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The challenge of China's rise as a science and technology powerhouse

Reinhilde Veugelers

Executive summary

CHINA IS BUILDING UP ITS GLOBAL COMPETITIVENESS in knowledge-intensive sectors and its ambition to be a global leader in science and innovation by 2050 seems well within reach. China outperforms the European Union in terms of expenditure on research and development as a share of its GDP, and already produces about the same number of scientific publications, and more PhDs in natural sciences and engineering, than the United States.

CHINA ASPIRES TO PRODUCE AND CAPITALISE ON HOME-GROWN SCIENTIFIC TALENT, but its growth model for science still involves sending out its increasingly better locally-trained scholars to the best institutes in the world and reaping the benefits when they return in the later stages of their careers, after they have fully developed their capabilities and built their networks. The US remains the favoured destination for Chinese students, which has led to the creation of US-Chinese science and technology networks and connections that are mutually beneficial: enabling China to catch up and helping the US to keep its position at the science frontier.

THE EU HAS MUCH LESS-DEVELOPED SCIENTIFIC CONNECTIONS to China than the US. The EU should take steps to engage more with China if it is not to miss out in the future multipolar science and technology world.

REINHILDE VEUGELERS (reinhilde.veugelers@bruegel.org) is a Senior Fellow at Bruegel.

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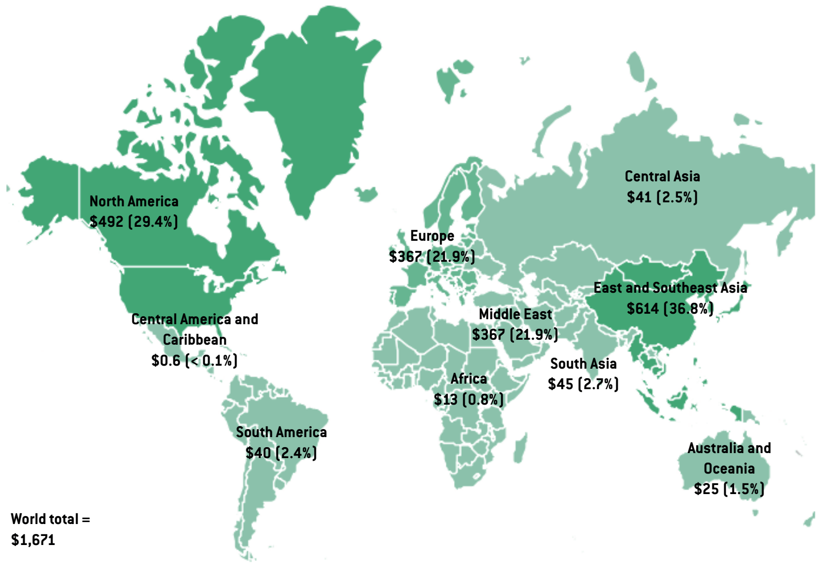
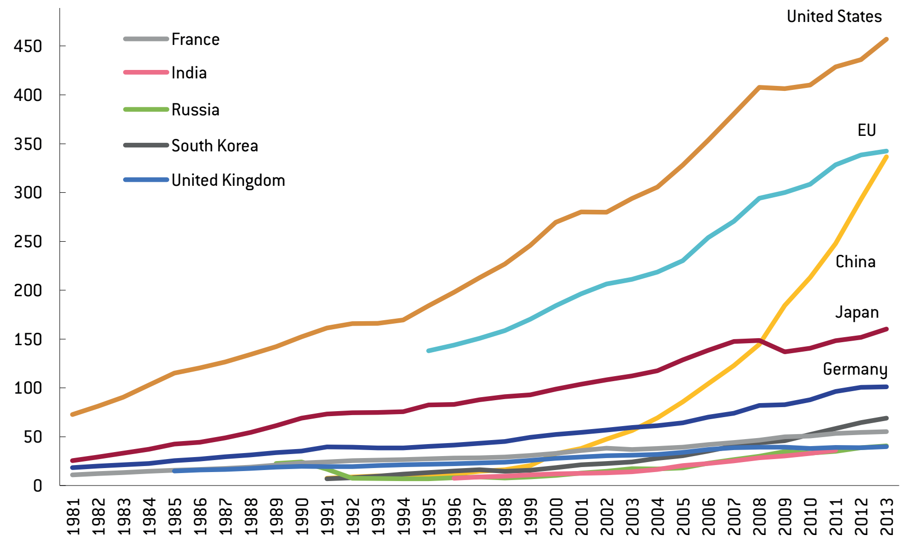
1 Introduction

The creation of scientific 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 scientific development, but China in particular has emerged as a new science and technology (S&T) powerhouse.

A key indicator of the rise of China in S&T is its spending on research and development (R&D). Chinese R&D investment has grown remarkably, with the rate of growth greatly exceeding those of the United States and the European Union. China is now the second-largest performer of R&D, on a country basis, and accounts for 20 percent of total world R&D (Figure 1).

Figure 1: The world R&D landscape (R&D spending in billions of current PPP)

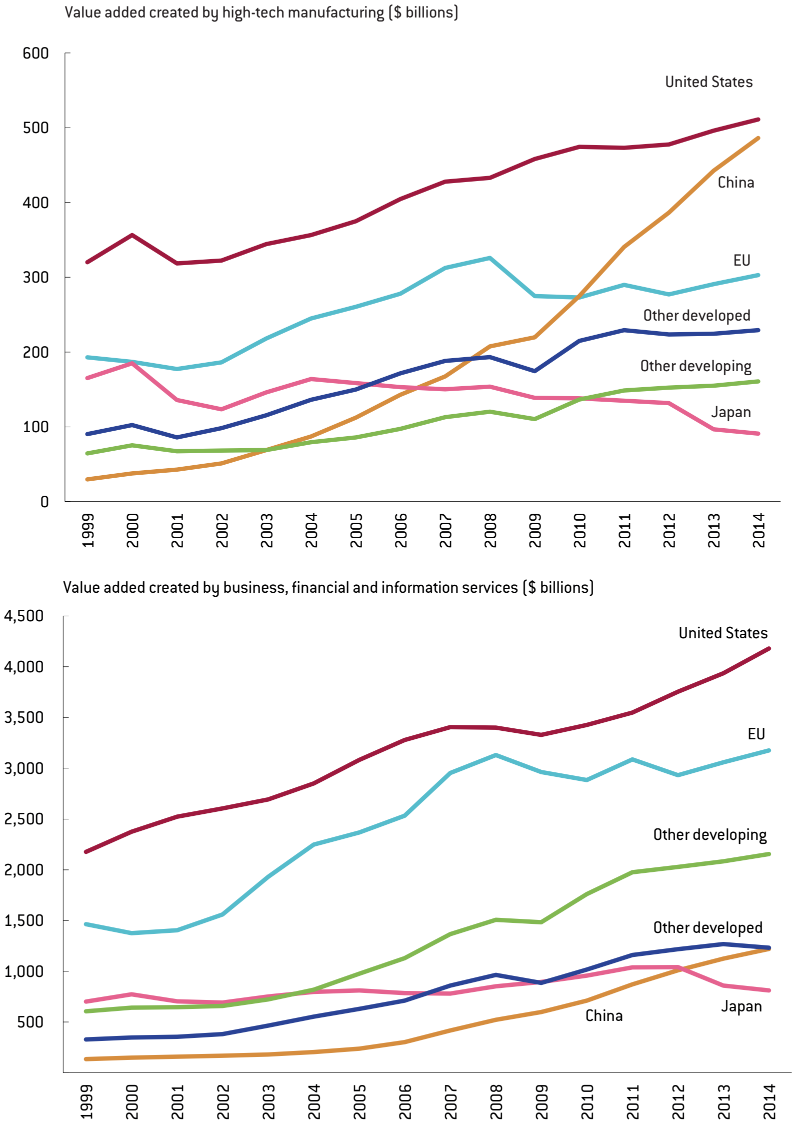




Source: Bruegel based on NSF (2016). PPP = purchasing power parity. NOTES: Foreign currencies are converted to dollars through PPPs. Some country data are estimated. Countries are grouped according to the regions described by The World Factbook, www.cia.gov/library/publications/the-world-factbook/.

China is increasingly prominent in industries that intensively use scientific and technological knowledge. China ranks second behind the US in terms of the share of total value added created by high-tech manufacturing (Figure 2, upper panel). In commercial knowledge-intensive services (business, financial and information), China has now surpassed Japan to move into third place behind the US and the EU (Figure 2, lower panel).

Figure 2: The rise of China in high tech (current US dollars, billions)



Source: Bruegel based on NSF (2016).

China's rise in science and technology is not an accident. Successive Chinese leaderships have seen S&T as integral to economic growth, and consequently have taken steps to develop China's S&T infrastructures. In the twelfth five-year plan (2011-15), China listed the promotion of scientific and technological progress and innovation as a major tool for supporting strategic economic restructuring. Technology development and innovation also figure prominently in the current thirteenth five-year plan (2016-20). China's *National Medium-and Long-Term Programme for Science and Technology Development* (MLP), introduced in 2006, is an ambitious plan to transform the Chinese economy into a major centre of innovation by the year 2020, and a global leader in science and innovation by 2050. Among the goals of the MLP are that R&D expenditure should rise to 2.5 percent of GDP – a target that has largely already been reached. The MLP also puts the emphasis on *"indigenous innovation"*, with a goal for the country's reliance on foreign technology to decline.

The rise of China as an S&T powerhouse is likely to affect S&T in the US and Europe. The US S&T model has traditionally been at the frontier and very open. Because the US science and engineering workforce is highly dependent on migrants, especially from Asia, the rise of China has provoked deep concern about the sustainability of the American capacity for innovation and international competitiveness. An added concern is the more recent trend in the US to move to a more restrictive immigration policy. This comes on top of a reluctance to allocate public funding to support the building of S&T infrastructure[1].

The EU has focused on catching up in S&T terms with the US. The failure to attract and keep the best scientific brains is also a persistent area of concern for the EU (Veugelers, 2017). However, the EU is mostly focused on building and sustaining its integrated internal market for research (the European Research Area, ERA) and removing barriers to intra-EU mobility of researchers. Although ERA is posited to be an open area, its international strategy is marked by pronounced EU-supported, intra-EU collaboration, with the risk of overlooking the US and emerging Asia as partners.

2 A multipolar science world: trends

2.1 China's increasing share of scientific output

The US has led the world in the production of scientific knowledge for decades, in terms of both quantity and quality. However, since 1994, the EU, considered as a bloc (including the United Kingdom), has outperformed the US in quantity, measured by the number of scientific papers published in internationally peer-reviewed journals[2]. But the biggest change has come from outside the traditional science powers of the US, EU and Japan: China now publishes more than any other country apart from the US (Table 1).

Table 1: The rise of China in science

	Share of world scientific papers 2003	Share of world scientific papers 2013	Average annual growth rate in scientific papers 2003-13
US	26.8%	18.8%	7.0%
EU	31.0%	25.4%	4.9%
Japan	7.8%	4.7%	1.7%
SKorea	2.0%	2.7%	10.4%
China	6.4%	18.2%	18.9%

Source: Bruegel based on NSF (2016).

China's scientific priorities are shown by the big increase in its share of published papers in the fields of *computer sciences* and *engineering* (Table 2). In *engineering*, China accounted for more than one third of papers published worldwide in 2013 –by far the largest national share. The US share is 12 percent and the EU share 19 percent. In *computer sciences*, China is responsible for more than one fifth of all papers published worldwide, compared to 14 percent for the

1 See eg http://www.kauffman.org/key-issues or https://itif.org/publications.

2 Publications and citations as recorded by Thomson's ISI-Web of Science journals, which includes only journals that satisfy a number of quality criteria (internationally peer-reviewed). These journals have an English-language bias as well as a disciplinary bias in favour of biomedicine and life sciences.

US. The EU as a bloc accounts for 30 percent of published computer sciences papers. In *chemistry*, China produces one quarter of all published papers. In *mathematics*, the Chinese share is 18 percent. In *life sciences* (biological and medical sciences), China's rise has been much less pronounced. The EU and the US retain for the moment their predominant roles in this area.

Table 2: The rise of China by scientific field

Field	China's share of published papers, 2013	Chinese scientific publications, annual growth rate (2007-2013)
All fields	18.2%	18.9%
Medical sciences	7.5%	15.0%
Biological sciences	13.9%	14.4%
Chemistry	24.5%	14.8%
Physics	19.6%	14.7%
Mathematics	18.0%	17.8%
Computer sciences	21.1%	25.1%
Engineering	34.8%	22.1%

Source: Bruegel based on NSF (2016).

Quality of research is another matter. In terms of research impact, measured by the number of times scientific papers are cited, the US's dominant position is less contested (Table 3). Proportionally, more papers produced in the US are included among the top 1 percent of most-cited papers, and the US contribution is still growing. The EU is also improving its position in the top cited segment, but still scores below the US.

China for now is making only very modest inroads into the top segment. The share of Chinese scientific papers included in the top 1 percent cited segment is still below 1 percent, but China is progressing and is already on par with Japan.

In *chemistry* and in *mathematics*, more than 1 percent of Chinese papers are already in the top 1 percent segment for citations. And in *computer sciences,* China has made impressive progress.

Table 3: Quality of scientific output measured by number of citations *

	United States		EU		China		Japan	
	2002	2012	2002	2012	2002	2012	2002	2012
All fields	1.76	1.94	0.96	1.29	0.50	0.81	0.62	0.82
Engineering	1.79	2.01	1.06	1.30	0.52	0.73	0.78	0.90
Chemistry	1.99	1.82	1.01	1.01	0.61	1.30	0.83	0.58
Physics	1.76	2.08	1.15	1.35	0.56	0.85	0.69	1.09
Mathematics	1.61	1.29	0.92	1.03	1.20	1.28	0.87	0.47
Computer sciences	2.04	2.23	0.72	1.13	0.21	0.80	0.24	0.39
Biological sciences	1.65	1.96	0.95	1.45	0.18	0.53	0.61	0.98
Medical sciences	1.91	2.05	0.88	1.37	0.30	0.55	0.42	0.71

Source: Bruegel based on NSF (2016). Note: * the citation percentile is the share of each country's scientific papers in the top 1 percent of papers cited worldwide; it is a commonly used measure for the quality of scientific publications: the higher the share is above 1 percent (the world average), the higher the quality.

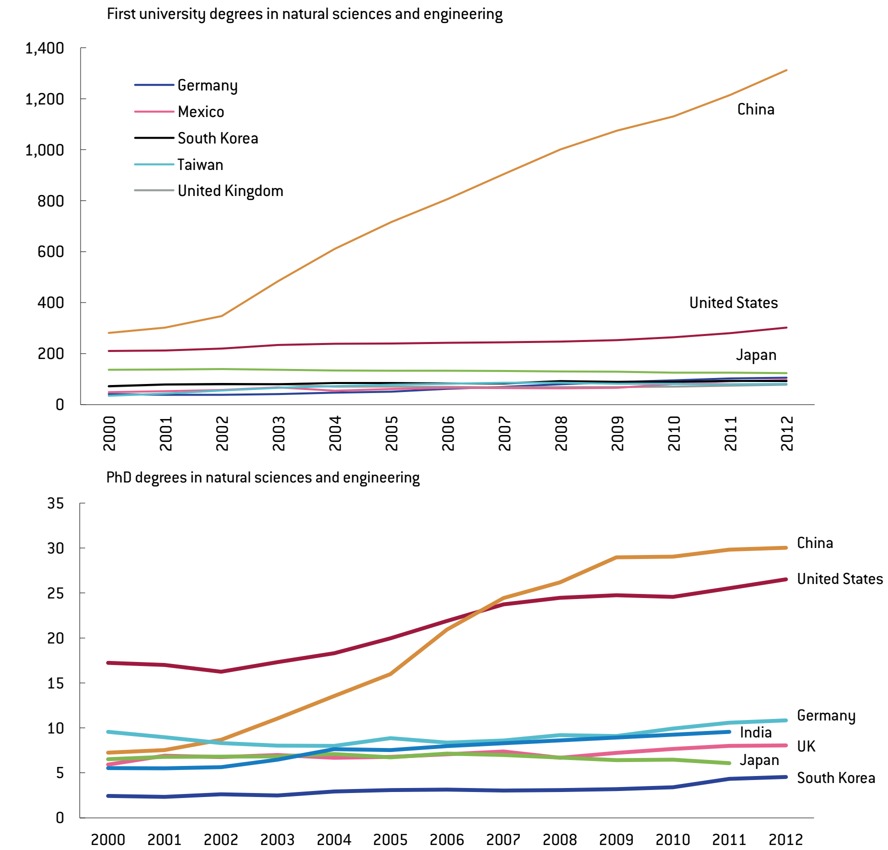
2.2 China's growing R&D workforce

The rise of China in science and in knowledge- and technology-intensive industries requires a growing R&D workforce. The share of China's workforce active in public and private R&D was only 0.19 percent of total employment in 2013, considerably below the levels in the US (0.87 percent), EU (0.77 percent) or Japan (1.02 percent). But the Chinese score has been rising rapidly: its average annual growth rate between 2009 and 2013 was 11 percent (compared to 2 percent in the EU and no growth in Japan; NSF, 2016). Numbering about 1.5 million, China had in 2014 more full-time equivalent researchers in employment than the US (1.3 million), more than twice the number in Japan, and about 85 percent of the EU number[3].

This steep increase in the number of researchers in China's workforce has been underpinned by significant strides in science and engineering education. China has massively increased the number of bachelor, master and PhD degrees it awards. This is particularly the case for *natural sciences* and *engineering*. While western governments are concerned about lagging student interest in these areas, which are considered vital for knowledge-intensive economies, the number of university degrees awarded in these fields in China has risen very rapidly since 1999, when university admission was expanded (Figure 3, top panel). China is now the world's number-one producer of undergraduates with science and engineering degrees, delivering almost one quarter of first university degrees in science and engineering globally.

There has been a similar trend in the award of PhD degrees in China, with the number of natural sciences and engineering doctorates increasing more than tenfold between 2000 and 2006. Since 2007, China has awarded more PhD degrees in natural sciences and engineering than any other country. This contrasts starkly with the EU, where there has been little increase in the number of science and engineering doctorates.

Figure 3: The rising number of degree awards (thousands)



Source: Bruegel based on NSF (2016).

3 If we exclude the UK from the EU calculations, China would have the same size of R&D workforce as the EU.

The Chinese programme to build-up scientific capacity has been concentrated on a selected set of institutes. Of China's 1700 chartered institutes of higher education, 6 percent absorb 70 percent of scientific research funding and produce about a third of all Chinese undergraduate students, two-thirds of graduate students and four-fifths of doctoral students. China's top universities are Tsinghua University and Beijing University. Both are among the top 100 universities in the Shanghai Academic Ranking of World Universities[4]. The US continues to dominate this ranking. In the 2016 edition, 15 of the first 20 places are taken by US universities, with Harvard persistently in first place. UK universities take three positions in the top 20 (Cambridge, Oxford, University College London), while Switzerland and Japan each have one institution in the top 20. Chinese universities are not yet to be found in the top 50. Nevertheless, Tsinghua is ranked 58 and Beijing 71.

But the position of Chinese universities in the ranking of the world's top institutes is already stronger in the scientific fields that have been targeted to support China's economic build-up in selected high-tech sectors: in *engineering*, Tsinghua is in fourth position (with Massachusetts Institute of Technology in first); in *sciences* Beijing is in twenty-second position (with University of California, Berkeley in first); in *computer sciences* Tsinghua is in twenty-fifth place (with Stanford first); and in *mathematics*, China has four slots in the top 50.

3 A multipolar science world: the impact on science in the west

In this section we look at the impact of China's scientific rise on science on the west: will a shift of scientific power to China dry up the flows of scientific talent from east to west, crippling the western science machine? And are the rising Chinese scientific centres new partners for scientific collaboration with the west?

3.1 Shifting patterns in the international mobility of students & scholars

Increasing Chinese scientific power has provoked concern in the west that the flow of Chinese talent will slow. US universities import much of their scientific talent from abroad, particularly from Asia, and particularly from China. There are therefore particular worries in the US about being able to continue to attract the best of the world's brains to power the US science machine. This concern, however, is so far not justified by the data, as this section will show.

More internationally mobile students (both undergraduates and graduates) go to the United States than to any other country. Although the numbers of international students going to the US continue to increase, the US share declined from 25 percent in 2000 to 19 percent in 2013 (OECD, 2015a). Still, the number of international undergraduates enrolled in the US in 2013-14 was 42 percent above the number in 2001-02. China accounts for 30 percent of foreign students in the US and the numbers keep on rising: about 45 percent of the growth in US international undergraduate enrolment between 2013 and 2014 was accounted for by the increase in the number of students from China (18 percent compared to the previous year; NSF, 2016).

Among PhD students, the Chinese represent by far the largest group of foreign PhD recipients in the US, taking 29 percent of all PhDs awarded to foreign students in 2013, representing

4 ARWU (Academic Ranking of World Universities) ranks world universities according to six indicators, including the number of alumni and staff winning Nobel Prizes and Fields Medals, number of highly cited researchers selected by Thomson Reuters, number of articles published in the journals Nature and Science, number of articles indexed in the 'Science Citation Index – Expanded and Social Sciences Citation Index', and per capita performance.

about 7 percent of all PhDs awarded in the US (Table 4)[5]. While the number of Chinese PhD students kept growing until 2009, it has since declined, although only slightly (by 3 percent) between 2009 and 2013 (NSF, 2016). This drop, although still small, might indicate the start of a trend for Chinese graduate students to substitute foreign PhDs with domestic PhDs.

One could interpret the evidence provided so far as showing that China has been building its S&T capacity in natural sciences and engineering by sending its students to the best training ground in the world – the US – and then bringing them back home.

The data, however, does not show high return rates for Chinese students who have obtained a PhD in the US, at least in the short-term after their PhD graduation (Table 4). The vast majority of Chinese PhDs in the US have plans to stay (84 percent compared to 75 percent for all foreign PhDs). And although Chinese PhD stay rates have decreased more recently, they are still very high, including in *mathematics and computer sciences*.

The share of Chinese among foreign PhDs in the US is particularly high in *mathematics and computer sciences* (Table 4). The Chinese share of PhDs awarded to foreigners in this area increased to 38% in 2009. Although the share has remained flat since, mathematics and computer sciences is still the scientific field with the largest share of Chinese PhDs.

Table 4: Stay rates for Chinese PhDs in the US; by scientific field

	Chinese share of foreign PhD recipients in the US, 2002-05	Chinese share of foreign PhD recipients in the US, 2010-13	% with plans to stay 2002-05	% with plans to stay 2010-13
All fields	28%	29%	92%	84%
Physical sciences	33%	35%	93%	85%
Life sciences	31%	28%	95%	87%
Maths & computer sciences	27%	38%	91%	86%
Social sciences	9%	14%	78%	64%

Source: Bruegel based on NSF (2016), on the basis of Survey of Earned Doctorates results[6].

While the data does not seem to show strong return flows immediately following graduation, Chinese scientists could be returning home at later stages in their careers. There is no doubt that China is aggressively seeking to bring home talented individuals. To increase the return rate of scholars, government institutions offer positions, housing, equipment, research teams, funding and preferential tax treatment[7]. But hard data on the scale of these return flows is still lacking. In any case, if researchers postpone their returns until later career stages, there is still plenty of scope for the US to benefit from imported foreign talent. Foreigners contribute disproportionally to top US scientific excellence: foreigners in the US are twice as likely to be the lead author on frequently cited 'hot papers', or among the most-cited authors (Stephan and Levin, 2007). A virtuous circle thus seems to have been established: the US's top position in science is based on its openness to the best foreign researchers, who stay long

5 The temporary residents' share of science and engineering doctorates in the US was more than one third (37 percent) in 2013; they earned half or more of the doctoral degrees awarded in engineering, computer sciences and economics (NSF, 2016).

6 Although the numbers in Table 4 show the intentions of survey respondents to stay, they correlate very well with actual stay rates. Data from the US Oak Ridge Institute (https://orise.orau.gov/) shows that of those with temporary visas who obtained a science and engineering PhD, 75 percent were still in the US in 2007, 66 percent in 2011. For Chinese science and engineering PhDs, these numbers were much higher at 92 percent and 85 percent respectively.

7 See the Chinese government's *Thousand Talents Plan*, http://www.1000plan.org/en/.

enough to contribute to the build-up of quality science, maintaining the US in its top position, which ensures it can keep on attracting the best foreign talent (Veugelers, 2017).

The presence of foreign PhD students in the EU, including Chinese students, is less systematically recorded. In general, the imperfect evidence shows that the PhD student populations of EU countries have fewer foreigners compared to the US, and the geographic sources of foreign PhD students are different, with geographical, cultural and political links being more important relative to the US, and a less strong Asian presence compared to the US (see for example Moguerou, 2006).

The EU introduced in 2007 a new programme to support the research ideas of individual scientists, who are selected by peer review on the basis of scientific excellence: the European Research Council (ERC) grants. So far about 7,000 grants have been granted. In addition to supporting EU scientists, the intent was to use the ERC grants to attract leading scientists from outside the EU. So far, only about 8 percent of ERC grants have been allocated to scientists from non-EU countries. Of these, the greatest amount went to US scientists (40 percent), and only 4 percent to Chinese nationals. Nevertheless, ERC grants attracted researchers to Europe (most of them PhD or post-doctoral students), not as established principal investigators, but rather as team members on ERC projects: about 17 percent of ERC team members come from a non-ERA country (ERA includes the EU countries and Switzerland, Israel and Norway), amounting to more than 9000 scientists so far. Of these non-ERA team members, the country of origin for the largest proportion is China, with 18 percent, closely followed by the US with 16 percent. The ERC case thus shows that Chinese graduates can be attracted to the EU, at least to scientific excellence hubs.

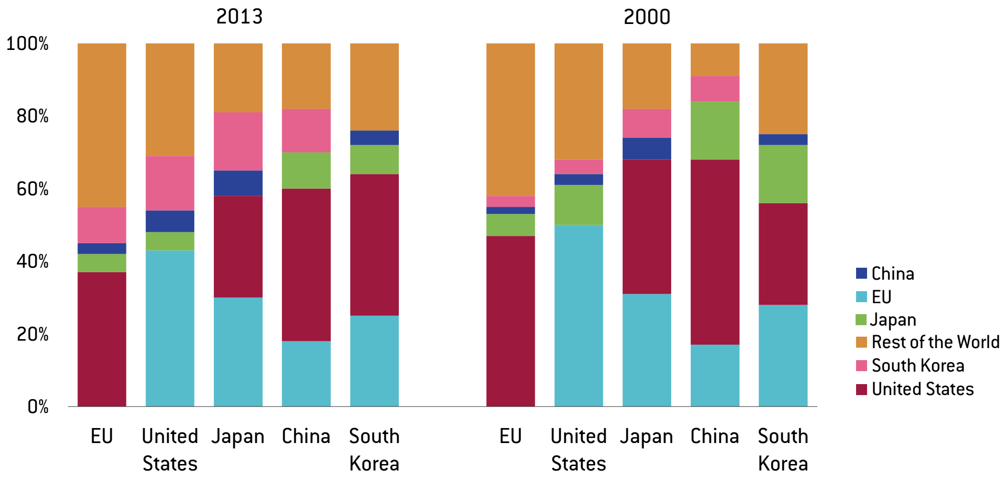
3.2 International collaboration in science

International collaboration allows scientists from different countries to partner with leading experts elsewhere. Scientists engaged in international collaboration tend to produce higher quality research (OECD, 2015b; European Commission, 2016). In the context of its increasing scientific heft, is China becoming a more important partner for the west for scientific cooperation?

Of the world's leading science economies, the EU is most inclined to collaborate internationally. But for the EU, international collaboration is first and foremost intra-European collaboration. In most EU countries, at least 70 percent of papers that are internationally co-authored involve researchers from other EU countries (with the UK having the lowest share of intra-EU international collaboration, at 'only' 56 percent). China is the least inclined to collaborate internationally. However in all countries/regions, the share of international scientific collaboration has been increasing since 2000 (see European Commission, 2016).

The data on who collaborates with whom does not show major shifts in collaboration patterns (Figure 4). Collaboration patterns are linked to student and researcher mobility patterns and tend to change only gradually over time. China, although on the rise as a partner for international scientific collaboration, is still relatively under-represented as a scientific collaboration partner despite its growing scientific weight. The US has seen the greatest increase in collaboration with China, while the increase has been more modest for the EU. Reciprocally, the US was and is China's major partner for scientific collaboration. The intense flow of scientists between the US and China undoubtedly contributes to stronger US-China collaborative networks. European countries are less in the Chinese focus for cooperation. The EU's collaboration with China, although on the rise, has not tracked the growth of China's scientific power.

Figure 4: Partners in international scientific collaborations, measured by internationally co-authored publications (2000, 2013)



Source: Bruegel based on European Commission (2016).

In terms of the international collaboration financed by the EU through its Seventh Framework Programme (FP7, 2007-13), Chinese involvement is marginal[8]. Although FP7 was designed to be open to non-EU countries (although non-EU parties typically cannot receivg20

e EU funding) in practice there was little support for non-EU partnerships. For all collaborative projects in the FP7 period a total of about 1.5 million pairings were supported (European Commission, 2014). Of these 89 percent involved partners from different EU countries. Only 0.4 percent involved a US partner and only 0.2 percent involved a Chinese partner.

4 A multipolar science world: the impact beyond science

The rise of China as a scientific powerhouse will have an impact beyond science on the technology, innovation, entrepreneurship and economic growth potential of the west. Chinese companies will leverage China's scientific power to increase their competitiveness on world markets, challenging their western competitors.

In the list of the firms worldwide that spend the most on R&D, tracked by the EU Industrial R&D Investment Scoreboard (Table 5), the number of Chinese companies is still low, but the Chinese presence is fast increasing. The size and intensity of the R&D activities of Chinese companies is also still limited compared to their western counterparts, but also here the pace of change is rapid. Chinese companies are in particular increasing their investment in digital hardware and software. One example is Huawei, which over a short period became the eighth biggest R&D spender worldwide (second in the technology hardware sector). Huawei has also filed the most patent applications at the World Intellectual Property Organisation in recent years.

8 Source: E-CORDA, data extracted on 14 September 2016. E-CORDA is a non-public European Commission database.

Table 5: R&D spending by companies by region, from EU Industrial R&D Investment Scoreboard

	China	EU	US	Japan
Number of firms (out of 2500), 2016	327	590	837	356
Number of firms (out of 2500), 2014	199	633	804	387
Share of total R&D expenditure, 2016	7%	27%	39%	14%
Share of total R&D expenditure, 2014	7%	30%	36%	16%
Average annual growth rate of R&D spend, 2014-16	20.5%	4.5%	6.5%	4%
R&D-to-sales ratio 2016	2.5%	3.2%	5.8%	3.3%

Top Chinese companies							
Name	World rank 2014	World rank 2016	Industrial sector (ICB-3D)	Rank in their industrial sector	R&D spend 2015-16 (€ mns)	Growth in R&D spend, 2014-16	R&D to sales ratio
Huawei	26	8	Technology hardware & equipment	2	8357.9	26.3	15.0
ZTE	105	65	Technology hardware & equipment	12	1954,1	12.4	13.8
Baidu	203	93	Software & computer services	7	1444.5	63.3	15.4
Tencent	179	117	Software & computer services	9	1177.4	25.8	8.1

Source: Bruegel based on EU Industrial R&D Investment Scoreboard, 2500 largest R&D spenders worldwide, 2016 edition compared to 2014 edition, see http://iri.jrc.ec.europa.eu/scoreboard.html.

The rise of Chinese science will also have other impacts on the west, beyond the competitiveness impacts. Western firms and economies rely on being able to source available and accessible pools of knowledge globally. If China keeps more of its scientific talent at home, western firms could find that the accessible knowledge pool dries up and that their strategies for S&T-based competitiveness are hampered. If however western companies can continue to access the growing knowledge pool, they can improve their S&T-based competitiveness alongside their Chinese counterparts.

We list below a few stylised facts to show the importance of foreign inflows for the west's technology innovation performance. We rely on US data because of issues of data availability for the EU.

- Foreigners made up 27 percent of tertiary-educated workers in science and engineering occupations in the US in 2013, a substantially higher share than the share of foreigners in the overall population (13 percent in 2013) (NSF, 2010, 1016). And this share increases the higher the education level: for holders of doctorates in the workforce, the share of foreigners was 40 percent (NSF, 2016).

- In 2013, 57 percent of foreign-born individuals in the US workforce with a science and engineering degree were from Asia. While the leading country of origin was India (20 percent), China was in second place with 8 percent, which is somewhat lower than in 2003 when it was 11 percent.
- Source countries for the 402,000 foreign-born holders of science and engineering doctorates were somewhat more concentrated, with China providing a higher proportion (22 percent) than India (14 percent).
- One quarter of engineering and technology companies founded in the US between 1995 and 2005 had a least one key founder who was foreign-born. Over half of Silicon Valley start-ups had one or more immigrants as key founders (Wadhwa *et al*, 2007). Of all immigrant-founded companies, 26 percent have Indian founders, with Chinese (including Taiwanese) founders coming second (about 13 percent). In computers and communications, Chinese (including Taiwanese) immigrant start-ups in the US make up more than one third of foreign start-ups. Chinese (mainland- and Taiwan-born) entrepreneurs are heavily concentrated in California, with 49 percent of US companies with founders from mainland China located there.
- Foreigners are also increasingly responsible for US patents. One quarter of US patent applications filed at the World Intellectual Property Organisation in 2006 were authored by a non-US national, up from seven percent in 1998. The largest group of immigrant non-citizen inventors was Chinese (mainland and Taiwan-born) (Wadhwa *et al*, 2007).

The data shows the importance for the west's S&T system of being able to tap into global talent pools, and the importance of China within the global talent pool.

The rise of China as a scientific powerhouse and as a producer of science and engineering graduates also has implications for the west's portfolio of partners for technology and innovation collaboration. As for scientific collaboration, we can look at whether China's increasing S&T heft is making it a more important partner for western companies for RTI (research, technology, innovation) collaboration.

Table 6 shows that US, EU and Chinese patents are substantially more likely to be co-invented with international partners than those of Japan and South Korea[9]. However while the share of internationally co-authored patents has been increasing for the US and the EU, it has been declining in Asia generally, including in China. The rising number of Chinese patents increasingly relies on domestic inventors, though China remains more open to international collaboration than Japan or South Korea.

Table 6: Share of total patent applications involving foreign co-inventors 2000-12

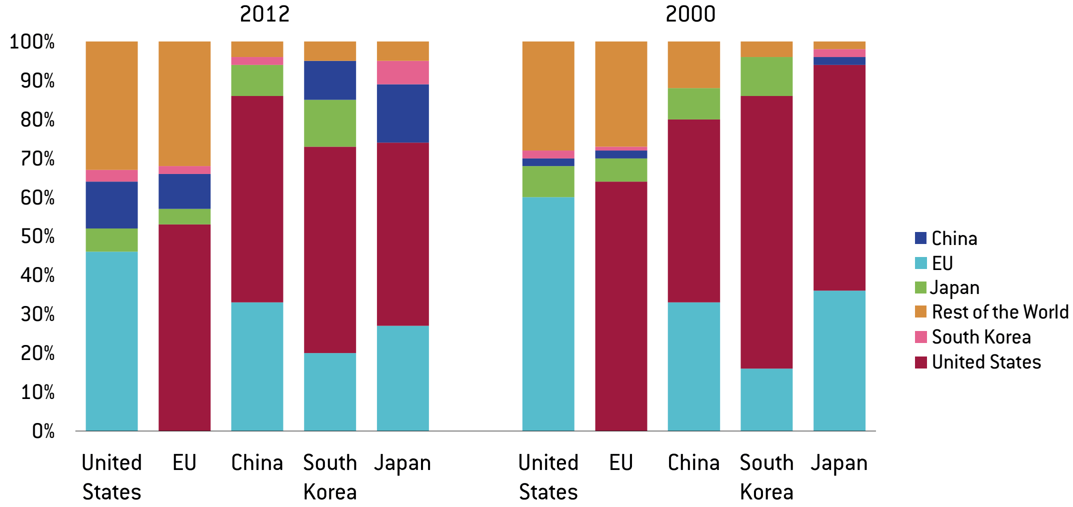
	2000	2012
US	10%	12%
EU	10%	11%
Japan	5%	2%
South Korea	4%	3%
China	9%	8%

Source: Bruegel based on European Commission (2016).

9 Although patents with internationally located co-inventors may only be the tip of the iceberg of all international research and innovation collaborations, it is a convenient traceable source for spotting trends.

Figure 5 breaks down international co-invention partnerships. Who collaborates with whom in international co-invention partnerships is sticky and doesn't change fast. For the US, the EU is still the major partner, but the EU's relative importance is gradually declining, while China is becoming gradually more important as partner for US international technology collaborations. For the EU, the US remains by far the major partner. China is still a minor partner for the EU and is not becoming more important in relative terms. The growth of China as an S&T powerhouse is therefore reflected more in changes to the choice of international partners in the US compared to the EU. For China, the US is the major partner for international co-invented patents, with the EU in second place.

Figure 5: Partners for international co-invented patents



Source: Bruegel based on European Commission (2016).

Multinational firms and their subsidiaries account for a substantial portion of international technology collaboration.

China's increasing S&T importance has led to China becoming an increasingly attractive location for the research activities of multinational companies. In a 2005 UNCTAD survey of the world's biggest corporate R&D spenders, China was already the third-ranked destination country for their foreign investment in R&D. In terms of future target locations, China was ranked first. In 1995, about 90 percent of all overseas R&D by US-headquartered multinationals took place in Europe, Canada and Japan; by 2006, the combined percentage of these economies had declined to 80 percent (NSF, 2010).The combined share of emerging Asian markets, excluding Japan, increased from 5 percent to 14 percent.

More recent surveys have confirmed these trends. For example, the PwC 2015 *Global Innovation 1000* study ranked China as the second most important destination after the US for R&D investment by the surveyed companies. The main foreign investors in China are US companies. The most important benefit listed by the surveyed companies of moving R&D functions to Asia, specifically China, is proximity to the Chinese market. But it is not only the growth potential of the Chinese market that attracts western R&D activities to China. The quality of R&D resources and the access to universities and institutes is also listed as an important factor in location decisions (Thursby and Thursby, 2006). The rise of China's indigenous scientific capacity is therefore increasingly turning into a factor that attracts foreign R&D investment.

5 The implications for the EU of a multipolar science world

China has firmly built investment in higher education and science into its economic development policies, as it vies to build global competitiveness in knowledge-intensive sectors. It has consequently risen rapidly as a scientific power, and its rise has created a more multipolar global scientific landscape.

There will be many benefits from a more multipolar science world, but some will benefit more than others. The open US science system has traditionally benefitted from foreign brains. The US's dominant position in science is based on its openness to the brightest talents of all nationalities. Its top position in science continues to make the US attractive for the best talents, who in turn contribute disproportionally to US scientific, technological and economic success.

Foreign talent is vital for the US's science and engineering capacity, which is why the US fears its S&T machine will become less powerful if the pool of mobile foreign talent dries up. There is no clear evidence so far to justify this fear. For the moment, China's increasing capacity to produce science and engineering graduates does not seem to have disconnected the US from the pool of potential Chinese candidates to recruit from.

With the continued high attractiveness of the US as destination for foreign talents and high stay rates, this open model, at least for the moment, continues to bear fruit for the US. The most important source country for the US – China – is rapidly developing its own scientific capability and wants to bring its foreign-based scholars back home, but scientists tend to return in the later stages of their careers, leaving a long enough period during which the US can still benefit from the imported talents and during which networks can be built, which persist when the Chinese talents return home.

China's growth model for science, although aspiring to be indigenous, still involves sending out its increasingly better locally-trained scholars to the best institutes in the world, and reaping the benefits when they return, in the later stages of their careers after they have fully developed their capabilities and built their networks. This has created a China-US connection that is virtuous, mutually beneficially for both science systems and so far robust.

The EU is largely holding its own in scientific terms, based on the intensifying process of EU integration, which stimulates collaboration among scientists from EU member states. However, the process of EU integration is bumpy, and with the United Kingdom leaving the union, faces a major challenge. Furthermore, the EU does not have the same deep openness as the US to scientific talent from outside, particularly from China. The EU therefore misses out on the large inflows of students and researchers from China and the longer-term networks that are built out of these flows.

The globalisation of science has the potential to bring unprecedented scientific and economic benefits to the world, addressing global health, environment and security challenges. But it will also undeniably provoke concerns about increased competition, and raises a number of questions for the EU: how to leverage China's science and innovation potential to generate worldwide benefits? How to engage with China? What position to take when unfair policies are deployed that would prevent the sharing of benefits?

When Freeman (2005) asked a top Harvard physicist, who had published important work in cooperation with overseas scientists and engineers, *"So, you are helping them catch up with us?"* the scientist replied, *"No, they are helping us keep ahead of them"*. Can Europe master this game of engagement? For the EU, with a much less-developed scientific connection to China than the US, the engagement game will require steps to be taken if the EU is not to lose out.

The EU must show a stronger commitment to participation in the globalisation of science, and to ensuring subsequently that European economies benefit from it.

An integrated European area for science and technology, characterised by scientific and technology excellence, is a necessary condition for this. Excellence will ensure that European research institutes will be more attractive hubs for the best student talents from abroad and that they will become preferred partners for international S&T cooperation and networks with the best researchers abroad. Excellence will also ensure that European research institutes and firms will be better able to learn and absorb the new knowledge generated abroad into their own research activities to produce frontier research.

European S&T policymakers should promote scientific collaboration not only within the EU but also with non-EU countries, and should remove barriers that prevent such collaboration. The EU should do more to attract the best foreign talent, wherever it is located in the world, and should remove barriers that prevent such mobility. EU talent should be encouraged to be mobile outside the EU and go to the best universities and institutes, wherever they are in the world. Connections with these European outflows must be maintained, and incentives must be provided to encourage scholars to return home at optimal stages in their careers. Similarly, connections with foreign scholars who return home after their research stays in the EU should be supported.

None of this requires major new initiatives at the EU level, but rather a stronger commitment to implementation of existing initiatives that are aimed at those parts of the world that are at the scientific frontier. EU programmes that support extra-EU cooperation and mobility should be based on excellence in terms of destinations for, and sources of, researchers. This is most notably the case for the Marie Curie Fellowships and the collaborative research programmes under the EU's Horizon 2020 framework initiative. The degree to which frontier S&T countries, such as the US and China, become destinations for or sources of researchers in these programmes should be monitored and if there are lags, barriers should be identified and removed. Bilateral S&T agreements with frontier countries, most notably China and the US, should be the first priority in the EU's international S&T relations. In these S&T agreements, the EU should ensure mutual openness of funding programmes for bilateral cooperation, and support for bi-directional mobility programmes.

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