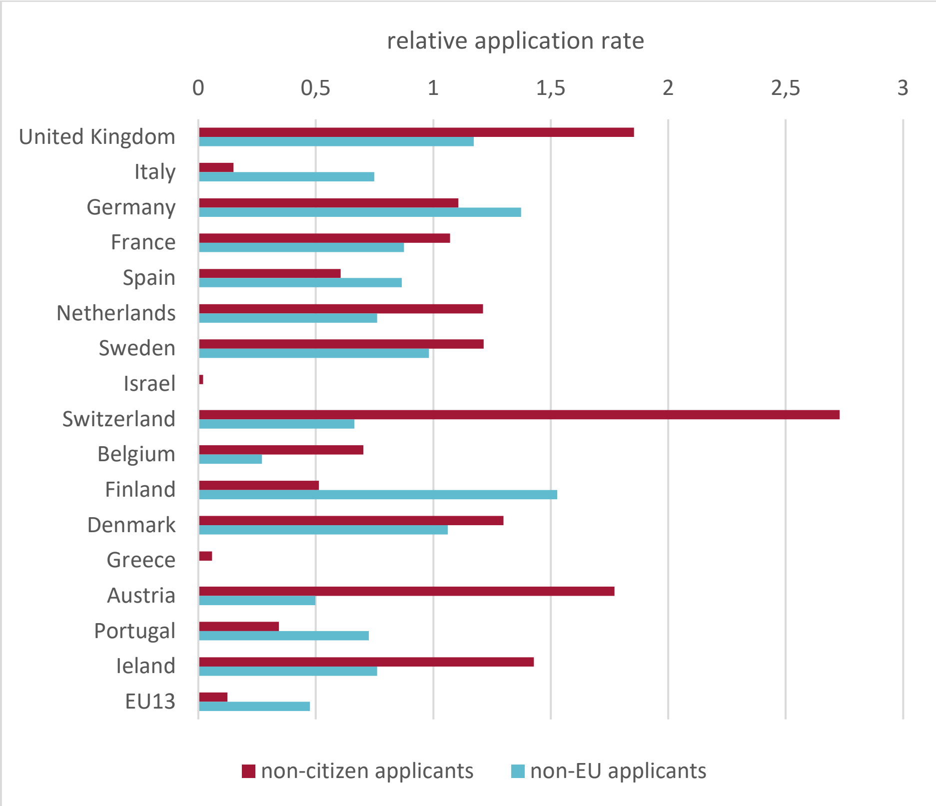
In this section we look at the major destination countries where ERC applicants apply when they apply outside their country of nationality.

On average a quarter of all ERC applications are made by researchers who are non-nationals in the host country where they apply. Most of this mobility is intra-EU: only a quarter of non-national applicants are from outside the EU.

By far the most important destination country for mobile ERC applicants is the UK. It has the highest number of non-citizens among its applicants (33 %). The importance of the UK as a destination for foreign researchers is even more pronounced for researchers from outside the EU, with the UK research institutions hosting 39 % of all applications from non-EU nationals, i.e. 28 % of its non-national ERC beneficiaries are from outside the EU.

Figure 22 shows the shares for the major destination countries, in relative terms (i.e. relative to the overall number of applications from the country). It shows that the UK is in relative terms the most open to foreign researchers. Switzerland and Austria are also open systems for foreign researchers, but are relatively less attractive to non-EU researchers, compared to the UK. Germany is also a relatively open host country, in particular for non-EU researchers. Northern countries are also more attractive to foreign researchers (more so for researchers from other EU countries), while the south and the EU13 countries are less attractive to foreign talent. Italy and Greece in particular score very poorly, as does Israel[12].

Figure 22: Share of Foreign Applicants in Total ERC Applications from major destination countries



Note: Countries are ordered by size of all ERC applicants. Only major applicant countries are reported. EU13 is the average of EU13 countries.

First bar shows the share of the country as host in all applications from non-citizen applicants and this relative to the share of the country as host in all applications. Numbers above 1 indicate that the country is relatively more attractive to applications from non-citizens.

Second bar shows the share of the country as host in all applications from non-EU/AC citizens relative the share of the county in all non-citizens applications. Numbers above 1 indicate that the country is relative more attractive for talent from extra-EU than for intra-EU.

Source: Bruegel based of ERCEA.

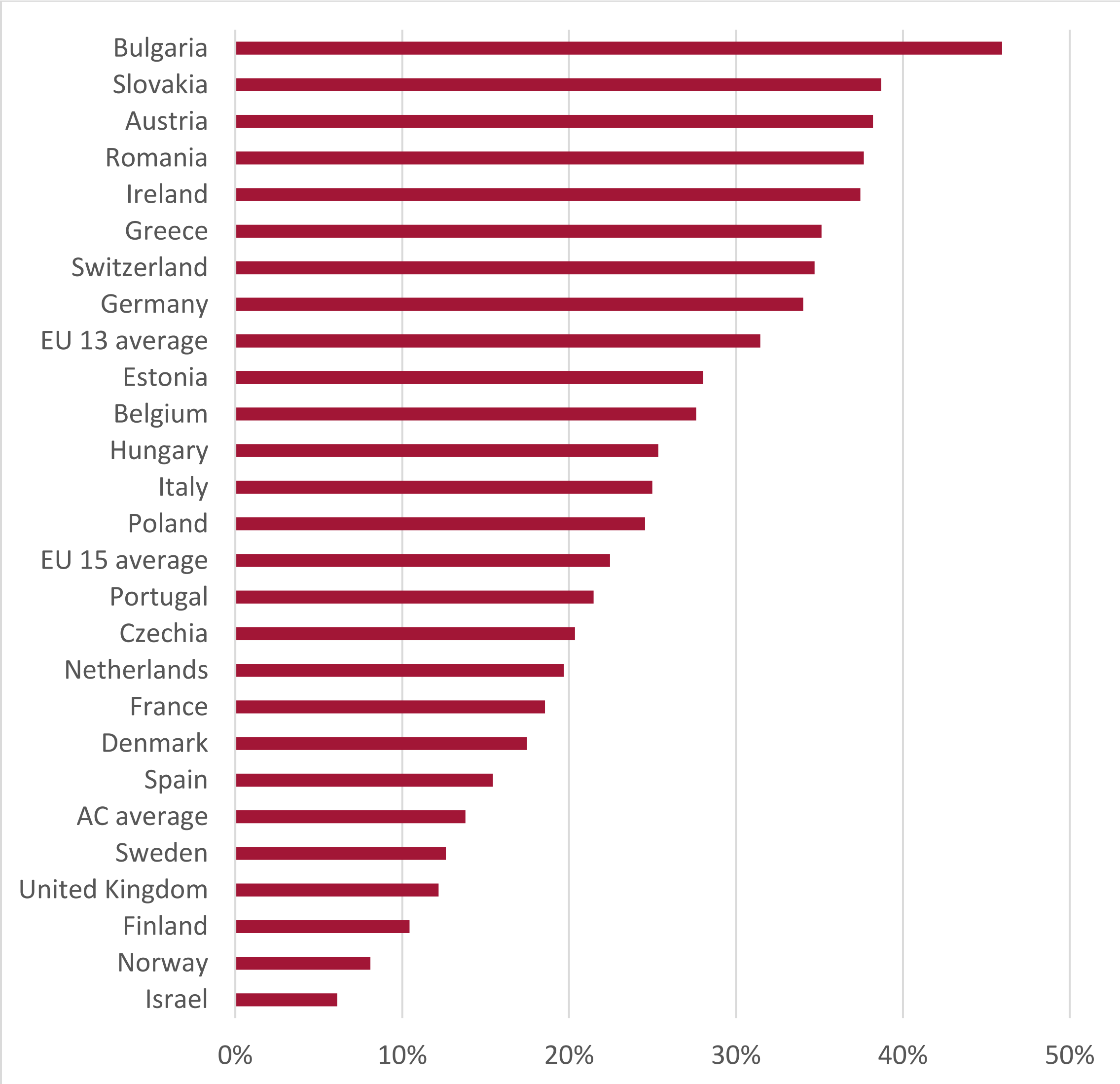
(ii) Major source countries for ERC applicants applying outside their country of nationality

In this section we look at the flip side of the non-domestic ERC applications, i.e. which are the major source countries for ERC applicants who apply outside their country of nationality. From the perspective of the source country, i.e. the country of the nationality of the ERC applicant, we call this outward mobility.

[12] We can only record foreign mobility from applicants with non-national citizenship. This excludes returnees, which for these countries constitute important inward flows.

Outward mobility is most pronounced for EU13 countries; on average one third of applicants with EU13 citizenship apply with research institutions abroad (Figure 23).

Figure 23: Share of researchers that apply to the ERC from outside their national country, by nationality



Source: Bruegel based of ERCEA.

But outward mobility is also high for some EU15 countries. For Greece, Italy and Portugal, more than one in five of their ERC applicants apply abroad. Germany, Switzerland and Austria also have high outward mobility rates, as does Ireland[13].

(iii) Quality of the ERC applicants by mobility profile as measured by their relative success rate to obtain an ERC grant

In this section, we assess the quality of the ERC applicants by mobility profile. We measure quality through their relative success rate to obtain an ERC grant, i.e. we look at how often ERC applicants from the various mobility groups are successful in obtaining ERC grants relative to the success rate of all ERC

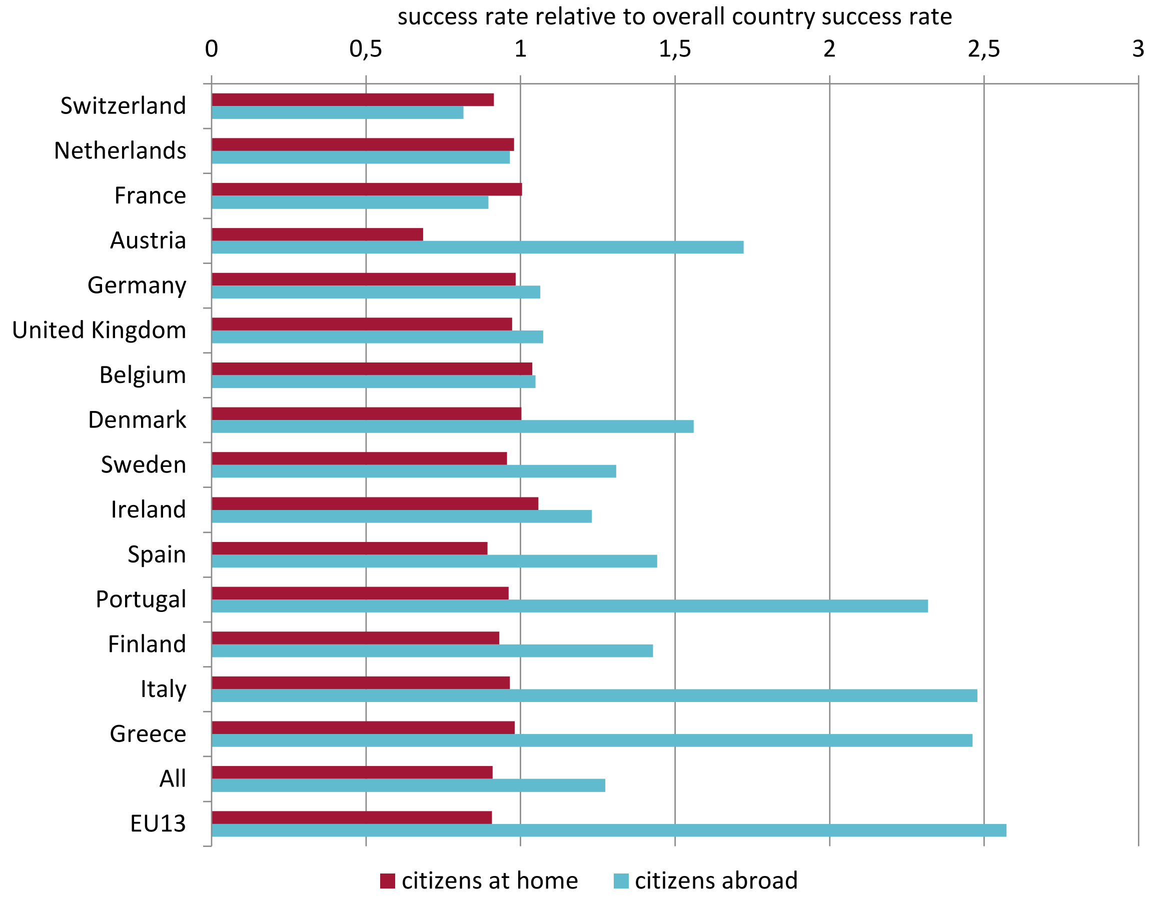
[13] For German citizens applying abroad, the UK is the major destination country (31%), followed by Switzerland (15%); For Swiss, the UK and Germany are about equally sized major destination countries (about 25%). For Ireland, the most important destination is the UK (67%).

applicants. This will allow us to assess how the inward mobility of researchers helps ERC-hosting countries to access talent and how outward mobility of researchers is a drain on talent.

Compared to an overall ERC application success rate of 12 % (and a success rate for home-country applicants of 11 %), the success rate for those applicants that are applying in a destination country which is not their country of nationality is 15 %, showing a quality premium for mobile applicants. This holds both for extra- and intra-EU mobile applicants.

Figure 24 shows for the major countries the rates of success at winning ERC funding for various mobility groups expressed relative to each country's overall success rate. In most cases, Austria being the main exception, the success rates of non-mobile researchers are on average about or somewhat below each country's average. Success rates of outwardly mobile researchers are typically above the average, suggesting that outwardly mobile researchers are of higher quality. This premium is high for EU13 countries, but it is also high for the south (Greece, Italy, Portugal and Spain), suggesting a push factor for mobile researchers, away from low-quality research environments, supportive of a brain "drain" especially for these countries.

Figure 24: Relative success rates of mobile and non-mobile ERC applicants



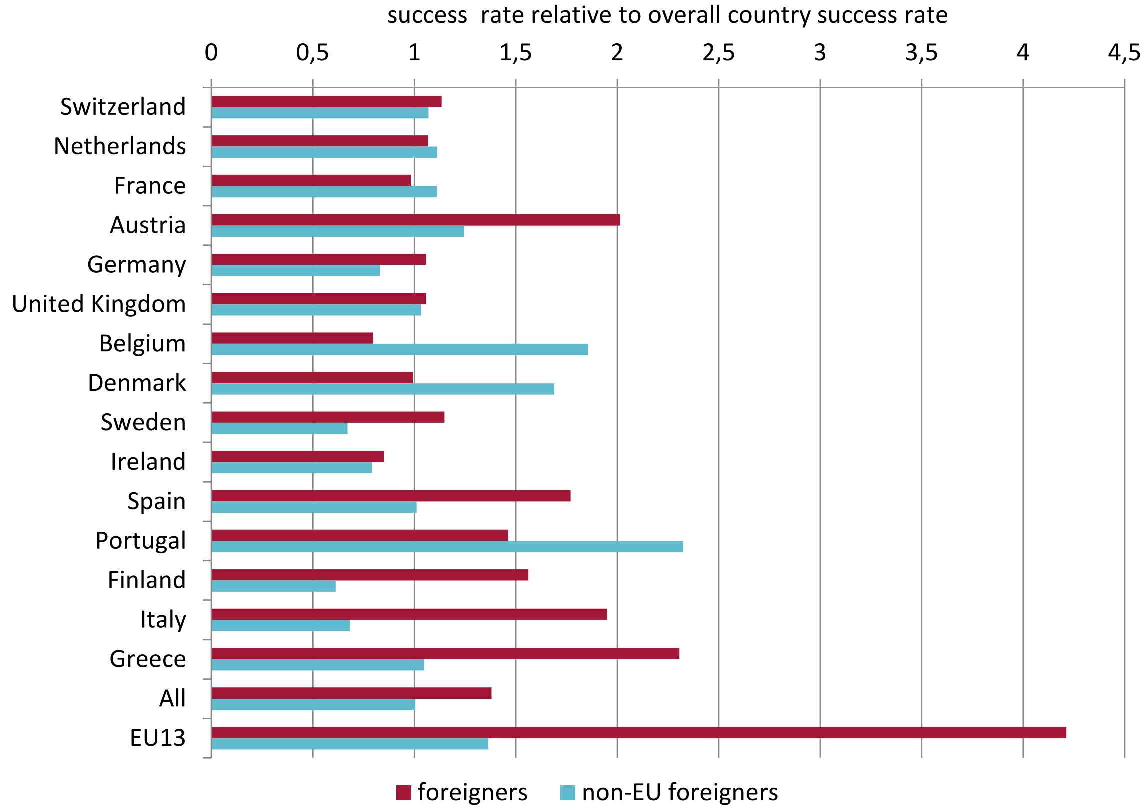
Note: Countries are ordered according to their overall ERC success rate. Success Rates of the various mobility groups are expressed relative to the overall success rate of the country.

Source: Bruegel based on ERCEA.

With respect to inward mobility, Figure 25 shows that on average the success rate of foreign applicants is higher in most cases than each country's average, suggesting on average a gain in talent for the host country. This gain is similar in relation to researchers from other EU countries and from non-EU countries. This gain from inward mobility is very high for EU13 countries.

Unfortunately, although attracting foreign researchers via ERC grants seems a good channel for EU13 countries to attract better researchers, the flows are very small. The gains are also higher for the south (Spain, Italy, Portugal, Greece), and for Austria.

Figure 25: ERC success rate by EU and non-EU foreigners



Note: Countries are ordered according to their overall ERC success rate. Success Rates of the various mobility groups are expressed relative to the overall success rate of the country.

Source: Bruegel based on ERCEA.

Table 20 further zooms in on ERC applicants from outside the EU+ (non-EU/AC) by source and destination country. The largest group of third-country applicants comes from the US. Their primary destination is the UK, followed by Germany. Consistent with the position of the US at the frontier of global S&T, the success rate of US citizens who apply for ERC grants is 16.5 %, which is substantially higher than the average ERC success rate. Even though the major destination countries for US applicants are countries with high research quality, the difference between their success rate and the average success rate in those countries (their premium) is still substantial, especially for Switzerland, but also for the UK and Germany. Canadian and Indian applicants also have superior success rates. This contrasts with Russian applicants, the second largest batch of extra-EU applicants. Their primary destination is Germany, followed by the UK, but their success rate is significantly below these countries' average success rates, especially for Germany. China is still a minor source country for non-EU applicants, with again the UK receiving the bulk of them (about one third). But the success rate of Chinese applicants is significantly below that of UK applicants, suggesting that this flow so far has not been a major brain gain for the UK. For Germany, which is the second destination country for Chinese applicants, the success rate of its Chinese applicants is much higher.

Table 20: ERC applicants from extra-EU countries by source and destination country

	Share of total extra-EU applicants	Share of major destination country	Success rate		Success rate relative to nationals in destination country
USA	39 %		17 %		
US-UK		36 %		17 %	1.29
US-DE		12 %		19 %	1.28
US-FR		8 %		16 %	1.06
US-CH		7 %		33 %	1.63
US-NL		6 %		18 %	1.11
China	12 %		7 %		
CN-UK		32 %		7 %	0.49
CN-DE		18 %		16 %	1.07
Russia	16 %		8 %		
RU-UK		17 %		8 %	0.59
RU-DE		28 %		6 %	0.40
Canada	11 %		16 %		
CA-UK		42 %		15 %	1.09
India	10 %		11 %		
IN-UK		41 %		16 %	1.18

Note: The Non-EU countries (USA, Canada, China, India, Russia) considered cover 75 % of all non-EU (EU28+AC) citizens applying.

Source: Bruegel based on ERCEA.

2.3.2. Impact on International cooperation

a. International collaboration in FP7

Table 21: Share and index of international collaborative links under FP7

	Share of links					Weighted index of links				
	EU28	AC	THIRD	Of which US	Of which CN	EU28	AC	THIRD	Of which US	Of which CN
EU28	0.89	0.06	0.04	0.13	0.07	2.83	1.13	0.05	0.36	0.29
AC	0.88	0.06	0.04	0.14	0.06	2.80	1.20	0.06	0.38	0.25

	EU15	EU13	EU15	EU13
EU15	0.90	0.10	1.00	0.78
EU13	0.82	0.18	0.91	1.39

Note: For each project p with n partners, a link is a connection between partner i and partner j. For example, for a project with 3 partners, there are 3 links, for a project with 4 partners, 6 links etc. The right part of the table has the shares of collaborative links expressed as a ratio relative the weight of the partner, as measured by its size in world publications (for US, CN share in third countries world publications), measured in 2010. A list for a scoring for all individual EU28 countries can be found in Appendix table A.8.

Source: Bruegel based on FP7 collaborative links in all programmes from European Commission (2018b).

Table 21 shows clearly the emphasis of the EU's Framework Programmes (in this case, FP7) on fostering intra-EU collaboration. Not surprisingly, given its aim, the overwhelming majority, 90 % of all links in FP7, are intra-EU (see the note to table 1 for an explanation of 'links'). This is almost three times higher than what one could have expected from the EU's scientific size in the world. However, even if fostering intra-EU links is the major aim of the EU's FP, links need not be exclusive: intra-EU collaboration could be combined with extra-EU collaboration within FP7 projects. Nevertheless, these extra-EU links occurred infrequently: 6 % of links in EU28 projects were with Associate Countries and only 3.5 % were with third countries, massively lower than what could have been expected based on the scientific size of these regions. Although the US is the largest third-country partner, followed by China, both countries were still massively underrepresented as third countries, relative to their scientific sizes.

The lower part of Table 21 zooms in on the intra-EU collaborative links, split down into the EU15 and EU13. Within the EU, partners from the EU15 are the most important for intra-EU collaboration, both within the EU15, and projects based in EU13 countries. With 89 % of all EU publications coming from EU15, the importance of partners of EU15 for intra-EU collaboration is at par with their scientific size. Intra-EU13 collaboration accounted for only 18.4 % of all intra-EU links for the group of EU13 countries. Although this is small compared to the importance of links with the EU15, this is nevertheless a larger share than what could have been expected based on the scientific size of the EU13 (representing 13 % of all EU publications in 2010). This shows that FP7 boosted the EU13 as partners for scientific publications beyond what could have been expected from the EU13's scientific size.

b. International co-publications from FP projects

We next look at the output from FP7 and the extent to which it has led to international co-publications. We use the Elsevier (2017) analysis, which assesses international collaboration through analysis of co-publications between a geographical group member and at least one co-author from a country outside that geographical group.

For the EU as a whole and the EU15 groups, the share of FP-related publications that involve international collaboration reaches 37 % and 39 %, respectively. For the EU13 and AC groups the score is much higher, at 78 % and 75 % respectively. This confirms analysis in section 2.3.2.a that collaboration in FP7-funded research projects primarily involves EU members. The share of the EU's FP7-associated *publications* that involve external partners is however not negligible, and is definitely more important than the share of its *links* with external partners (section 2.3.2.a), suggesting that even within intra-EU FP links, co-publications with extra-EU collaborators occur.

On the impact of FP7-funded co-publications, Table 22 shows that FP7-associated publications written with non-EU partners had on average an FWCI of more than 3, i.e. with an expected impact at least 3 times greater than the world average. This higher quality score is not only relative to the world average, but is also relative to FP7-associated publications that involved only EU authors, as the last column of Table 22 shows. Thus, although publications written by EU authors and funded by the FP7 programme overall had a greater impact in terms of average citations than the overall average of publications written by EU authors, FP7-funded publications that were collaborations between EU and non-EU researchers had on average a greater impact than FP7-funded publications written only by EU researchers.

This result shows that external collaboration, i.e. collaboration with partners outside one's own block, although substantially infrequent under FP collaboration, holds the highest scope for an increment in research quality, as measured by the higher FWCI for these co-publications.

Table 22: FP7 publications with external co-authors

	Share of FP7 pubs with external co-authors	FWCI of pubs with external co-authors	FWCI of external co-pubs relative to internal
EU28	37 %	3.4	1.34
EU15	39 %	3.4	1.32
EU13	78 %	2.5	1.10
AC	75 %	3.4	1.12

Note: The period covered is 2007 until 2015 which includes the FP time frame plus 2 extra years in view of the processing lag (cf 2.2.1)[14].

Source: Bruegel based on Elsevier (2017).

Although it is early to evaluate H2020 and the data is limited and incomplete, the Elsevier (2017) analysis of H2020 uncovered similar patterns: "*Finally, looking at publications in 2015 and 2016 that were funded by Horizon 2020, the same pattern emerges. The impact of publications that have been written by*

[14] Research collaboration is indicated by articles with at least two different entities listed in the authorship by-line. International: at least one author is from a country outside of the geographic group.

EU 28 authors in collaboration with EU-external partners was approximately three times as large as the impact of publications written by EU 28 authors only" (Elsevier 2017).

In terms of publications, the ERC is by far the largest programme in the FP. With its focus on research excellence, it is also more oriented towards international collaboration than is the FP overall. This is even more evident for the most successful (top 1 % cited) ERC-related publications, as noted by European Commission (2017, p. 96):

- *"The share of ERC publications with international co-authorship is 56 %.*
- *"34 % of all ERC reported publications have at least one author affiliated to an institution based in a non-ERA country.*
- *"For the ERC top 1 % highly-cited publications this rate is 46 %.*
- *"The collaboration with third countries is most intense with US-based authors: 22 % of all ERC reported publications have at least one US-based author or 64 % of ERC reported publications written in a non-ERA collaboration (75 % if only top 1 % papers are considered)."*

2.4. A summary of the main findings on the EU's Framework Programmes and their impact on EU research excellence

- The EU has committed an increasing share of its total budget to the Framework Programmes for Research and Innovation. In 2017, expenditure on Horizon 2020 was EUR 10.8 billion, or 8 % of the total EU budget. The Framework Programme Horizon 2020, running from 2014 to 2020, allocates 32 % of its budget to "Pillar 1 – Excellent science", 22 % to "Pillar 2 – Industrial leadership" and 39 % of the Framework budget to "Pillar 3 – Societal Challenges".
- The instruments most geared towards research excellence belong to Pillar 1. The most specific instrument is the European Research Council (ERC). It runs a bottom-up, individual-based pan-European competition, selecting high-gain/high risk projects and beneficiaries, which can extend the frontier of research.
- Member states with high scores on research excellence (e.g. the UK, Denmark, Sweden and the Netherlands, as measured by shares of top-cited publications) receive about or close to half of their FP funding under Pillar 1.
- Using the Field-Weighted Citation Impact (FWCI) as an indicator of research quality, publications funded under FP7 are found to be of significantly higher quality than the world average. FP7 publications are also of substantially higher quality compared to regions' average publication quality.
- Between 2007 and 2013, the EU's FP7-funded output was 3.31 times more represented than the EU's overall output in the top 1 % of most-cited publications. 7 % of ERC publications made their way into the top 1 %, a ratio that is not only substantially above the world and EU averages, but is also above that for overall FP7 output.
- The overwhelming majority of FP-funded international scientific collaborative links are intra EU28; under FP7 these were 90 % of all links. Only 3.5 % were with third countries.
- FP7-funded publications co-authored by EU researchers with non-EU researchers had, on average, a higher citation impact than FP7-funded publications written only by EU researchers.

This shows that external collaboration, although infrequent, has the greatest potential to improve the quality of the research funded by the FP.

3. RECOMMENDATIONS FOR THE FUTURE EU R&I PROGRAMME: HORIZON EUROPE

Extrapolating from the trends we have examined in this report, will the EU be part of a global S&T landscape with open, connected multiple (US and Chinese) poles? Or will the EU face an inward-looking US and Chinese in terms of research? Table 23 sets out optimistic and pessimistic scenarios.

Table 23: Scenarios for the future global S&T landscape

	United States	China
Optimistic	The US's pole position in frontier research will mean it continues to attract the best foreign talents, contributing to US science, technology and economic success, and connected to the best locations in the world.	While Chinese science domestically continues to grow in extent and quality, China continues to send out its talents to the world's best locations, and continues to be connected to and working with the best in the world.
Pessimistic	US science retrenches behind national borders, cutting itself off from its source of success: foreign talent.	China becomes closed in S&T terms, though remains a top producer of science

Our analysis in part 2 of this report tends to provide grounds for an optimistic view of a trend towards a connected, open, multipolar global R&I landscape. This would be the best possible scenario for delivering research excellence globally, driving global growth and addressing global challenges. In this scenario, the EU should ensure it is itself integrated and open, with ever deeper internal interaction (including with its associated members) and also by bringing in the best extra-EU talent, most notably from the US and China.

However, a more pessimistic scenario of science being done in an increasingly disconnected way cannot be excluded. In this scenario, China will, by now be sufficiently big and strong to be viable on its own, with its indigenous S&T driving its growth and prosperity. The US position at the frontier will undoubtedly continue to erode if it is less able to rely on foreign talent as it traditionally has done, but the US could still for a long time thrive on its stock of (imported) talent, which would only gradually depreciate or emigrate. This pessimistic scenario would be the most challenging for the EU. It would only be viable as a research-excellence driven society if it is integrated internally. And even if the US and China retrench, it remains in the EU's interest to be open and connected to extra-EU talent. This is first of foremost the case with a number of closely-related countries that are also Horizon 2020 Associated Country, such as Switzerland, or with which the EU shares a history of former EU membership, a likely scenario for the UK. No matter what scenario prevails, the EU will need to work further on its internal integration alongside an ambitious strategy for external connectedness.

What implications does this have for the design of the next Framework Programme, Horizon Europe, which will be the most important policy instrument for the EU to support its research excellence standing?

The analysis in section 3 in this report on how FPs in the past have contributed to support EU's research excellence position in the world. Table 24 summarises the strengths and weaknesses of the FPs:

Table 24: Evaluation of FP's role in supporting EU's research excellence position in the world

Strengths	Weaknesses
Increasing budget	Increasing budget, commitment for research not a given
Long-term (7-years) commitment	Allocation of budget supporting research excellence not a given
Commitment of budget to excellence	Attraction of foreign talent through FP underrepresented
Improved research excellence performance publications out of FP of higher quality	Support for collaboration with extra-EU underrepresented
Helped catching-up of lagging countries with respect to research quality	Quality of extra-EU links is weak as driver of which third parties to collaborate with; relatively little with important science countries: US & China
Improved intra-EU collaboration and mobility	
EU13 catching up thanks to FP collaboration	

Given the challenges the EU is faces in taking a pole position in global S&T, and given the strengths and weaknesses of its past FPs in supporting its position as a global centre of research excellence, we would make the following recommendations for the next FP, Horizon Europe.

First, the long-term (i.e. 7 years) commitment to an increase in the EU budget for research and innovation is important. Our analysis does not provide any evidence that past FP funding has been ineffective in supporting the EU's progress in becoming a global centre of excellence. On the contrary, the sufficiently positive trends associated with past FPs provide support for an increased future budget. The positive trends are that past FPs have contributed to supporting the EU's improvement in research excellence, most importantly by improving internal integration and reducing dispersion internally, through improving intra-EU collaboration and intra-EU mobility of researchers. At the current stage of negotiations, with the final budget not yet voted on, the analysis in this report is supportive of the amendments adopted by the European Parliament as recommended by Rapporteurs Dan Nica and Christian Ehler, calling for an increase in the Horizon Europe budget to €120 billion, beyond the European Commission proposal for a budget increased to €100 billion.

However, our analysis has also indicated some weaknesses or missed opportunities, as past FPs have failed to exploit the potential for supporting research excellence through extra-EU connectedness and attraction of extra-EU talent. Horizon Europe would be a more effective instrument to establish the EU as a global centre of research excellence if it would address these weaknesses. The amendments adopted in December 2018 by the European Parliament as recommended by Rapporteurs Dan Nica and Christian Ehler explicitly clarified one of the operational objectives of the programme to be *"attracting, training and retaining EU and international researchers and innovators, including through mobility of researchers, with the aim of establishing the European Research Area as the world's most excellent and competitive"*.

Aligned with this clarification, our analysis suggests that EU research policy and Horizon Europe should indeed be more ambitiously: (i) engaged in openness, and (ii) able to benefit from its openness;

1) This requires first a continued and even further upscaled commitment and support to building excellence in S&T capacity. Excellence in S&T capacity is a necessary condition:
   - To attract external talent;
   - As a bargaining chip for scientific cooperation, trade and ideas networks;
   - For absorptive capacity for more effective learning through absorbing external S&T when flowing in and out.
2) Next benefiting from openness requires continued commitment and support for open circulation within an integrated single European market for research. This is because Europe will need a large internal integrated market for research to be able to specialise, to improve diffusion and to allow for catching-up and cohesion. This open circulation requires first and foremost the free cross-border flow of researchers and the ability to work together with partners across borders. This open circulation is most important for the EU member states, but a similar level of circulation should be allowed for researchers from Associated Countries. This means that these association agreements should not only be focused on access to funding, but also on removing any barriers to the deep integration of associated partners into the European Research Area, particularly in relation to to researcher mobility. With the likely scenario of the UK ceasing to be an EU member state, it is in the interest of both the UK and the EU27 to strive for an association in S&T that is as closely integrated as possible (see also de Meulenaer and Veugelers, 2019).
3) Further internal integration among EU member states and with associated partners should however not crowd out extra-EU/AC openness. A third requirement is an upscaled openness to the rest of the world, with much more support than in the past for: (i) collaboration with extra-EU+ partners, and (ii) flows of research talent from and to extra-EU+ (including return mobility). In order for the EU to benefit from this external openness, it will be important for it to be built on the basis of third parties' complementary research excellence.

As research excellence is critical in terms of being able to engage in openness and benefitting from it, research excellence should be the major criteria for selecting and evaluating the impact of FP projects under all of its pillars. This holds *a fortiori* for the Excellent Science pillar, for which scientific research excellence is the sole criteria. But this should also hold for the other pillars (Global Challenges & Missions and Open Innovation), which require excellence to be assessed for the research ideas development stage as a necessary, but not necessarily sufficient, condition. The cohesion criteria, although reflecting a societal objective, should not be mixed with the excellence criteria for selection and impact assessment under the main pillars. It should be addressed via specific instruments within and outside the EU's FP. The proposed increased budget for the Sharing Excellence programme in Horizon Europe and other EU funds, such as the Structural Funds, should address the cohesion criteria, allowing the other parts of the Horizon Europe budget to focus on excellence.

Another aspect to consider in the design of Horizon Europe is the extent to which it should target top-down specific areas in which Europe could become a global centre of research excellence. This targeting, if done, should be embedded in an overall balanced allocation of funding to bottom-up and top-down programmes. The pillars on Excellent Science and Open Innovations should be primarily investigator driven, funding their best ideas. Targeting is the hallmark of the pillar on Global Challenges and Missions. This pillar accounts in the current proposal for about half of Horizon Europe. To avoid the likely mistakes of not selecting winners, such targeting should be on impact while being sufficiently neutral on the ways to achieve this impact. In other words, reducing CO2 emissions should be targeted rather than specific technologies, such as wind or geothermal. As targeting should allow the EU to build a sustainable strong position in world markets in the long-term, it requires looking beyond current short-term strengths and weaknesses in particular technologies, and also a prospective analysis of longer-term positions across the whole value chain from scientific strengths in technology development to market development.

The recommended EU scenario of an FP committed to research excellence through an internally integrated S&T pole & externally open to the best poles worldwide, works best in a first best scenario of an open, interconnected multipolar global S&T landscape, but even if other poles are not open & cooperative, it is important for the EU to keep being open and internationally connected with strong extra-EU partners, a fortiori with our strong associated countries.

In support of this more ambitiously open FP, the EU should systematically monitor and evaluate its FP at the overall programme level and at the individual instrument level in terms of:

- Selection and contribution to research excellence.
- Selection and contribution to pathways to building research excellence
- Improvements in research excellence from these pathways

These pathways are international collaboration and international mobility of research talent, both intra-EU+ and extra-EU+.

Finally, it should be assessed how the contribution of FP-selected and induced research excellence has impacted technology development, innovation capacity, EU growth and competitiveness and societal challenges. This assessment should be made for the EU in total and also for each member state.

Such an FP research excellence monitoring and evaluation strategy requires *ex-ante* specified key performance indicators at the programme level and at the individual instrument level. For Research Excellence, the focus should be on frontier top research outcomes, rather than counting of publications and patents from FP funded projects, the emphasis should be on high-impact publications and patents, which are sufficiently novel to push the frontier, even if they are higher risk. For pathways to research excellence and their effectiveness, this requires tracing more systematically the research excellence of FP-funded international collaboration and FP-funded international mobility of researchers.

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APPENDIX

Table A. 1: Number of citable documents, by subject area, published in 2007

	EU	United States	China	Japan	South Korea	RoW
Agricultural and Biological Science	32 %	20 %	7 %	4 %	2 %	34 %
Arts and Humanities	41 %	34 %	3 %	2 %	1 %	20 %
Biochemistry, Genetics, Molecular Biology	34 %	27 %	7 %	7 %	2 %	22 %
Business, Management and Accounting	33 %	31 %	5 %	2 %	1 %	28 %
Chemical Engineering	30 %	20 %	15 %	6 %	4 %	26 %
Chemistry	32 %	16 %	16 %	7 %	3 %	27 %
Computer Science	32 %	20 %	15 %	5 %	3 %	25 %
Decision Sciences	35 %	23 %	10 %	2 %	3 %	27 %
Dentistry	34 %	20 %	2 %	8 %	2 %	34 %
Earth and Planetary Science	35 %	22 %	12 %	4 %	1 %	26 %
Economics, Econometrics and Finance	39 %	31 %	3 %	2 %	1 %	24 %
Energy	26 %	18 %	20 %	8 %	2 %	26 %
Engineering	27 %	19 %	20 %	7 %	4 %	23 %
Environmental Science	33 %	23 %	9 %	4 %	1 %	30 %
Health Professions	35 %	34 %	1 %	4 %	1 %	24 %
Immunology and Microbiology	36 %	24 %	5 %	6 %	3 %	27 %
Materials Science	29 %	16 %	18 %	9 %	4 %	24 %
Mathematics	35 %	19 %	15 %	5 %	3 %	24 %
Medicine	37 %	26 %	5 %	6 %	2 %	24 %
Multidisciplinary	23 %	26 %	24 %	3 %	1 %	24 %
Neuroscience	38 %	31 %	3 %	6 %	1 %	21 %
Nursing	35 %	35 %	2 %	2 %	2 %	24 %
Pharmacology	31 %	24 %	10 %	7 %	2 %	26 %
Physics and Astronomy	34 %	18 %	13 %	8 %	3 %	24 %
Psychology	36 %	40 %	1 %	2 %	0 %	21 %
Social Sciences	35 %	35 %	2 %	1 %	1 %	25 %
Veterinary	38 %	19 %	2 %	4 %	2 %	35 %

Notes: The table shows what share of total publications in a specific field have originated from a specific region in 2007.
Source: SCImago (2019).

Table A. 2: Number of citable documents, by subject area, published in 2017

	EU	United States	China	Japan	South Korea	RoW
Agricultural and Biological Science	29 %	15 %	13 %	3 %	2 %	38 %
Arts and Humanities	42 %	24 %	3 %	1 %	1 %	29 %
Biochemistry, Genetics, Molecular Biology	30 %	19 %	16 %	4 %	3 %	28 %
Business, Management and Accounting	32 %	18 %	7 %	1 %	2 %	40 %
Chemical Engineering	23 %	12 %	26 %	3 %	4 %	31 %
Chemistry	26 %	12 %	23 %	4 %	3 %	31 %
Computer Science	27 %	14 %	18 %	4 %	3 %	34 %
Decision Sciences	29 %	14 %	17 %	2 %	1 %	37 %
Dentistry	29 %	14 %	4 %	6 %	3 %	44 %
Earth and Planetary Science	32 %	16 %	18 %	3 %	1 %	31 %
Economics, Econometrics and Finance	37 %	20 %	5 %	2 %	2 %	35 %
Energy	24 %	13 %	23 %	3 %	3 %	34 %
Engineering	24 %	13 %	24 %	4 %	3 %	32 %
Environmental Science	29 %	15 %	17 %	2 %	2 %	36 %
Health Professions	33 %	26 %	4 %	3 %	3 %	32 %
Immunology and Microbiology	32 %	19 %	13 %	3 %	3 %	30 %
Materials Science	23 %	11 %	26 %	4 %	4 %	31 %
Mathematics	30 %	13 %	19 %	3 %	2 %	33 %
Medicine	32 %	21 %	11 %	4 %	2 %	30 %
Multidisciplinary	30 %	18 %	19 %	4 %	4 %	25 %
Neuroscience	36 %	25 %	9 %	4 %	2 %	25 %
Nursing	33 %	27 %	4 %	2 %	3 %	31 %
Pharmacology	26 %	17 %	16 %	4 %	3 %	35 %
Physics and Astronomy	29 %	13 %	18 %	5 %	3 %	33 %
Psychology	37 %	32 %	3 %	1 %	1 %	26 %
Social Sciences	35 %	24 %	5 %	1 %	1 %	34 %
Veterinary	31 %	15 %	6 %	2 %	2 %	44 %

Notes: The table shows what share of total publications in a specific field have originated from a specific region in 2017.
Source: SCImago (2019).

Table A. 3: Share of top 10% cited publications worldwide, by field

	2004				2014			
	United States	EU	China	Japan	United States	EU	China	Japan
All fields	*15.0*	*10.8*	*5.8*	*7.5*	*15.4*	*12.1*	*9.7*	*7.7*
Agricultural sciences	12.3	**13.5**	6.4	4.9	14.8	**14.6**	11.3	5.5
Astronomy	**15.4**	10.7	5.5	**10.0**	**17.7**	12.1	6.8	**15.2**
Biological sciences	14.9	11.0	3.4	8.3	16.0	**13.1**	7.6	9.3
Chemistry	15.2	10.8	8.3	**10.0**	14.0	10.1	**12.8**	8.0
Computer sciences	**16.5**	9.4	4.9	5.7	**18.5**	11.4	10.0	5.3
Engineering	14.5	**12.6**	5.4	7.7	14.0	11.5	10.2	6.6
Geosciences	13.3	**12.6**	5.8	**8.8**	15.8	**13.8**	9.4	8.5
Mathematics	15.1	10.3	**12.4**	8.4	13.2	12.0	10.9	**10.0**
Medical sciences	**16.4**	9.9	3.6	5.6	**16.5**	12.6	7.1	6.7
Other life sciences	10.2	11.1	7.8	5.7	10.7	10.7	**13.4**	6.6
Physics	15.0	11.6	7.5	8.7	14.7	12.6	10.0	**9.5**
Psychology	12.3	9.0	**9.5**	2.9	12.2	10.5	9.4	4.2
Social sciences	13.7	8.8	**12.0**	5.5	13.2	10.9	**17.1**	8.5

Note: The citation decile is the share of publications that are in the top 10% of the world's citations, relative to all the country's or economy's publications in that period and field. A value above 10 indicates that publications in a specific field from a specific country are more often among the highly cited articles in that field compared to the global average. Country of origin is assigned through the institutional affiliation of the author.

Source: National Science Foundation (2018).

Table A. 4: Indexes of internationally co-authored S&E publications, within Horizon 2020 countries

Country dyads	2006	2016	Country dyads	2006	2016	Country dyads	2006	2016
Austria - Belgium	1.29	1.8	Denmark - Ireland	1.4	1.94	Greece - United Kingdom	1.42	1.74
Austria - Czech Republic	2.36	3.64	Denmark - Italy	1.11	1.45	Greece - Norway	1.67	2.86
Austria - Denmark	1.19	1.83	Denmark - Netherlands	1.58	2.23	Greece - Switzerland	1.07	2.11
Austria - Finland	1.28	2.18	Denmark - Poland	1.06	2.05	Hungary - Ireland	0.92	2.9
Austria - France	0.73	1.24	Denmark - Portugal	1.32	1.82	Hungary - Italy	1.09	2.12
Austria - Germany	2.09	2.63	Denmark - Spain	1.16	1.47	Hungary - Netherlands	1.01	1.98
Austria - Greece	1.18	2.69	Denmark - Sweden	3.62	3.65	Hungary - Poland	1.84	4.95
Austria - Hungary	2.47	4.93	Denmark - UK	1.14	1.43	Hungary - Portugal	1.56	3.77
Austria - Ireland	0.97	1.77	Denmark - Norway	4.31	4.94	Hungary - Spain	0.94	2.18
Austria - Italy	1.24	1.76	Denmark - Switzerland	1	1.71	Hungary - Sweden	1.35	2.52
Austria - Netherlands	1.03	1.71	Finland - France	0.8	1.24	Hungary - UK	0.71	1.43
Austria - Poland	1.63	2.37	Finland - Germany	1.03	1.44	Hungary - Norway	0.85	3.17
Austria - Portugal	1.31	1.93	Finland - Greece	1.32	3.04	Hungary - Switzerland	0.8	2.38
Austria - Spain	1.01	1.42	Finland - Hungary	1.92	3.68	Ireland - Italy	0.93	1.63
Austria - Sweden	1.17	1.8	Finland - Ireland	2.08	2.79	Ireland - Netherlands	1.23	1.83
Austria - United Kingdom	0.67	1.03	Finland - Italy	1.16	1.53	Ireland - Poland	0.63	2.53
Austria - Norway	1.07	2.06	Finland - Netherlands	1.42	1.84	Ireland - Portugal	1.11	2.14
Austria - Switzerland	1.87	2.51	Finland - Poland	1.36	2.67	Ireland - Spain	1.07	1.75
Belgium - Austria	1.29	1.8	Finland - Portugal	1.39	1.84	Ireland - Sweden	1.28	1.56
Belgium - Czech Republic	1.42	1.9	Finland - Spain	1.15	1.56	Ireland - United Kingdom	2.04	2.16
Belgium - Denmark	1.28	1.65	Finland - Sweden	3.97	4.15	Ireland - Norway	1.26	2.03
Belgium - Finland	1.2	1.74	Finland - UK	1.03	1.28	Ireland - Switzerland	0.88	1.59
Belgium - France	1.66	1.97	Finland - Norway	3.31	3.79	Italy - Netherlands	1.22	1.6
Belgium - Germany	0.93	1.35	Finland - Switzerland	1.19	1.72	Italy - Poland	1.14	1.85
Belgium - Greece	1.63	2.31	France - Germany	0.87	1.16	Italy - Portugal	1.12	1.69
Belgium - Hungary	1.55	2.67	France - Greece	1.06	1.62	Italy - Spain	1.62	1.89

Country dyads	2006	2016	Country dyads	2006	2016	Country dyads	2006	2016
Belgium - Ireland	1.17	2.02	France - Hungary	0.86	1.68	Italy - Sweden	0.97	1.35
Belgium - Italy	1.22	1.7	France - Ireland	0.86	1.29	Italy - United Kingdom	1	1.27
Belgium - Netherlands	2.81	3.09	France - Italy	1.35	1.59	Italy - Norway	1.14	1.41
Belgium - Poland	1.38	1.87	France - Netherlands	0.96	1.25	Italy - Switzerland	1.42	1.77
Belgium - Portugal	1.22	1.89	France - Poland	1.11	1.49	Netherlands - Poland	0.85	1.63
Belgium - Spain	1.18	1.51	France - Portugal	1.13	1.33	Netherlands - Portugal	1.17	1.51
Belgium - Sweden	1.13	1.49	France - Spain	1.22	1.45	Netherlands - Spain	1.2	1.41
Belgium - United Kingdom	0.97	1.26	France - Sweden	0.78	1.11	Netherlands - Sweden	1.19	1.79
Belgium - Norway	1.05	1.5	France - UK	0.82	1.01	Netherlands - UK	1.21	1.5
Belgium - Switzerland	1.29	1.71	France - Norway	0.98	1.21	Netherlands - Norway	1.69	2.26
Czech Republic - Denmark	1.04	1.9	France - Switzerland	1.38	1.67	Netherlands - Switzerland	1.15	1.71
Czech Republic - Finland	1.58	2.52	Germany - Greece	1.02	1.52	Norway - Switzerland	0.92	1.58
Czech Republic - France	1.24	1.44	Germany - Hungary	1.35	1.91	Poland - Portugal	1.35	2.35
Czech Republic - Germany	1.32	1.51	Germany - Ireland	0.89	1.3	Poland - Spain	1	1.78
Czech Republic - Greece	2.11	3.72	Germany - Italy	0.99	1.3	Poland - Sweden	1.25	1.83
Czech Republic - Hungary	2.74	6.46	Germany - Netherlands	1.29	1.68	Poland - United Kingdom	0.7	1.12
Czech Republic - Ireland	1.91	2.06	Germany - Poland	1.3	1.63	Poland - Norway	1.2	2.48
Czech Republic - Italy	1.33	1.63	Germany - Portugal	0.85	1.08	Poland - Switzerland	0.99	1.85
Czech Republic - Netherlands	1.08	1.43	Germany - Spain	0.87	1.19	Portugal - Spain	2.97	3.43
Czech Republic - Poland	3.37	5.07	Germany - Sweden	1	1.38	Portugal - Sweden	1.16	1.28
Czech Republic - Portugal	1.66	2.61	Germany - UK	0.83	1.07	Portugal - UK	1.17	1.19
Czech Republic - Spain	0.98	1.67	Germany - Norway	0.89	1.26	Portugal - Norway	1.18	1.86
Czech Republic - Sweden	1.32	1.83	Germany - Switzerland	1.66	2.04	Portugal - Switzerland	0.98	1.49
Czech Republic - UK	0.81	0.96	Greece - Hungary	1.22	5.17	Spain - Sweden	0.94	1.34
Czech Republic - Norway	1.09	2.23	Greece - Ireland	1.26	2.94	Spain - United Kingdom	0.99	1.16
Czech Republic - Switzerland	1.29	1.92	Greece - Italy	1.54	2.46	Spain - Norway	1.15	1.51

Country dyads	2006	2016	Country dyads	2006	2016	Country dyads	2006	2016
Denmark - Finland	2.73	3.16	Greece - Netherlands	1.31	2.06	Spain - Switzerland	0.89	1.36
Denmark - France	0.84	1.14	Greece - Poland	1.62	3.38	Sweden - UK	1	1.27
Denmark - Germany	1.13	1.51	Greece - Portugal	1.75	3.23	Sweden - Norway	3.86	4.42
Denmark - Greece	1.36	2.4	Greece - Spain	1.3	2.19	Sweden - Switzerland	1.02	1.48
Denmark - Hungary	0.94	2.76	Greece - Sweden	1.08	2.08	UK - Norway	1.15	1.4
						UK - Switzerland	0.91	1.21

Source: NSF, SEI 2018.

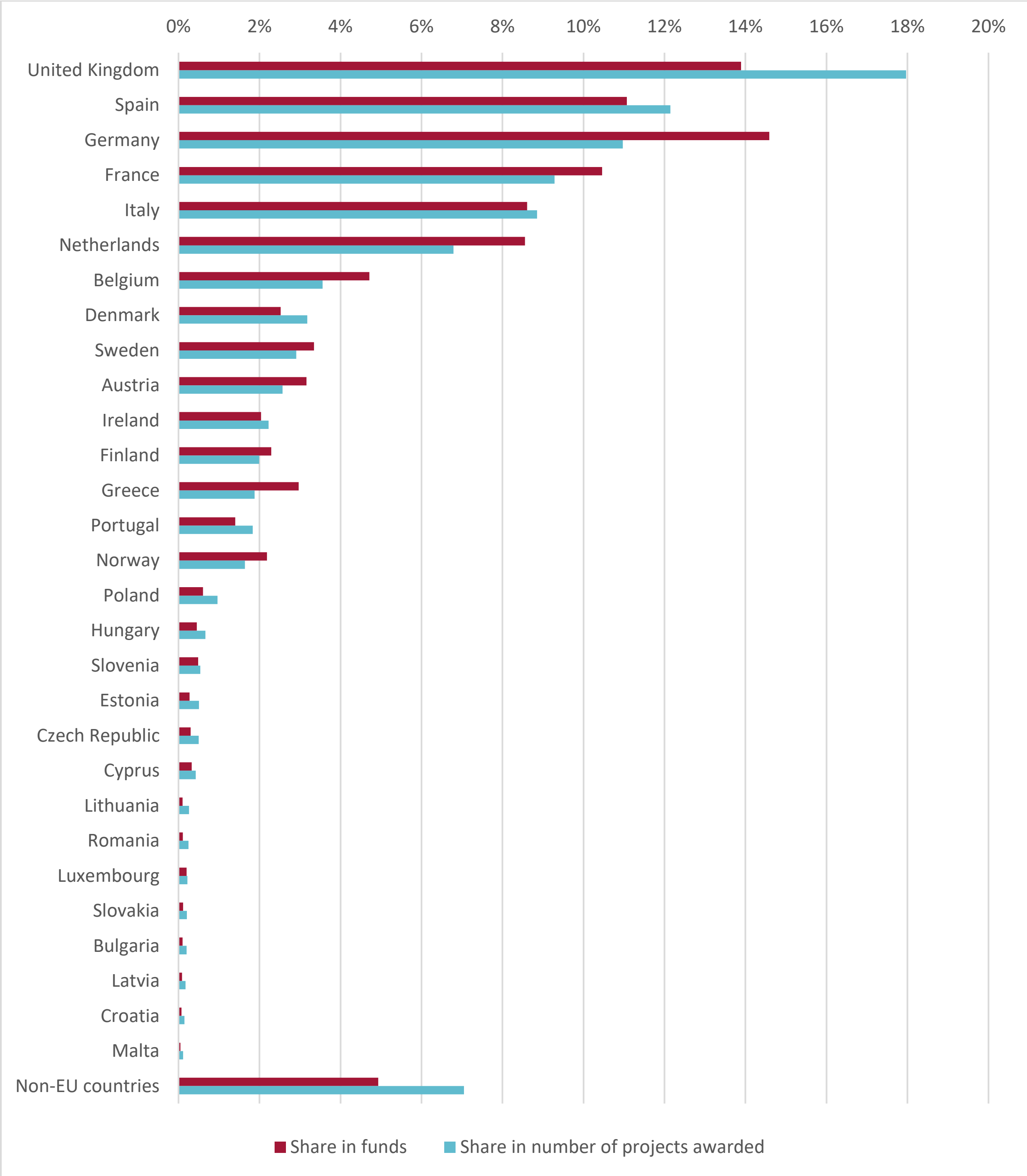
Note: The index of collaboration is calculated as follows: ICxy = (Cxy/Cx)/(Cy/Cw), where ICxy = index of collaboration between country x and country y, Cxy = number of papers coauthored between country x and country y, Cx = total number of international coauthorships by country x, Cy = total number of international coauthorships by country y, and Cw = total number of international coauthorships in the database.

Table A. 5: Share of international collaborative links under FP7

	Intra EU	*of which:*		Extra EU	*of which:*			Total links
		EU-15	EU-13		CH	US	CN	
Austria	89.6 %	80.0 %	9.6 %	10.4 %	3.1 %	0.3 %	0.2 %	48,292
Belgium	89.7 %	81.1 %	8.6 %	10.3 %	3.0 %	0.5 %	0.3 %	74,457
Germany	89.1 %	81.2 %	7.9 %	10.9 %	3.9 %	0.5 %	0.2 %	230,704
Denmark	88.3 %	80.2 %	8.1 %	11.7 %	3.0 %	0.5 %	0.3 %	37,151
Greece	87.8 %	77.3 %	10.5 %	12.2 %	2.6 %	0.4 %	0.3 %	46,988
Spain	89.9 %	81.2 %	8.7 %	10.1 %	2.7 %	0.3 %	0.2 %	143,717
Finland	90.1 %	80.8 %	9.3 %	9.9 %	2.9 %	0.4 %	0.2 %	42,805
France	89.1 %	81.5 %	7.6 %	10.9 %	3.2 %	0.4 %	0.2 %	164,536
Ireland	89.3 %	79.8 %	9.5 %	10.7 %	2.7 %	0.5 %	0.2 %	23,522
Italy	89.4 %	80.9 %	8.5 %	10.6 %	3.2 %	0.4 %	0.2 %	158,430
Luxembourg	88.1 %	74.5 %	13.6 %	11.9 %	2.7 %	0.4 %	0.2 %	3,652
Netherlands	89.2 %	81.4 %	7.8 %	10.8 %	3.0 %	0.5 %	0.3 %	107,480
Portugal	89.0 %	79.2 %	9.9 %	11.0 %	2.2 %	0.3 %	0.3 %	31,905
Sweden	90.2 %	82.1 %	8.0 %	9.8 %	2.9 %	0.5 %	0.2 %	63,536
United Kingdom	88.2 %	80.3 %	7.9 %	11.8 %	3.5 %	0.6 %	0.3 %	187,392
Bulgaria	84.5 %	65.1 %	19.5 %	15.5 %	1.9 %	0.2 %	0.2 %	10,678
Cyprus	85.8 %	70.5 %	15.3 %	14.2 %	2.5 %	0.4 %	0.1 %	6,326
Czechia	90.4 %	77.7 %	12.7 %	9.6 %	2.5 %	0.2 %	0.2 %	21,416
Estonia	86.7 %	69.9 %	16.9 %	13.3 %	2.0 %	0.2 %	0.2 %	7,589
Croatia	86.2 %	66.1 %	20.1 %	13.8 %	2.2 %	0.3 %	0.2 %	5,901
Hungary	89.3 %	72.4 %	17.0 %	10.7 %	2.7 %	0.3 %	0.2 %	21,541
Lithuania	88.4 %	68.0 %	20.4 %	11.6 %	2.5 %	0.2 %	0.1 %	5,990
Latvia	87.9 %	63.6 %	24.2 %	12.1 %	2.1 %	0.2 %	0.1 %	5,159
Malta	84.4 %	63.5 %	20.9 %	15.6 %	1.5 %	0.1 %	0.0 %	3,309
Poland	90.3 %	77.3 %	13.0 %	9.7 %	2.5 %	0.3 %	0.2 %	29,638
Romania	87.8 %	71.2 %	16.7 %	12.2 %	2.2 %	0.2 %	0.1 %	16,486
Slovenia	89.4 %	74.0 %	15.4 %	10.6 %	2.4 %	0.3 %	0.2 %	13,453
Slovakia	89.6 %	69.9 %	19.7 %	10.4 %	2.4 %	0.3 %	0.3 %	7,251
EU-28	89.1 %	80.0 %	9.2 %	10.9 %	3.1 %	0.4 %	0.2 %	1,519,304
EU-15	89.2 %	80.8 %	8.3 %	10.8 %	3.2 %	0.5 %	0.2 %	1,364,567
EU-13	88.6 %	72.3 %	16.3 %	11.4 %	2.4 %	0.3 %	0.2 %	154,737

Source: Bruegel based on European Commission (2018b).

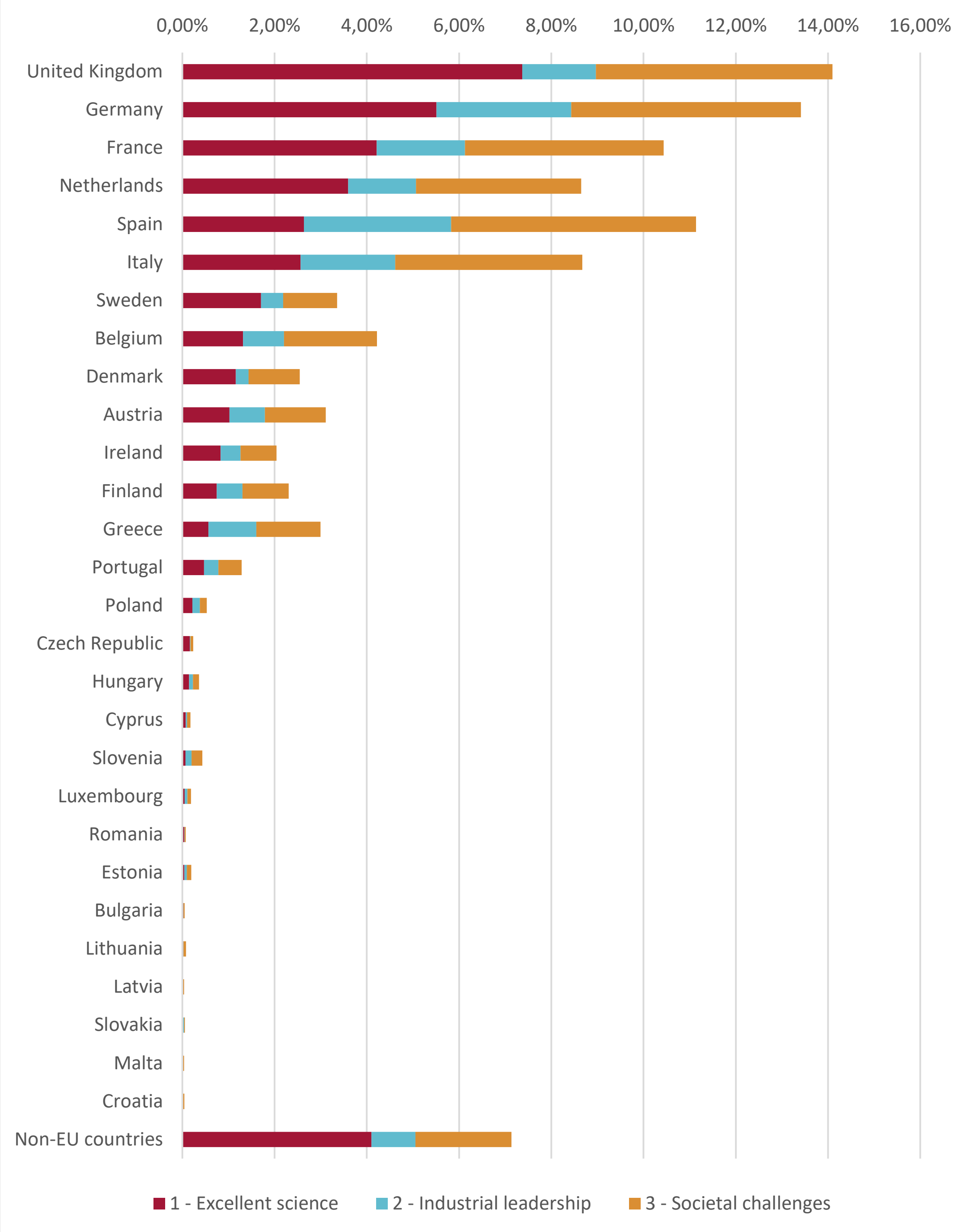
Figure A. 1: Distribution of Horizon 2020 projects to coordinator countries



Note: Project assignment as of December 2018.

Source: Bruegel based on data from European Commission (2018b).

Figure A. 2: Distribution of Horizon 2020 project-funds to coordinator countries, by pillar



Note: Project assignment as of December 2018.

Source: Bruegel based on data from European Commission (2018b).

The world of research and innovation is becoming increasingly multipolar with China joining the ranks of science and technology leaders. For the EU, increased global research capacities offer a larger global talent pool and opportunities for specialisation, but also increased competition for investment, talent and the position as world-leader in critical technological fields. To be a global centre for excellent research, the EU and its Framework Programme must support the further integration of the intra-EU excellent research pole and at the same time being open for foreign talent and internationally connected with strong extra-EU partners.

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