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Research Report

International mobility and collaboration of German scientists, 2005-2020

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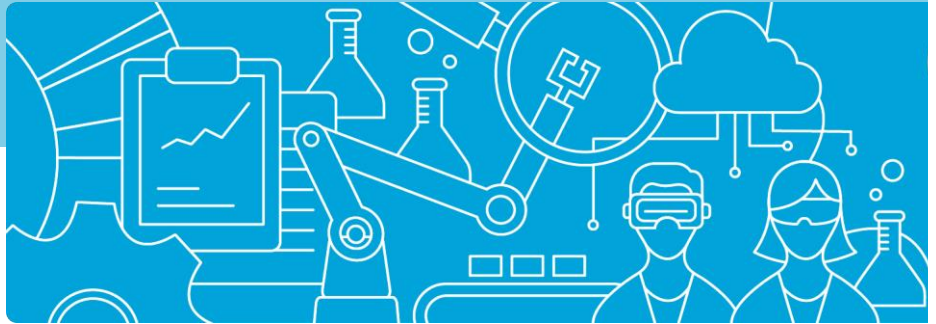
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Massimiliano Coda-Zabetta, Francesco Lissoni, Ernest Miguelez

International Mobility and Collaboration of German Scientists, 2005-2020

université
de **BORDEAUX**

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0 Executive Summary

Given its central position in global movements of goods, services, and people, Germany has been impacted by shifts in globalization trends that emerged at the start of the century. Notably, as the globalization of production and trade has decelerated, the momentum of globalization in science and technology has continued to grow. This trend is closely linked to the growing significance of teams in generating ideas, with teams becoming larger and more geographically dispersed. Coupled with the overall increase in highly skilled international migration, these long-term trends contribute to the high rates of global mobility among individuals in STEM occupations or with STEM education, scientists in particular.

This report presents evidence and policy recommendations regarding Germany's position in the global landscape of international scientific mobility and collaborations. Our analysis utilizes a comprehensive dataset from Scopus, a global scientific publication database, containing over 5 million articles authored by researchers affiliated with German institutions from 2005 to 2020. We identify mobile scientists and collaborations based on their declared affiliations when publishing, considering the locations of universities and other organizations. To enhance the mobility analysis, we cross-reference this data with an ethnic analysis of authors' full names using IBM's Global Name Recognition (IBM-GNR) library. Additionally, we incorporate data on doctoral theses conducted in Germany between 2000 and 2020. Our study examines trends within Germany and compares Germany's situation with other R&D-intensive countries in Europe and globally. It also contains a special focus on three, broadly defined disciplinary fields, namely: Artificial Intelligence (AI), Bioeconomy (BE), and Advanced Manufacturing (AM); and on the impact of key policy measures, such as the Excellence Initiative (EI) program, the Alexander von Humboldt (AvH) professorship program, and the AI Strategy.

Large shares of mobile scientists with German affiliation, increasingly inflows

During the analysed period (2005-2020), 69% of German researchers can be categorized as "stayers," indicating that they exclusively published scientific articles while affiliated with German institutions, without any indication of foreign affiliations. The remaining 31% of researchers have experienced various forms of mobility and can be further divided as follows:

- "Inflows" (8% of researchers): Scientists who initiated their publishing careers while affiliated with foreign institutions, bearing non-typical German names and surnames, and subsequently transitioned to German institutions.

- "Returnees" (also 8% of researchers): Similar to "inflows," these researchers initially published while abroad and later returned to publish with German affiliations. Their names and surnames are highly common in Germany, suggesting they are likely German graduates from foreign universities who eventually came back home. This category also encompasses researchers with a minimum of three publications during the considered period, with the first and last publications in Germany and the middle one abroad.
- "Outflows" (6% of researchers): Researchers with names and surnames indicative of German origin that began publishing in Germany and later moved to foreign institutions.
- "Transient" researchers (9% of researchers): These individuals launched their careers abroad, published in Germany for a certain period, and then departed again.

When the data is segmented into three distinct time periods (2006-2010, 2011-2015, 2016-2020), a noticeable trend emerges: there is a decreasing pattern in outflows and an increasing one in inflows. Meanwhile, the proportion of individuals returning remains relatively constant. Significantly, the proportion of inflows nearly triples, implying a progressively growing international appeal of the German scientific system.

Most exchanges of researchers occur with European countries and the US, but those with China and India increase

Breaking down the inflows of researchers by their countries of origin reveals that Europe hosts the primary sources, followed by Asia and North America at a distance. European countries also are the primary recipients of outflows, followed by North America, while Asia does not emerge as a significant destination for researchers leaving Germany. Generally, Asia displays a lower degree of permeability to international STEM immigration.

When aggregating inflows and outflows and examining bilateral corridors, Germany's key partner countries include the United States, the United Kingdom, and Switzerland. In each of these instances, as well as in the cases of Denmark and Canada, the number of researchers leaving Germany exceeds those arriving from the partner country. In contrast, the dynamics are reversed for developing economies such as China, Russia, India, and Brazil.

This suggests that the appeal of Germany as a destination for scientists fluctuates based on bilateral factors, encompassing the partner country's developmental level, the robustness of its scientific ecosystem, research prospects, and other socio-economic elements, relative to those of Germany. Overall, Germany is not yet attracting more scientists than it sends to more research and development-intensive or wealthier nations, but it has cultivated positive exchanges with all other countries.

Germany net inflows international scientists have turned positive

Throughout the period, Germany's net scientist flows have undergone a change of sign. While from 1996 to 2011 there was a negative net flow of scientists (4,000 more scientists left than entered), the years 2005 to 2020 witnessed a positive net inflow of over 5,000 scientists. This trend of net inflows to Germany has notably strengthened in recent years.

Nevertheless, when compared to other European countries, these figures are not particularly notable. Countries like France, Spain, Italy, and even the United Kingdom have experienced more significant fluctuations in their net inflow trends over the same time span.

Women are less mobile than men, especially among returnees

The percentage of stayers is higher among women, with 73% compared to 65.6% for men. Additionally, among female mobile researchers, the category with the smallest share is returnees, indicating that women, while less mobile in general, are also less inclined to move more than once and especially back to Germany.

The quality of researchers leaving Germany is higher than that of inflows, but the gap is closing

Outflow scientists publish on average on higher-quality journals than inflow ones, while returnee or transient ones exhibit intermediate values and stayers the lowest ones. This indicates that, on average, the quality of researchers leaving Germany is higher than the quality of those entering it, which in turn is higher than that of those who never move. The difference is most noticeable for the life sciences, and much less for the social sciences.

Yet, while *on average* Germany is losing talent, the same does not apply to the very top of the quality distribution. When focusing on the top 10% cited researchers in the sample, this sees a prevalence of "returnee" scientists.

Over time, the publications' quality of outflow scientists has declined, while that of stayers has increased, which might imply that Germany has become more capable of retaining high-calibre researchers. Moreover, the quality of both inflows and returnees also exhibit an upward trend, "closing the gap" with outflows, especially in more recent years. This might suggest that Germany has been evolving into a more appealing destination for accomplished researchers.

Increasing relevance of international scientific collaborations

In 2020, nearly half of the multi-authored publications in the Social and Health sciences that included a German author had at least one international co-author. This percentage rises to approximately 60% in the Life and Physical sciences. These figures stem from a steady and continuous increase since at least 2005. The most rapid growth has been observed in the Health and Life Sciences.

The two countries with which Germany collaborates throughout the observation period are the United States and the United Kingdom. France and Switzerland have also been collaborators, although they have been overtaken in recent years by China, whose contribution to total collaboration has impressively surged in less than a decade. Finally, it is important to highlight the decline in collaboration with Russian science, which fell out of the top 10 in 2011.

International mobility and collaborations tend to correlate at the institutional level

Institutions such as LMU Munich and the University of Heidelberg rank prominently in both the inflow of scientists and international collaboration rankings, indicating a correlation between these two factors. Likewise, at institutions like TU Munich and the University of Erlangen-Nuremberg, the rise in inflows has corresponded with an increase in international collaborations.

International mobile researchers might be sources of international collaborations, and conduits of knowledge diffusion and opportunities back home

Approximately 50% of outflowing scientists continue to collaborate with authors affiliated with German institutions even two years after relocating abroad. This percentage remains relatively consistent over time, implying that outflows can facilitate knowledge exchange and scientific interactions between Germany and other nations.

Artificial Intelligence (AI) and Bioeconomy (BE) are more internationalized than advanced manufacturing (AM)

Among the three scientific fields the report examines in greater depth, AI and BE exhibit the highest levels of international collaborations, with over half of the articles featuring co-authors from various countries. Conversely, AM stands out with notably lower levels of international collaboration, despite a recent increase, where the proportion of internationally co-authored articles remains under 40%.

Furthermore, the fields of AI and BE have benefited from a notable influx of researchers from the United States, United Kingdom, and Switzerland. In contrast, AM has depended relatively more on France, the Netherlands, and Austria, as well as Asian countries such as China, Japan, and Russia.

Based on name analysis, we also estimate that the share of AM foreign scientists having earned their PhD from a German institution is around 17.5%. This is a rather low value compared to around 25% for BE and 22% for AI.

Concerning outflows, AI German scientists have moved mostly to the top five destination countries for Germany as a whole (United States, United Kingdom, Switzerland, France, and the Netherlands), while BE ones have disproportionately moved to China. On the other hand, the AM field shows a higher proportion of researchers relocating to Australia and Brazil.

The different evaluations of the Excellence Initiative (EI) program is positive, though causal effects are difficult to establish

An external evaluation of the EI program found that the successful recruitment of new personnel under its funding. The evaluation suggests that the program effectively facilitated the expansion of research teams and the creation of new academic positions at universities and clusters of excellence. However, the evaluation also highlighted that there might have been a shortage of suitable candidates for some of the newly created positions. Additionally, the report pointed out that the salaries offered for these positions remained uncompetitive compared to those offered by non-academic and private research institutions. On the positive side, the evaluation revealed that the EI played a significant role in fostering both domestic and international cooperation between universities.

A second evaluation of the program noted an overall increase in publications over the funding period. However, it did not explicitly attribute this increase solely to the funding provided by the EI. The evaluation suggests that various factors, including the researchers' efforts, institutional support, and external collaborations, could have contributed to the observed increase in publications.

Inflows towards institutions funded by the EI are geographically more diverse over time

During the initial EI phase, significant source regions for scientists included the United States and Western Europe, in particular from countries like Switzerland, France, the United Kingdom, and Austria. In the subsequent phase, the United States maintains its prominence as the primary source country for the highest number of inflows. However, the second phase also exhibits an interesting shift in the landscape of origin countries, in particular with the rise of Asian countries, notably China and India. These countries have emerged as increasingly important sources of researchers. Conversely, sourcing from Russia has diminished. Southern Europe countries have also gained importance as inflow origins, in particular Italy and Spain. This suggests a diversification in the geographic sources of researchers entering the German scientific system during the second phase of the EI implementation.

The Alexander von Humboldt (AvH) professorship program seems to be successful in attracting highly reputed, international scholars

One significant achievement of the AvH Professorship program is its success in attracting international scholars to Germany, even if some of them were German nationals. The program played a crucial role in bringing talented researchers from around the world to contribute to the academic landscape in Germany. It also helped in terms of increased cooperation and networking. This finding highlights the program's role in fostering international research partnerships and knowledge exchange.

The AvH program have attracted world-class scientists, mostly returnees and men

Over the period spanning from 2009 to 2020, a total of 80 AvH Professorships have been conferred upon distinguished scientists, 37.5% of which to foreign academics. These professorships symbolize a concerted effort to bring in exceptional international talent, further enhancing the scientific landscape within Germany.

It is relevant to point out that the representation of women at this stage is relatively limited, with an overall share of 17.5% women researchers that have been awarded the AvH professorship.

AvH professorship holders increase the productivity of their peers upon arrival

Our report looks at the productivity of coauthors of AvH Professors following their arrival, drawing comparisons with similar scientists based on pre-arrival attributes. Employing a 1-to-1 matching process, we paired them with comparable researchers active in the same university and field prior to the AvH Professor's arrival, using observable metrics such as publication record, citation count, field of study, and scientific age (i.e., years since their first publication) at the time of the AvH Professor's appointment. Subsequently, we examined the publications produced by the two groups of researchers after the arrival of the AvH Professor, excluding articles coauthored with the AvH Professor, and find that publications of coauthors of the AvH professor to be of higher quality, in all fields analysed.

1 Introduction

While up until the end of the XX century the production of knowledge and technology was confined to a few, highly developed countries, the XXI century has been characterized so far by a process of globalization and internationalization of science and technology (Miguelez et al., 2019; WIPO, 2019). This has gone hand in hand with an increase in the importance of teams for the production of ideas (Jones, 2009; Wuchty et al., 2007) as well as of their geographical dispersion, due either to international collaboration (between universities and/or companies) or to division of labour inside large multinational companies (WIPO, 2019). Related to this and to a general increase in highly skilled international migration, the turn of the century has also witnessed a rise in the international mobility of men and women in STEM¹ occupations or with STEM education (Kerr et al., 2016; Lissoni & Miguelez, 2021).

STEM migration is crucial for the internationalization of knowledge because mobile STEM workers and students both diffuse and recombine knowledge acquired in different places. Not only the migrants' destination countries, but also their origin ones can benefit of these processes, as when a STEM migrant shares its knowledge with his/her home contacts, on either an informal or contractual basis; or when the same migrant returns home, bringing with him/her the newly acquired skills, knowledge and foreign contacts (Lissoni, 2018). Whether skilled or unskilled, migration also increases the cultural diversity of both cities and organizations, with potential influence on the production of ideas due to the recombination of different *savoirs*, approaches, and cultural backgrounds (Kemeny & Cooke, 2018; Niebuhr, 2010; Ottaviano & Peri, 2006). Finally, STEM migration generally increases the supply of researchers and allows for a finer division of research labour in receiving countries, with important consequences on their capacity to produce science and technology (Hunt, 2015; Hunt & Gauthier-Loiselle, 2010).

Given the characteristics of knowledge production since the turn of the XXI century, and the role of STEM migration and teamwork, it is of the utmost importance to understand where countries stand in the global system of science and technology. The aim of this report is hence to provide evidence and policy recommendations on the position of Germany in the global landscape of STEM mobility and collaborations, particularly for the case of scientists. To conduct our analysis, we employ a comprehensive dataset from Scopus, a global database of scientific publications, out of which we extract 5 million articles authored by researchers affiliated with German institutions between 2005 and 2020, augmented with information on the ethnic origin of researchers' full names, obtained from

¹ STEM stands for Science, Technology, Engineering and Mathematics.

IBM's Global Name Recognition (IBM-GNR) tool. In addition, we cross this data with those on doctoral theses conducted in Germany between 2000 and 2020. Our investigation primarily focuses on the evolution of mobility and collaboration patterns among German scientists, and research institutions, over time and on the comparison with similar countries and global leaders.

A previous EFI Report (2014) had already produced, among others, some statistics on the same topic, which suggested that Germany was losing many of its best scientists as a result of migration, though some returnees seemed to (only partially) cover this lost. Moreover, those retained or returned seem to be negatively selected, i.e., they were not among the most productive researchers. The report concluded that with respect to the best scientists (highest impact numbers), the German research system did not appear to be attractive enough.

Our own results suggest instead that Germany has demonstrated stability in attracting talent in the 15 years period analysed, with a slight increase in its intake capacity. When it comes to attracting foreign talent, Germany does better than most European countries, including the United Kingdom, but still lags behind global leaders like the United States and Switzerland. Besides, when considering the bilateral exchanges with other R&D-intensive countries in Europe or North America, Germany turns out to attract fewer scientists than it sends abroad. The opposite pattern holds instead for exchanges with developing economies such as China, Russia, India, and Brazil. These emerging players, in particular China and India, have gained importance as sources of talent and international collaborators for Germany, especially in recent years.

When comparing the average scientific record of the scientists migrating to and from Germany, we also find that, on average, this is more remarkable for the outgoing scientists than for the incoming ones. However, the situation changes when focusing on the top of the distribution, due to the relatively high propensity of many of top-cited German researchers to return home from abroad, indicating that the country continues to be an attractive destination for scientific excellence.

With respect to international collaborations, Germany seems to be more (and increasingly) internationalized compared to other large economies. Concerning international scientific collaborations, these have been constantly on the rise, with the Health and Life Sciences experiencing the fastest growth. In 2020, almost half of the German publications in Social and Health sciences and over 60% of those in the Life and Physical sciences involved at least one international co-author. Throughout the observation period, the United States and the United Kingdom have been Germany's primary collaborators, followed by other European countries, with China quickly catching up. Finally,

we also find that a significant proportion of German scientists who leave the country to work abroad continue to maintain connections and collaborations with researchers in Germany.

The report is organized as follows. Section 2 presents the data sources, as well as the methodology utilized for collecting the information and the subsequent data preparation procedures. Section 3 delves into the analysis of German scientists' international mobility and collaboration. Section 4 focuses on an in-depth examination of specific subfields, namely Advanced Manufacturing, Artificial Intelligence, and Bioeconomy. In Section 5, we explore funding programs and initiatives designed to enhance the internationalization of the German science system. Finally, Section 6 provides the concluding remarks, summarizing key findings and insights gathered throughout the report.

2 Methodology

In this section, we provide a comprehensive overview of the methodology used in this study. First, we outline the data sources utilized for our research. Then, we present a detailed account of how we built the baseline dataset on scientists' mobility, along with additional information used for the in-depth analyses and the evaluation of funding programs and initiatives.

2.1 Data sources

2.1.1 Scientific articles

The key data of our study consist of scientific articles provided by Elsevier's Scopus, an abstract and citation database of scientific literature that includes over 77 million publications. To access the data, we utilized the API provided by the Elsevier Developer Portal.

Our initial step was to obtain all scientific articles with at least one German-affiliated author during the period from 2005 to 2020. We will refer to this set of documents as the *German publications set*, which amounts to around 1.5 million articles. From this set, we identified 878,246 authors who were associated at least once with a German organization (whether a university, a public laboratory or a firm). We will refer to these researchers as the *German authors set*.

Subsequently, we gathered all the publications authored by the researchers in the *German authors set* throughout their careers. This resulted in a total of 5,387,098 articles, which we will refer to as the *final publications set*. This operation was made possible by the fact that Scopus not only provides unique identifiers for both authors and affiliations, but also indicates clearly, in publications with many authors and affiliations, each author's affiliation(s).

To classify articles across scientific fields, we utilized Scopus' All Science Journal Classification (ASJC) system, which categorizes journals into four broad areas: Life Sciences, Physical Sciences, Health Sciences, and Social Sciences.

As a mean of assessing the quality of articles, we employed two main metrics. Firstly, we considered the citation count reported by Scopus. This metric considers all the citations received by each article up to the moment of data retrieval. Secondly, we incorporated the SCImago Journal Rank (SJR), an indicator computed by Elsevier. The SJR assesses the prestige of scholarly journals by considering both the number of citations received by a journal and the prestige of the journals from which these citations originate.

To establish SJR values for the period from 1999 to 2020, we relied on currently available data. As for the articles published prior to 1999, for which no SJR is available, we assigned that of 1999.

2.1.2 Scientists' countries of origin

The second major source of information for our study is IBM's Global Name Recognition (IBM-GNR). We utilized IBM-GNR to gather data on the country of associations (CoAs) for the names and surnames of authors within the "German author set". The raw data used by IBM-GNR is sourced from the archives of the US Immigration Authorities, which documented names and nationalities of all entrants to the United States during the 1990s. This comprehensive collection of records allows us to determine the distribution of names and surnames within each country worldwide, excluding the United States.

The IBM-GNR data library links each name or surname to all the countries in which it appears. For each country, the library also supplies various statistics, including the relative *Frequency* of each name or surname, expressed in percentiles. The highest frequency is denoted as 90, while the lowest is denoted as 10. Based on the frequency distribution of names and surnames associated with the German author set, we make educated guesses on the authors' countries of origin.

IBM-GNR also provides data on the gender associated with first names, which we use to compare the gender composition of German authors across fields and between migrants and natives.

For more comprehensive details on the data provided by IBM-GNR, including other information not employed in this particular study, interested readers we remind to Breschi et al. (2014, 2017), Coda Zabetta et al. (2022), and Toole et al. (2019, 2020).

2.1.3 Doctoral theses

The third main source of information is Dissonline, an archive of German Electronic Doctoral Theses (EDTs) maintained by the German National Library (DNB). The dataset consists of all the dissertations that have been made available online on the German National Library's website since 2020. We downloaded all the dissertations in STEM subjects and medicine, covering the years 2000 to 2020. STEM dissertations were identified using the subject classification, academic titles, and faculty information included in the dissertations. The main information that we used for our purposes are the author's name, year of publication, and *alma mater* (the university of PhD).

For more comprehensive details on this particular data source and its characteristics, interested readers can refer to the work by Buenstorf et al. (2022), Buenstorf & Geissler (2014), Heinisch & Buenstorf (2018). Their study provides in-depth insights into the nature, scope and representativeness of the data available in the German EDT repository and may offer additional information about how these data were collected and curated for research purposes.

2.1.4 Other sources

In addition to our three main sources of information, we also utilized a few other ones. One of these is the Shanghai Academic Ranking of World Universities (ARWU). The ARWU is an influential ranking system that annually assesses and ranks universities worldwide based on various academic indicators. For our study, we extracted information from the ARWU regarding the universities that ranked within the top 500 list each year from 2005 to 2020.

We also gathered information the funding programs and initiatives most relevant for German scientists. We specifically focused on the Excellence Initiative (EI) and the Alexander von Humboldt (AvH) Professorships. We collected the list of institutions selected to be part of the EI's Graduate Schools, Clusters of Excellence, and Institutional Strategies in the two rounds of the initiative, covering the period from 2006 to 2019.² Additionally, we gathered information on individual scientists who were awarded the AvH Professorship from 2009 to 2020. This information included the name of the scientists, the host institution where the professorship was granted, and the year in which the position was awarded. By collecting data on both institutional and individual funding from

² The Excellence Initiative funding came to an end in 2017. However, the universities selected were granted an additional two years of funding to provide them with continued financial support during the transition period before the launch of the Excellence Strategy in 2019.

the EI and the AvH Professorship, we aim to gain insights into the impact and influence of these funding programs on the internationalization of the German scientific landscape.

2.2 Data preparation

2.2.1 Identification of international mobile researchers

In this section we explain how, by combining data on scientific articles with information on authors' name and surnames, we produced a comprehensive taxonomy of international mobile researchers, considering both their affiliations and ethnic origin.

2.2.1.1 Authors' affiliations

The first step in identifying international mobile researchers involves the disambiguation of scientific authors. This is necessary to track the same researcher over time and across affiliations. To achieve this disambiguation, we rely on Scopus author identifiers (AU-ID). Scopus, in fact, uniquely identifies authors through AU-IDs assigned by Elsevier.

Kawashima and Tomizawa (2015) have demonstrated that Scopus AU-IDs are highly precise and complete. Precision refers to the proportion of AU-IDs associated with a single individual, ensuring that each researcher is accurately represented with a unique identifier. Completeness, on the other hand, measures the share of AU-IDs linked to all the publications of an individual, ensuring that all the works of a researcher are correctly attributed to him/her.

Given the reliability and accuracy of Scopus AU-IDs, they are well-suited for investigating the international mobility of researchers. Previous works by Aman (2018), Moed et al. (2013) and Moed and Halevi (2014) have also utilized Scopus AU-IDs to study various aspects of researchers' mobility, highlighting their suitability for such analyses.

Secondly, Scopus also provides an affiliation identifier (AF-ID) for authors' affiliations. While its overall quality in terms of precision and completeness is satisfactory (Zhao et al., 2022), a few issues remain to be solved.

One of them is that not all affiliations are properly disambiguated. This means that the same university or department can be written differently or appear in different languages, each of which receive a distinct AF-ID, leading to multiple AF-IDs for the same institution. However, for our analysis, this issue is not overly problematic since our primary interest lies in determining the country associated with the affiliations and this is typically well covered and reported in AF-IDs. In cases where a precise

identification of the affiliation institution is required, and there are multiple AF-IDs associated with the same institution due to variations in reporting, we simply retain the AF-ID that is associated with the largest number of publications. This approach allows us to recover more than 95% of the publications of an institution.

To handle situations where an author lists more than one affiliation within the same publication, we consider only the *first* affiliation mentioned, which we employ as a proxy for the researcher's *main* affiliation. This approach helps simplifying the analysis by focusing on the primary institutional association of the researcher for each publication.

2.2.1.2 Authors' countries of origin and gender

In order to build the taxonomy of mobile researchers, we couple information on affiliations to information regarding the possible countries of origin of scientists' names and surnames. We obtain this information through the name analysis of authors' names and surnames, based on information from IBM-GNR. Figure 1 presents an example of the information retrieved through IBM-GNR for an author named Rajiv Fowler.

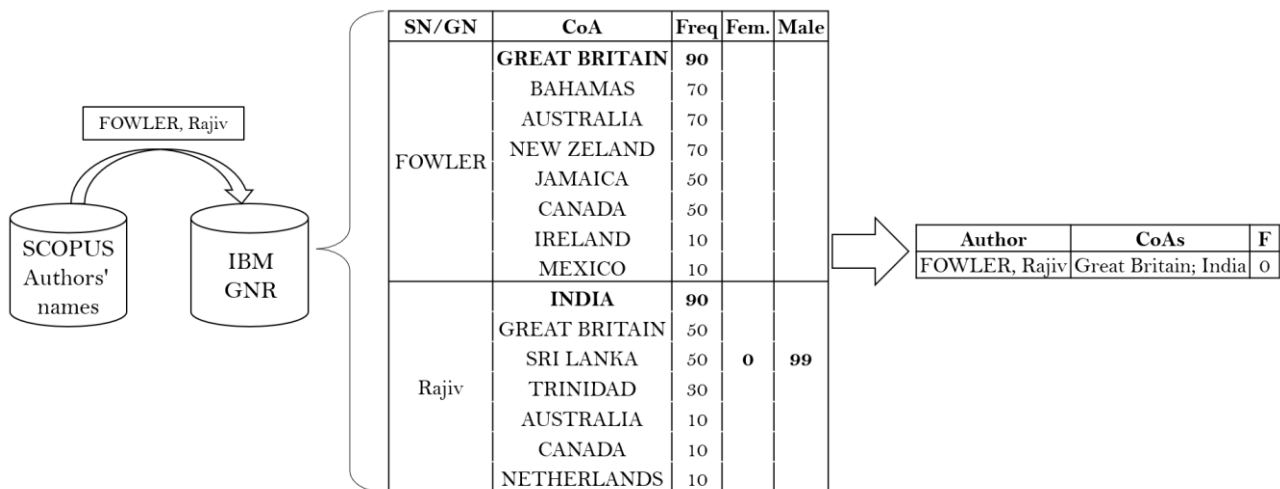


Figure 1 – Example of name analysis using IBM-GNR

IBM-GNR associates each first name and surname with a list of countries of associations (CoAs) where they are present. For each CoA, IBM-GNR provides a *Frequency* value, which indicates the percentile ranking of the name or surname in that particular country, from 90 (highest frequency) to 10 (lowest frequency). To determine the most relevant CoAs for a specific author, we select the countries where the first name or surname have the highest frequency. In the example in figure 1, the

surname "Fowler" is most frequent in Great Britain, while the first name "Rajiv" is most frequent in India. Hence, India and Great Britain will be the two CoAs associated with this author.

Furthermore, IBM-GNR offers two additional variables: "Female" and "Male", which indicate the probability of the first name being associated with a female or male gender, respectively. Utilizing this information, we create a dummy variable for female authors, setting it to one if the probability of the name being female is higher than the probability of it being male.

2.2.1.3 *Final mobility taxonomy*

Based on the two pieces of information (affiliation information and CoAs of authors), we can create a mobility taxonomy that considers authors with at least 2 publications in 2 different years within the specified time period. Based on the affiliation information in the publications, we establish the country of affiliation of each author in each year.³ This, in turn, allows us to categorize all authors in our database according to their mobility pattern, whether over the entire observation period or any shorter time interval, as follows:

1. *Stayers*: Authors whose affiliation country is always Germany, regardless of their name and surname.
2. *Inflows*: Authors whose country of affiliation is first a foreign one, then is Germany, and whose name and surname do not include Germany among their countries of association (CoAs).
3. *Outflows*: Authors whose country of affiliation is first Germany, then a foreign one, but not one included among the CoAs associated to the author's name and surname.
4. *Returnees*:
 - a. Authors with at least 3 publications in 3 different years, with Germany as the first and last country of affiliation, a foreign one in between, and whose name and surname includes Germany, but not the foreign country, among their countries of association (CoAs).

³ When a researcher reports different affiliations in multiple articles published in the same year, we will retain only the affiliation of the *last* article published in that. This is the same approach used by the OECD Science, Technology and Innovation Scoreboard (OECD, 2017). See: <https://www.oecd.org/sti/scoreboard.htm> (last visited: 30/07/2023)..

- b. Authors whose country of affiliation is first a foreign one, then is Germany, and whose name and surname includes Germany, but not the foreign country, among their countries of association (CoAs).

5. *Transients*:

- a. Authors whose country of affiliation is first Germany, then a foreign one, with the foreign one, but not Germany, included among the CoAs associated to the author's name and surname
- b. Authors with at least 3 publications in 3 different years, with the first and last country of affiliation both foreign, and Germany in between.

2.2.2 Identification of collaborations

To identify the collaborative ties of authors in the *German publications set*, we consider the countries of affiliations of their coauthors. For coauthors with multiple affiliations listed on the same publication, we retain only the first one, considering it as a proxy for their main affiliation. This approach allows us to distinguish between collaborations with authors who indicate a foreign affiliation as their first affiliation, indicating a primary research association with a foreign institution, and collaborations with authors who list foreign affiliations as second or further affiliations. The latter case might not necessarily qualify as international collaboration, as the researcher could be listing multiple affiliations for reasons of prestige or other motivations without significant research involvement with those institutions.

2.2.3 Identification of fields for the in-depth analyses

We produce a more in-depth analysis for three specific scientific fields, namely: Advanced Manufacturing (AM), Artificial Intelligence (AI) and Bioeconomy (BE). The procedure we followed consisted first in using specific keywords and ASJC codes to identify all publications related to the three subfields, in which at least one of the authors had an affiliation with a German institution.⁴

Once obtained this set of articles, we cross-referenced their authors with our "*German publications set*" (as explained in section 2.1.1). We flagged the authors who appeared at least once in these

⁴ These keywords and ASJC codes were provided by the Fraunhofer Institute for Systems and Innovation Research, which developed them in consultation with field experts.

publications and categorized them as belonging to one of the three subfields for in-depth analysis if they had at least one publication falling under the corresponding subfield. If an author had publications in more than one of the three fields, we assigned him/her to the field in which he/she had the highest number of publications. In cases where an author had an equal number of articles in multiple fields, we considered them as belonging to more than one field, fractionally distributing their contributions across the respective subfields.

Finally, after identifying the authors associated with the subfields of interest, we considered all of their publications to build the dataset for investigating their mobility and collaborations. This means that we included all of their publications, even those not belonging to the specific subfields, in the analysis.

The complete list of ASJC codes and keywords for each subfield is provided in Appendix A.

2.2.4 Identification of German PhD holders for the in-depth analyses

To identify holders of a German doctorate among the sample of scientists in the *German publications set* (see section 2.1.1), we adopted the following procedure. First, the names and surnames of the doctorate holders, as per Dissonline, were cleaned. Second, these names and surnames were searched on Scopus, so as to retrieve the associated AU-ID. Multiple searches per author were performed, using different combinations of first names and last names to increase the chances of finding each author in Scopus⁵. Despite this approach might lead to some false positives, we undertook no deduplication of the matches, due to time constraints. Instead, we employed a conservative strategy that consisted in reducing the matched sample to those PhD holders for which it was possible to identify a unique AU-ID resulted from the search on Scopus.

In particular, we retained the results obtained from the following queries:

1. Complete full names
2. Complete full names with transliterated characters (when applicable)
3. First name initial and complete last name

The first query was conducted using the complete full name of the PhD holders. If a unique result was found for this query, it was retained as the true AU-ID of the PhD holder. If applicable, an additional query was performed on the transliterated full name, where special characters were

⁵ We gratefully acknowledge the help from Alberto Corsini (IPP-CSIC).

transformed into plain ASCII letters (e.g., “ö” becomes “oe”). If a unique AU-ID result was obtained for this query (in case it did not already have a unique result from the previous one), it was retained. In cases where none of the previous queries led to a unique result, the results from the query on the first name initial and the complete last name were analysed, retaining the author if a unique AU-ID could be identified. Finally, the AU-IDs of the retained PhDs were matched to those in the *German publications set*.

This approach privileges accuracy in the identification of PhD holders, thus sacrificing the sample size in order to limit false positives. This allows for a robust analysis of their research activities and collaborations.

Figure 51 in Appendix B illustrates the distribution of researchers within our sample who have been identified as having completed their doctorate at a German university, categorized according to the three fields of in-depth analysis. It is important to note that these shares represent a conservative lower bound estimate, due to two main factors. Firstly, our matching strategy, as explained, is deliberately cautious. Secondly, as explained in section 2.1.3, the EDT data begin in 2000, implying that our Scopus sample could encompass researchers who acquired their PhDs before this year. If we narrow our focus to researchers who published their first article from 2000 onwards, the proportion of researchers holding PhDs from Germany rises across all three groups (see Figure 52 in Appendix B).

Further, it is likely that a large number of authors in our *German publications set* could not be matched to an EDT simply because they did not do the PhD in Germany. According to a recent survey of academics in a selection of 16 countries by Franzoni et al. (2012), 23.2% of German scientists were born abroad. While some might have graduated in Germany itself, many more are likely to have graduated abroad. Besides, a certain number of German-born scientists may also hold a foreign PhD. While it is difficult to be more precise on the number of non-matched profiles that did their PhD abroad, we are convinced that this is not a negligible figure (as we shall see later on, we estimate around 8% of returnees).

3 Analysis of international mobility and collaborations

Based on the data we just presented, we have first analysed Germany’s place in the international mobility of scientists, then its positioning with respect to international collaborations.

3.1 German scientists' international mobility

To provide an initial overview of the German scientists' international mobility patterns during the observation period, we employ the taxonomy introduced in section 2.2, which incorporates information from name analysis. Figure 2 illustrates our results for researchers with at least 2 publications in the observation period. In Appendix B, Figure 53 and Figure 54 replicate the same graph, but for a classification that does not incorporate the name analysis, and illustrate how the results differ.

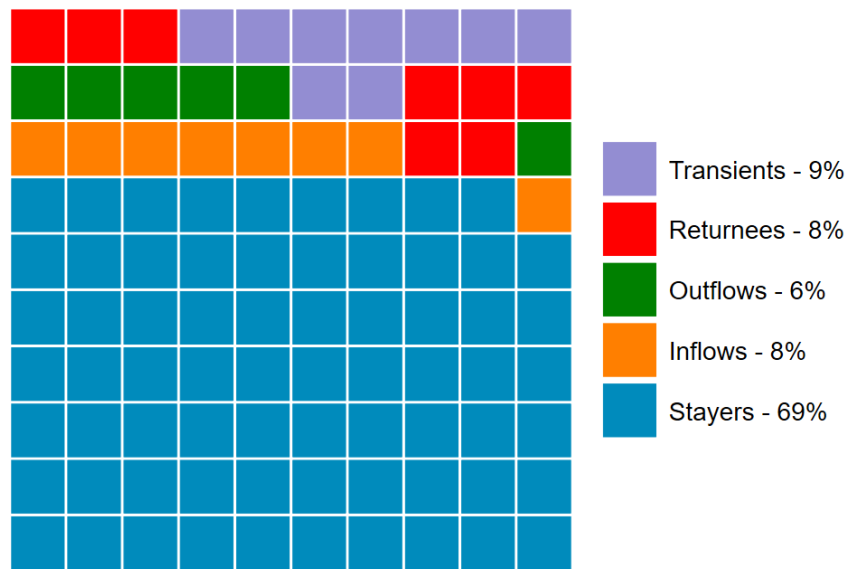


Figure 2 - Researchers by mobility type (2005-20)

We see that 69% of German researchers are categorized as "stayers", which means that they have exclusively published scientific articles while affiliated with German institutions, without any foreign affiliation.

The remaining 31% of researchers are all those having somehow moved internationally and can be further subdivided as follows.

- "Inflows", which account for 8% of all German scientists, and one fourth of the internationally mobile researchers. These are scientists who began their publishing careers while affiliated with foreign institutions, do not carry typical German names and surnames, and later transitioned to German institutions.
- "Returnees", which are as numerous as inflows and, like "inflows", initially published while abroad and later returned to publish with German affiliations. Different than inflows, however, they have names and surname that are very frequent in German, which make them likely to be

German graduates at foreign universities who at some point move back to their home country. The category also includes researchers possibly with non-German names, but with at least three publications over the period considered, the first and last in Germany, the middle one abroad.

- "Outflows", namely researchers with likely German names and surnames who start publishing in Germany and then move abroad, represent 6% of all German scientists and almost one fifth of the mobile researchers ($6\% \div 31\% = 19.3\%$).
- Transient" researchers (who initiated their careers abroad, joined the German science system for a certain period, and then subsequently left again) represent, 9% of all the German researchers.

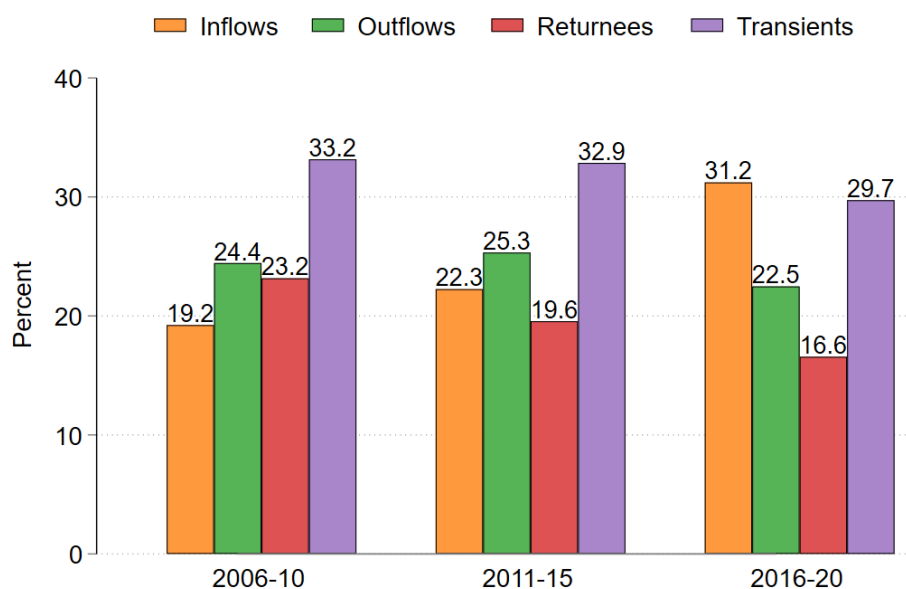


Figure 3 - Share of mobile researchers by mobility type and time window ("stayers" category omitted)

Notes: In this figure we assign each researcher into a specific time window based on when their mobility occurred. We do not provide the number of stayers, as we cannot assign them to any of the time windows due to their immobile status by definition. It is important to emphasize that these numbers are only comparable within each time window, this is why we present shares rather than absolute values.

In Figure 3, we illustrate the temporal evolution of the proportion of international mobile researchers within the span of our analysis. To achieve this, we categorized researchers according to their mobility status, as in Figure 2. Subsequently, we examined the year of each researcher's mobility event, allocating them to a specific time windows based on these events. Notice that we have omitted the

"stayers" category. This decision is based on the consideration that the central focus of the graph lies in the relative shifts observed within the shares of mobile researchers across these time windows.

The proportion of inflows experienced a substantial rise, ascending from 19% at the commencement of the observational period to 31% in the final time frame, signifying the growing attractiveness of the German science system in more recent years. Conversely, the percentages of outflows and transients exhibited stability during the initial two time windows, subsequently declining in the third interval. Concurrently, the share of returnees has been in a declining trajectory, decreasing from 23% to 16.6%.

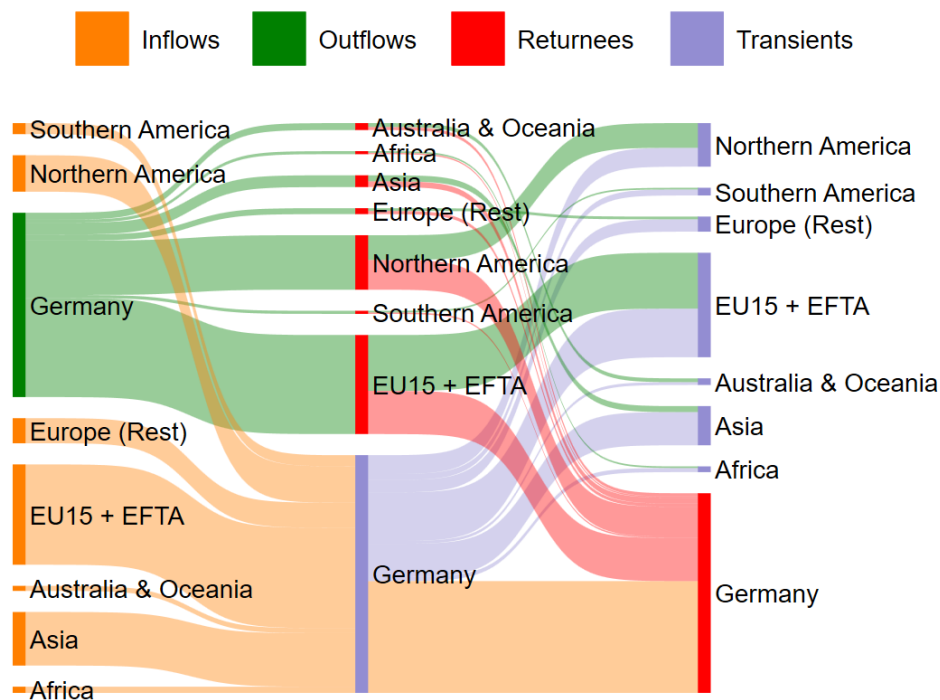


Figure 4 - Origin and destination world regions by mobility type

Notes: The category "Europe (Rest)" includes Eastern European countries and Cyprus.

In Figure 4, we present an overview of the primary origin and destination countries of mobile researchers. Note that this figure excludes again stayers, focusing solely on mobile researchers, and the colours of the flows correspond to those assigned to each group in Figure 2. In the graph, the bars on the left and on the right represent the first and last affiliation countries, respectively. The bar in the middle was created as follows: in the case of inflows and outflows, it was set to be identical to the country of the last affiliation; for returnees and transients, it was determined by the last affiliation before the return to (or departure from, in the case of transients) Germany.

From the graph, we can identify the main regions of origin of "inflow" researchers (indicated by the orange flows), which are predominantly located in Europe, followed at a distance by Asia and Northern America. European countries are also the top receivers of outflow scientists (indicated in green), followed once again by North America, but not Asia, which does not appear to be a highly favoured destination for researchers leaving Germany

When considering the origin of "returnees" (in red), most of them move back to Germany from the same areas of outflow destination, namely European countries and Northern America. Regarding "transients", the flows to Asia consist mainly of this category. These researchers often begin their careers in Asia, join the German science system for a period, and then move on to Asian countries.

In summary, the figure highlights the dominant role of European countries and Northern America in both inflow and returnee researcher movements, while Asia plays a significant role in the transient category.

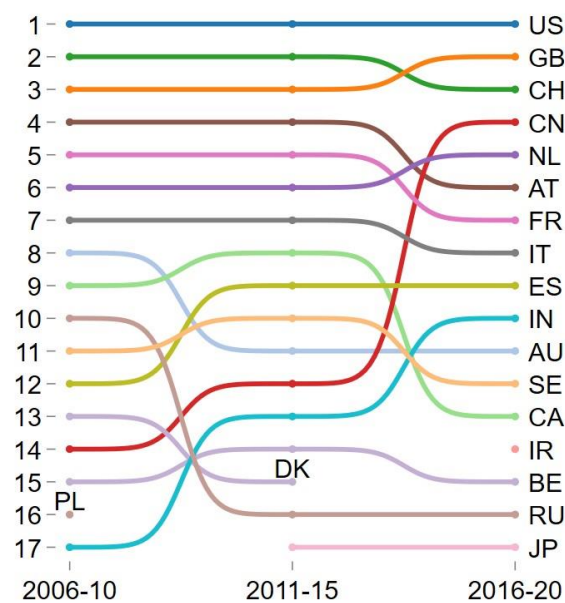


Figure 5 - Rank of top 10 bilateral flows countries

Figure 5 presents an analysis of the top 10 countries for bilateral flows (i.e. taking into account both inflows and outflows researchers) over the three distinct 5-year time windows. Notably, the top-

ranking countries have shown remarkable stability throughout all time windows, with the United States, the United Kingdom⁶, and Switzerland consistently occupying the podium.

However, there are interesting movements in the other positions of the ranking. For instance, Spain entered the top 10 rank between the first and second time windows, indicating a notable increase in its scientific mobility exchanges with Germany during that period – possibly as a result of the deep economic crisis that country went through, which pushed many Spanish scientists away from Spain.

Even more strikingly, China and India, especially in the last time window, emerged as significant global players in the world science system. Both countries have become vital sources of mobile scientists, as we observed earlier. Their substantial rise in importance reflects the rapid development and expansion of their research capabilities and exchanges with German researchers.

Conversely, some countries experienced a decline in prominence during the considered period. Austria, for example, slipped from the 4th to the 6th position in the last time window, while Russia from the 10th to the 16th position, suggesting a relative decrease in their scientific mobility exchanges with Germany over time.

These trends illustrate the dynamic nature of international scientific exchanges and how different countries have evolved in their roles as sources and destinations of mobile researchers over the analysed time windows. The emergence of China and India as major players demonstrates the shifting landscape of global scientific research and its impact on international mobility patterns.

Figure 6 illustrates the scientists' mobility trends in and out of Germany and a selection of other countries, highlighting both incoming and outgoing researchers. The comparative data is sourced from the OECD Science, Technology and Innovation (STI) Scoreboard (OECD, 2017)⁷ and is derived from the analysis of the primary affiliations of authors who published in 2021, juxtaposed with their nearest available publications from previous years. In the case of Germany, we utilized our dataset to construct a similar visualization for the year 2020. Note that OECD does not identify the “transients” category, so we report it only for Germany.

⁶ The ISO 3166 standard by the International Organization for Standardization (ISO) designates the entries for the "United Kingdom of Great Britain and Northern Ireland" as "GB" and "GBR." Consequently, these codes, namely "GB" and "GBR," will be employed in the figures, while the text will consistently refer to the country as the United Kingdom.

⁷ OECD's estimates are based on a comparison between the primary affiliation of an author who published in 2021, and the nearest accessible publication from an earlier year. They only consider authors with two or more publications in 2007-2021. In 2021, a mobility occurrence is identified when an author's last affiliation corresponds to an institution in a particular country, and this contrasts with their previous affiliation at a different country. Authors are attributed specific statuses from the viewpoint of their final destination in 2021. Those who have maintained their affiliation with the reference country for both 2021 and the pre-2021 period are designated as "stayers." The "returnee" status pertains to individuals who shift their affiliation into the reference country, yet were affiliated with it during their first recorded publication. From the perspective of the author's preceding country of affiliation, individuals are computed as outflows.

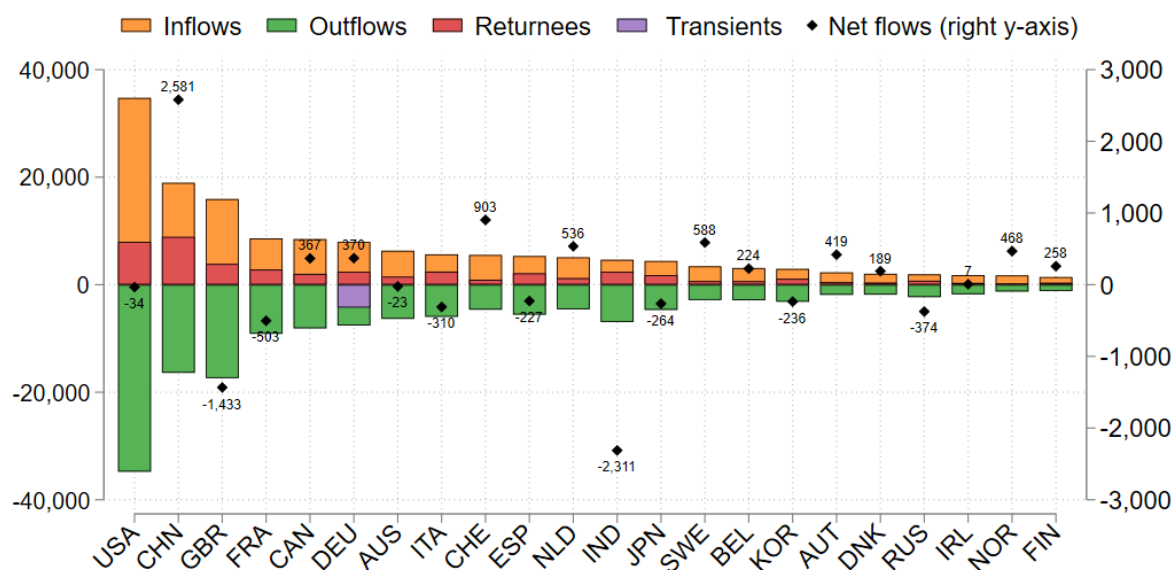


Figure 6 – Inflows, outflows and net flows of scientists in Germany (2020) and selected countries (2021)

Notes: Comparative data for other countries are sourced from OECD STI Scoreboard (OECD, 2017) and refer to year 2021. For Germany, we first assign a mobility status to all authors based on our baseline definition, i.e. taking into account their entire publication history (see section 2.2.1), and then select only those for whom the mobility event occurred in 2020 (including transients). This makes our data comparable with those sourced from OECD.

The figure reveals that Germany registers a total of 7,956 incoming researchers (comprising both inflows and returnees) and 7,595 outgoing (both outflows and transients). Consequently, the net scientist influx stands at 370 individuals. In terms of international rankings, Germany secures the 6th position in the roster of countries with the highest number of mobile scientists. This ranks it below the United States, China, the United Kingdom, France, and Canada. However, this marks a notable advancement compared to Germany's standing in 2011, when it held the 19th position (cfr. EFI, 2014, p. 85).

Moreover, it is important to notice that the OECD's strategy does not make use of name analysis to distinguish “returnees” from “inflows” nor “transients” from “outflows” (see sections 2.2.1.2 and 2.2.1.3). This can result in inflated figures for inflows and outflows. Take the cases of the US and China. A significant number of outflows from the US might involve foreign researchers leaving the country after graduating there, rather than US nationals. Similarly, the count of returnees to China might be underestimated due to this approach.

When considering the entire analysis period spanning from 2005 to 2020 and juxtaposing it with the preceding period examined in the previous EFI report (1996-2011), an enhancement in the count of

mobile scientists to and from Germany becomes evident. This improvement is underscored by a favourable shift in the net scientist influx over the complete time frame.

Specifically, Germany's trajectory reveals a significant transition. During the earlier period (1996-2011), the net flow of scientists stood at a negative value of approximately 4,000 individuals. However, in the subsequent period (2005-2020), this trend has been effectively reversed, resulting in a positive net inflow of more than 5,000 scientists. This shift is depicted in Figure 7.

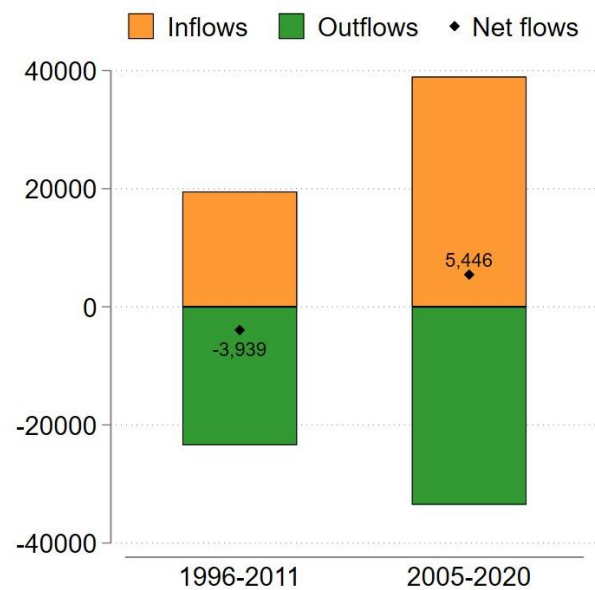


Figure 7 – Inflows, outflows and net flow of scientists in Germany, comparison between 1996-2011 and 2005-2020

Notes: In this figure, we use the approach outlined in section 2.2.1, which closely aligns with the methodology applied in the 2014 report (EFI, 2014). Specifically, this approach identifies researchers' mobility throughout the entire observation period (2005-2020 for the current report, 1996-2011 for the previous one).

From Figure 7, we observe that the overall number of inflows for Germany exceeds the number of outflows, indicating a net inflow of scientists. To understand the trend of net inflows over time for Germany, we followed the OECD strategy to identify yearly net flows of scientists.

The results show that, overall, the trend of net inflows for Germany has been increasing and has become particularly positive in the most recent years. It is even more interesting to compare Germany's trend with those of other European countries (Figure 8). Germany stands out with the stability of its trend over time, which it shares with Austria and Switzerland, albeit these two countries

are smaller in size. When compared to similarly sized European countries like France, Spain, Italy, and even the United Kingdom, we notice that these nations experienced significant fluctuations in their net inflow trends over the same time period. For example, one can see the steep drop in net inflows for the United Kingdom after 2016, which could be attributed to the implications of Brexit. Hence, when compared to other European countries of similar size, Germany appears to have a more stable science system with relatively consistent attractiveness to international researchers, which has slightly increased over time.

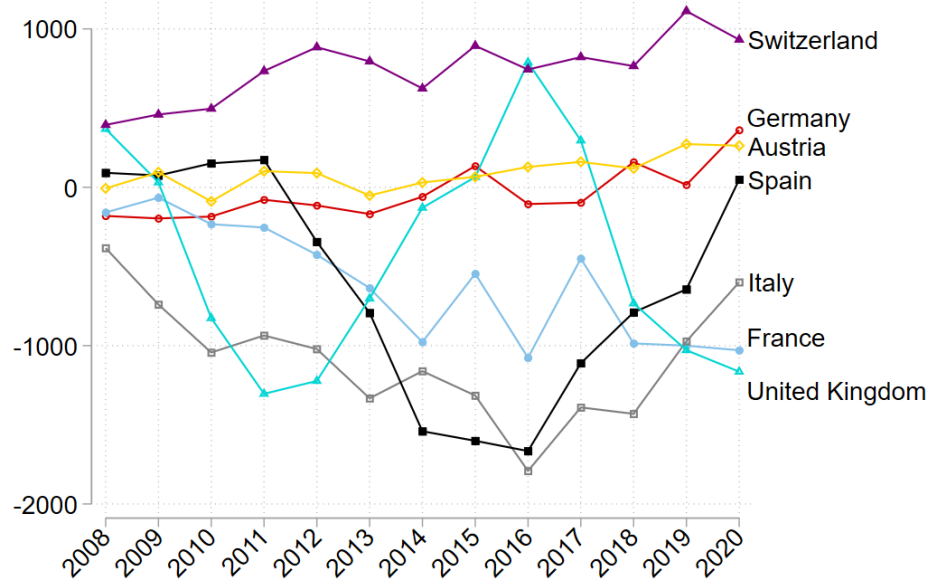


Figure 8 - Net flows of researchers by year. International comparison: Europe (selected countries)

Notes: In this figure, the emphasis is on the international comparison of Germany with other countries. To accomplish this, we utilize data provided by the OECD STI Scoreboard (OECD, 2017), which has been computed using a distinct methodology with respect to the one presented in section 2.2.1, to which we adapt for the sake of a meaningful comparison. Here, the focus lies on the years of observation, and each researcher who publishes in year t is designated the status of stayer or mobile (either inflow or outflow), contingent upon the affiliation of their immediately preceding scientific publication. Consequently, the same researcher may be labeled as an inflow/outflow more than once in the observational period. For these reasons, Figure 7 and this figure are not directly comparable, as they measure two different aspects: the stock of mobile researchers in the first case and their flux in the latter, employing distinct methodologies.

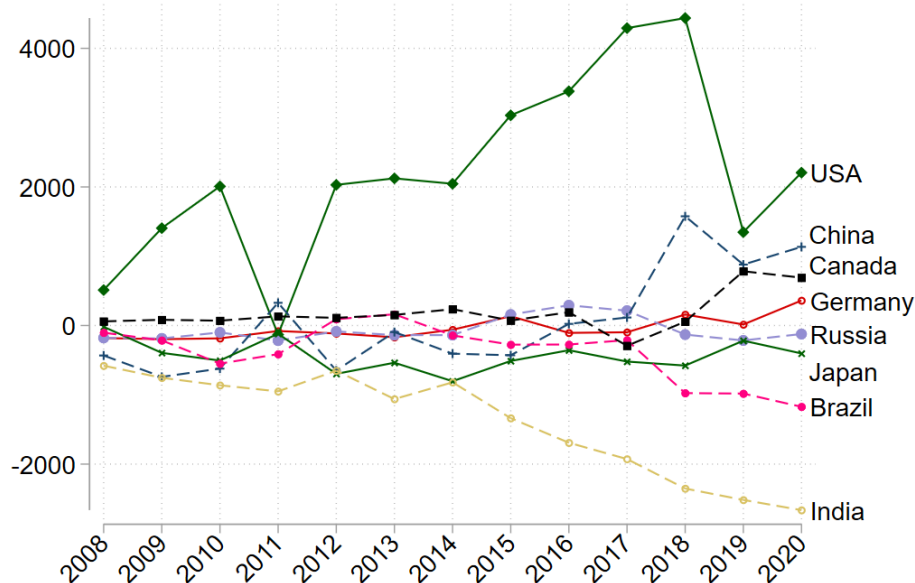


Figure 9 - Net flows of researchers by year. International comparison: World (selected countries)

Notes: In this figure, the emphasis is on the international comparison of Germany with other countries. To accomplish this, we utilize data provided by the OECD STI Scoreboard (OECD, 2017), which has been computed using a distinct methodology with respect to the one presented in section 2.2.1, to which we adapt for the sake of a meaningful comparison. Here, the focus lies on the years of observation, and each researcher who publishes in year t is designated the status of stayer or mobile (either inflow or outflow), contingent upon the affiliation of their immediately preceding scientific publication. Consequently, the same researcher may be labeled as an inflow/outflow more than once in the observational period. For these reasons, Figure 7 and this figure are not directly comparable, as they measure two different aspects: the stock of mobile researchers in the first case and their flux in the latter, employing distinct methodologies.

Comparing Germany with other global economies, it is no surprise that the United States still registers the highest net inflow of scientists, and that developing countries such as Brazil and particularly India have become important sources of international mobile scientists, thus with a negative trend of net inflows.

When considering Germany's positioning in the global ranking, even though China and Canada have performed better than Germany in recent years, Germany still maintains a higher net inflow of scientists compared to other significant world players such as Russia, Japan, and Korea (not shown in Figure 9).

Hence the analysis demonstrates Germany's steady and increasing attractiveness for international researchers, both in comparison to other European countries and in the context of the global science system.

3.1.1 Focus: Gender differences

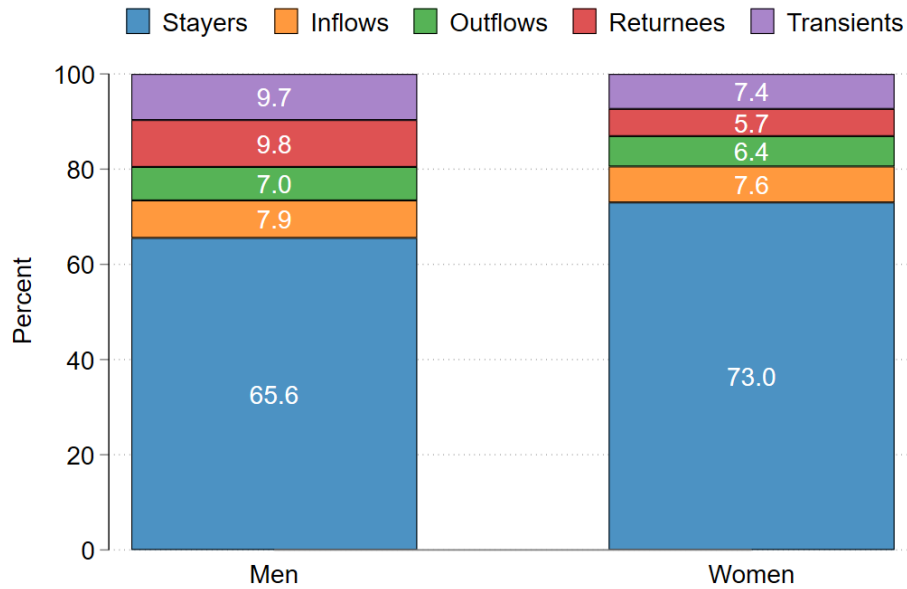


Figure 10 - Share of mobile researchers, by gender

Figure 10 splits our sample into two groups based on gender. Gender information is obtained through the analysis of scientists' names, as detailed in section 2.2.1.2. The figure shows that the percentage of stayers is higher among women, with 73% compared to 65.6% for men. Additionally, among female mobile researchers, the category with the smallest share is returnees, indicating that women, while less mobile in general, are also less inclined to move more than once and especially back to Germany.

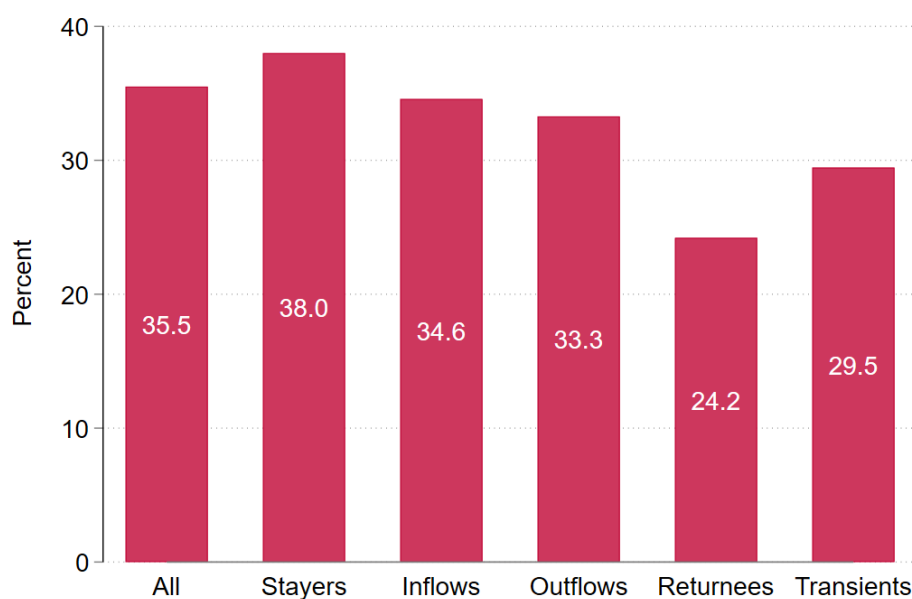


Figure 11 - Share of women researchers, by mobility type

This finding is further confirmed by Figure 11, which shows the share of female researchers across all mobility categories. While women represent 35.5% of the researchers analysed, they are 38% of stayers and only 24.2% of returnees.

Another interesting difference emerges when analysing the timing of mobility. In Figure 12, we consider the scientific age at which the mobility occurred, measured with the number of years since the first publication at the time of the mobility event. The distributions are concentrated in the early career phase, with mobility most frequently happening within the first 5 years after the first publication, both for men and women scientists.

Of particular interest is the modal scientific age of mobility, which consistently appears to be lower for women compared to men across all analysed mobility typologies, typically ranging from 1 to 2 years earlier with respect to men's. This means that while women are less mobile than men, when they move, they tend to do so at an earlier stage in their career. Moreover, when women move outside Germany, they are less likely than men to come back as returnees.

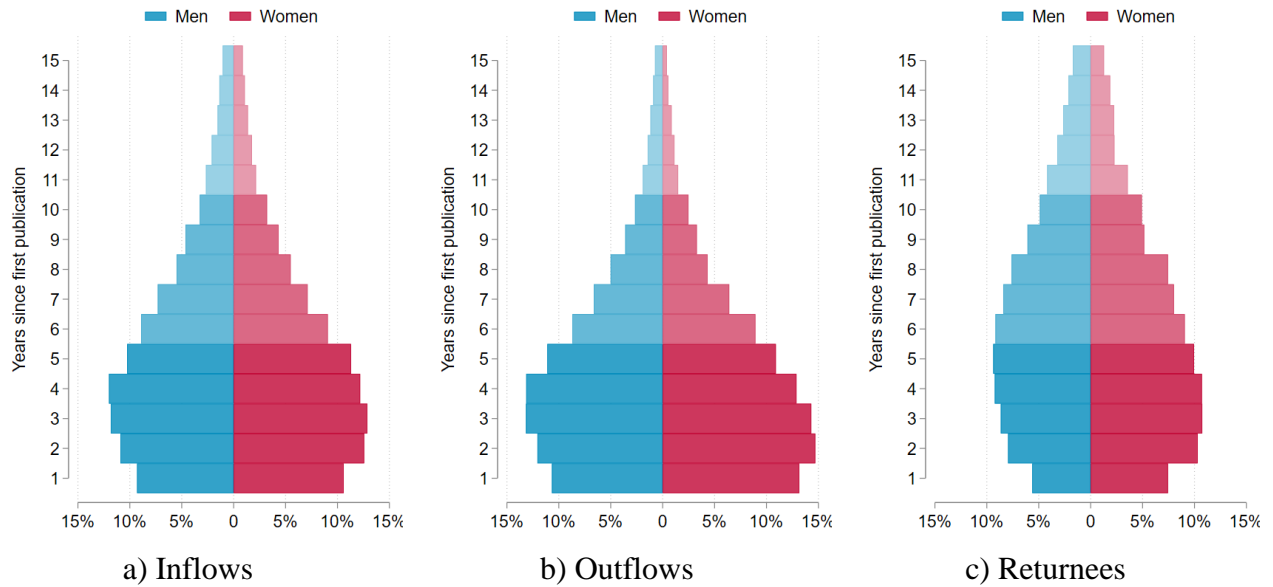


Figure 12 - Age pyramid by gender and mobility type

3.2 Comparison of outbound and inbound mobility

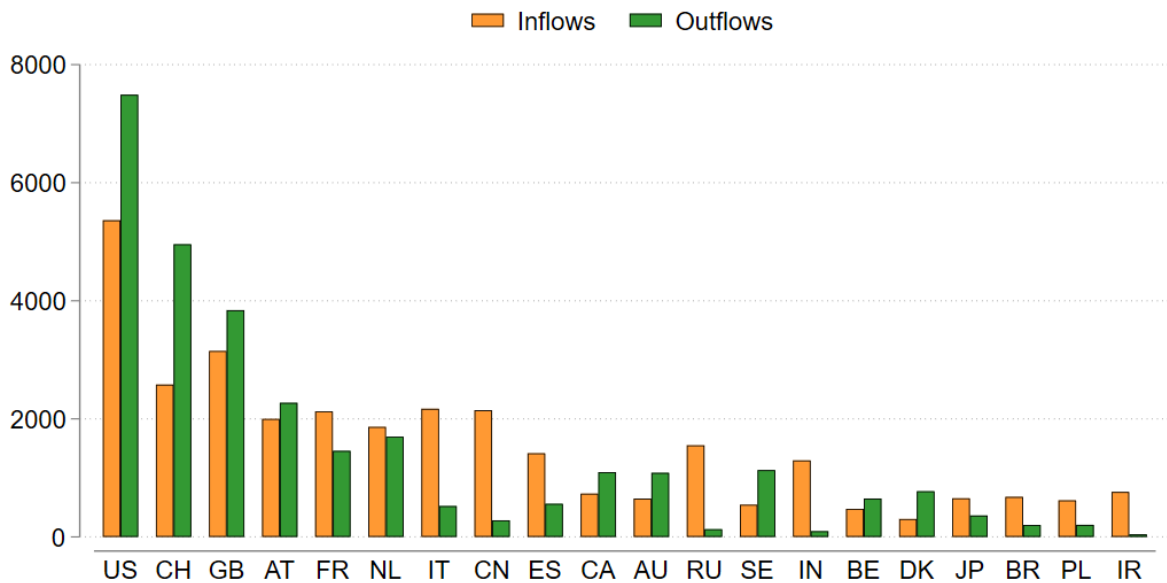


Figure 13 - Germany's inflows and outflows by country

Figure 13 presents an analysis of the inflows and outflows in the top 20 countries for bilateral flows with Germany, shedding light on the differences between these two dimensions.

When we examine the data, we observe that in the case of most developed countries, such as the United States, Switzerland, the United Kingdom, Denmark, or Canada, the number of outflows is

higher than the number of inflows. This indicates that these countries are more important destinations for German scientists relative to their role as sources of foreign ones moving to Germany. Conversely, the opposite pattern holds for developing economies like China, Russia, India, and Brazil. In these cases, the number of inflows is higher than the number of outflows, implying that German scientists are less drawn to these developing countries as destinations.

However, there are some exceptions to this pattern. Notably, countries like France, Italy, the Netherlands, Spain, and Japan, which are developed economies, generate more inflows than outflows, although both at lower overall scale than United States, Switzerland, the United Kingdom.

This suggests that attractiveness as a destination for scientists can vary based on bilateral factors, including the level of development of the partner country, the strength of its scientific ecosystem, research opportunities, and other socio-economic factors, relative to those of Germany. The complex interplay of these variables influences the direction and magnitude of mobility flows between countries.

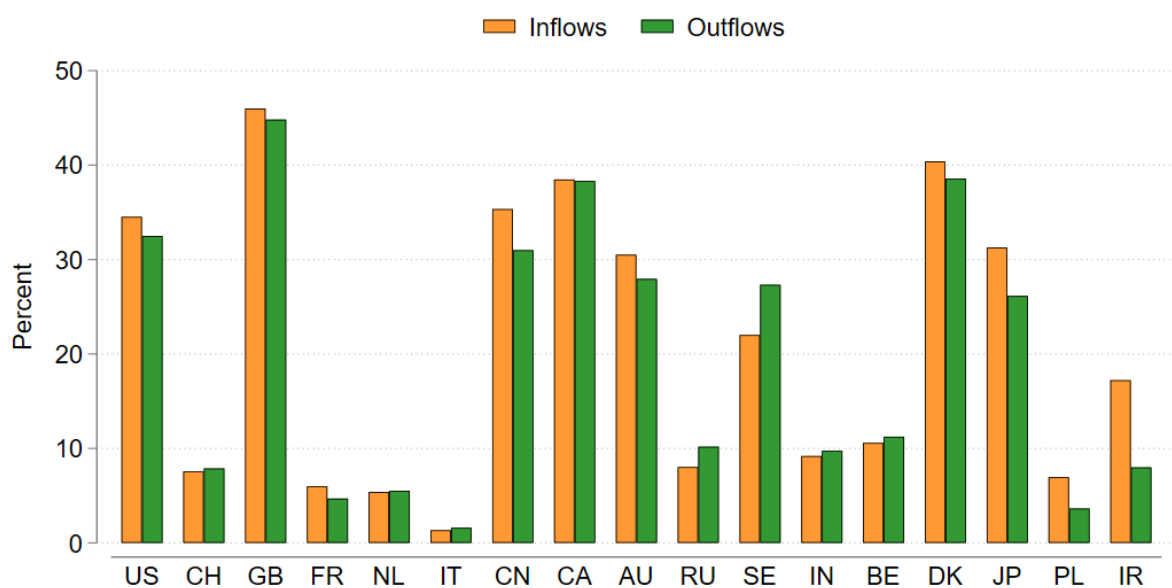


Figure 14 - Share of scientists in ARWU Top-500 institutions

Notes: We take into account the rank and the country of the affiliation immediately before/after the mobility event.

In Figure 14, we delve into a more detailed analysis by considering the share of inflows and outflows from Top-500 institutions according to the Shanghai ranking for each country (ARWU ranking). To

calculate the inflow share, we take into account the last institution before scientists moved to Germany, while for outflows, we consider the first institution after leaving Germany.

The graph shows that, in general, the share of inflows coming from Top-500 institutions tends to be higher than the share of outflows going to such institutions, with some exceptions like Sweden, Russia, and Belgium. Additionally, countries like Switzerland, the Netherlands, and Italy also demonstrate a similar trend, but the two shares are very close, suggesting a balanced exchange of researchers with top institutions. This implies that while Germany might be experiencing a net talent loss compared to scientific powerhouses like the US and UK, as highlighted in Figure 13, in relative terms, researchers relocating to Germany from these countries often originate from top-tier institutions more frequently than German researchers heading in the opposite direction.

In Figure 55 in the Appendix, we expand the analysis to include returnees and transients. The data reveals a consistent pattern across almost all countries analysed: returnees report the lowest share of scientists from top universities, while transients exhibit the highest share. This indicates that researchers who have moved back to Germany after working abroad are less likely to come from top institutions, whereas those who have transitioned to Germany and then moved on to other countries often land to prestigious universities.

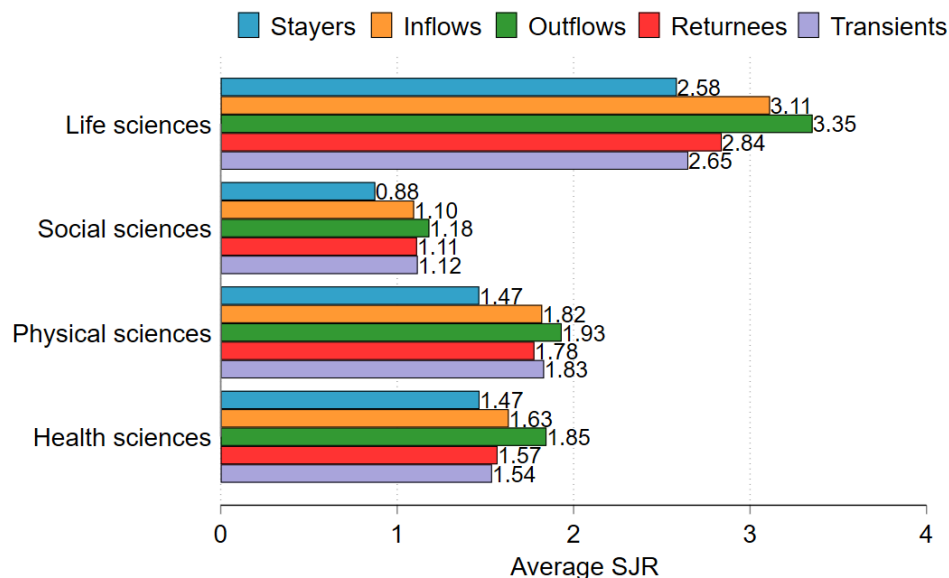


Figure 15 - Mobility and researchers' quality (SJR), by scientific field

To determine whether Germany is losing or gaining talent, we classify the publications of different category of scientists according to the importance of the journals in which they appear, the latter

measured with the Scopus Journal Ranking (SJR). In Figure 15, researchers are divided by their scientific field and mobility type, and the average SJR is computed. The results show a consistent pattern across all disciplines: outflow scientists have the highest SJR, followed by either inflow, returnees or transient ones, while stayers exhibit the lowest value. This indicates that, on average, the quality of researchers leaving Germany is higher than the quality of those coming to Germany, which in turn is higher than that of those who never move. The difference is most noticeable for the life sciences, where average SJR values are both larger and more variable across categories, and much less for the social sciences, where the SJR are generally compressed towards the bottom.

In Figure 16, the analysis is further expanded by considering countries. Here, incoming scientists (inflows and returnees) and outgoing scientists (outflows and transients) are grouped together. The findings indicate that the quality of incoming researchers is generally better than that of outgoing researchers for developing countries such as China, Russia, India, Brazil, Poland, and Iran. Conversely, the opposite is true for most developed countries, with the exception of Italy and Spain. However, it is important to note that from the error bars reported in the graph, not all differences are likely to be statistically significant.

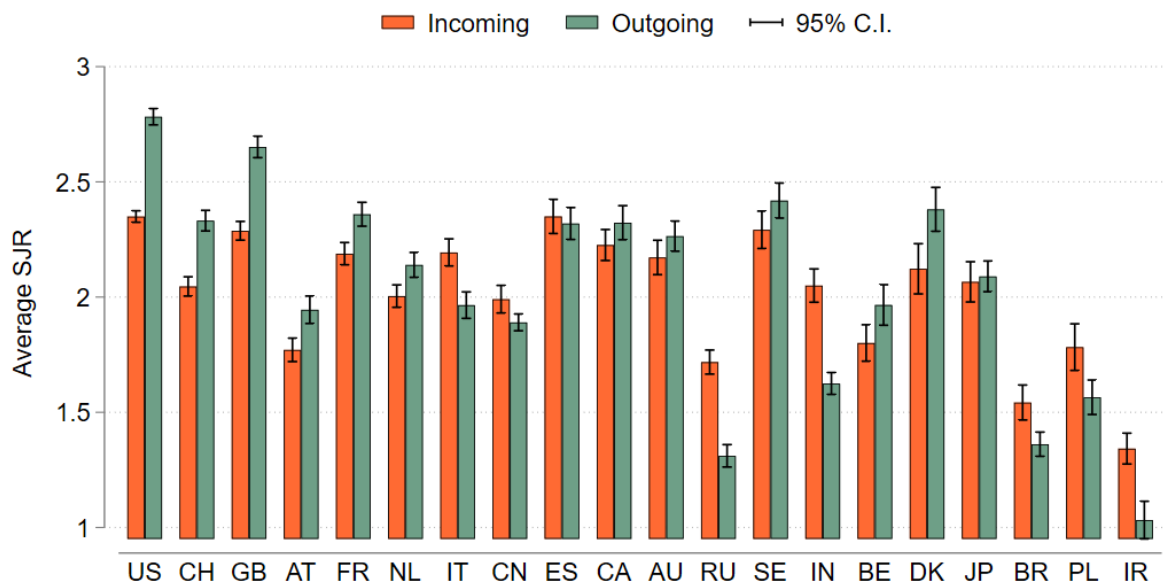


Figure 16 - Researchers' mobility and average SJR, by origin/destination country

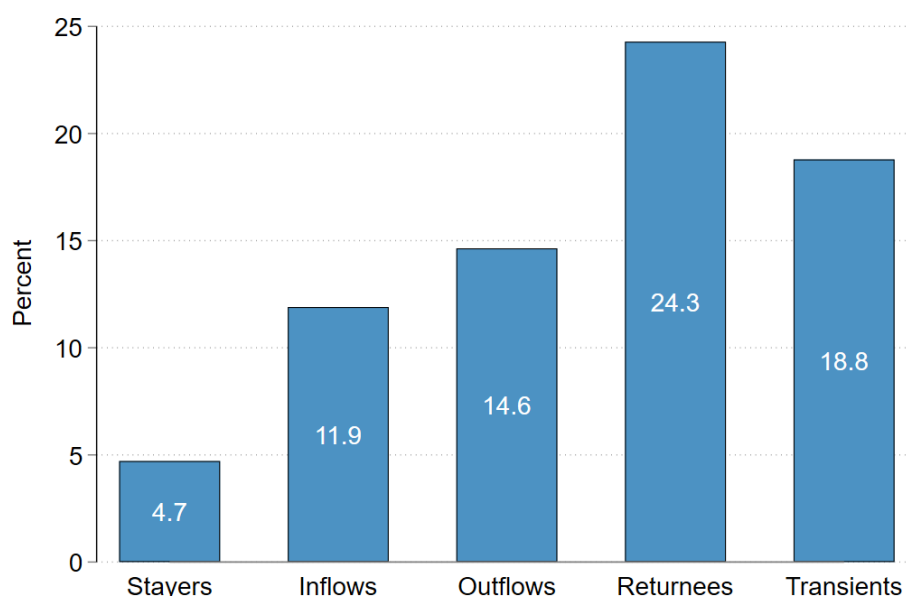


Figure 17 – Distribution of top 10% cited mobile scientists, by mobility type

The analysis of Figure 17 provides a crucial insight into the mobility patterns of researchers in Germany. While it may appear from the previous discussion that Germany is, *on average*, losing talent based on the overall mobility trends, the situation changes when focusing at the very top of the distribution. By identifying the top 10% cited researchers per field in the sample, it emerges that the "returnee" category holds the highest share of these top-cited scientists. Interestingly, more than 25% of the researchers in the "returnee" category belong to this group of highly cited researchers. This finding suggests that, despite the net outflow of talent, the best researchers are more inclined to return to Germany after spending a period abroad.

The likelihood of top-cited researchers to return to Germany indicates that the country continues to be an attractive destination for scientific excellence. It also suggests that German institutions and research opportunities hold significant appeal for these outstanding researchers, leading them to come back to contribute to the country's research landscape.

Figure 18 provides a comparative analysis of the SJR for different mobility types of German scientists as compared to other countries. To conduct this analysis, we use the comparison data from the OECD STI Scoreboard, which facilitates the computation of SJR for publishing scientists in the year 2021. The approach adopted by OECD to compute scientists' average SJR closely resembles our methodology, albeit with slight variations.⁸ For this comparative evaluation, we only consider mobile

⁸ OECD's estimates are derived from a comparison involving the SJR scores for documents published by scientific authors in 2021. These scores are based on the journal's ranking associated with an author's publications in the same year. Authors

scientists whose mobility event took place in 2020, and we compute the average quality of publications per category using the SJR values from 2021. In the figure, we do not report the value for the "transients" category, since it is not calculated by the OECD. Our primary aim is to produce values that are directly comparable with the data for the other countries provided by the OECD, prioritizing consistency for the purpose of meaningful comparisons. Countries situated to the left of the 45-degree line witness a greater impact from outflows compared to inflows. Conversely, countries positioned to the right of this line exhibit the opposite pattern. The size of the bubbles represents the number of mobile scientists, calculated as the average between inflows and outflows.

Germany's placement is on the left side of the 45-degree line, signifying that the influence of outflows surpasses that of inflows. Nevertheless, it is important to stress that both inflows and outflows show remarkably high quality. Specifically, the quality of inflows ranks second only to global scientific leaders such as Switzerland, the United States, the United Kingdom, and the Netherlands. Similarly, the quality of outflows stands as the highest after Switzerland, followed by China.

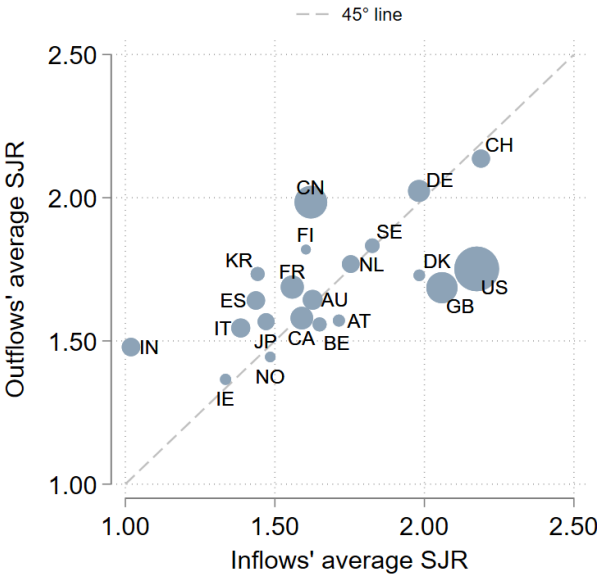


Figure 18 – Inflows’ and outflows’ average SJR, international comparison (selected countries)

Notes: Data for comparative countries are sourced from OECD STI Scoreboard (OECD, 2017). The size of the bubbles represents the number of mobile scientists, calculated as the average between inflows and outflows.

are classified in four categories (stayers, inflows, outflows and returnees) according to their mobility history from 2007 up to 2021. Only authors with at least two publications are included.

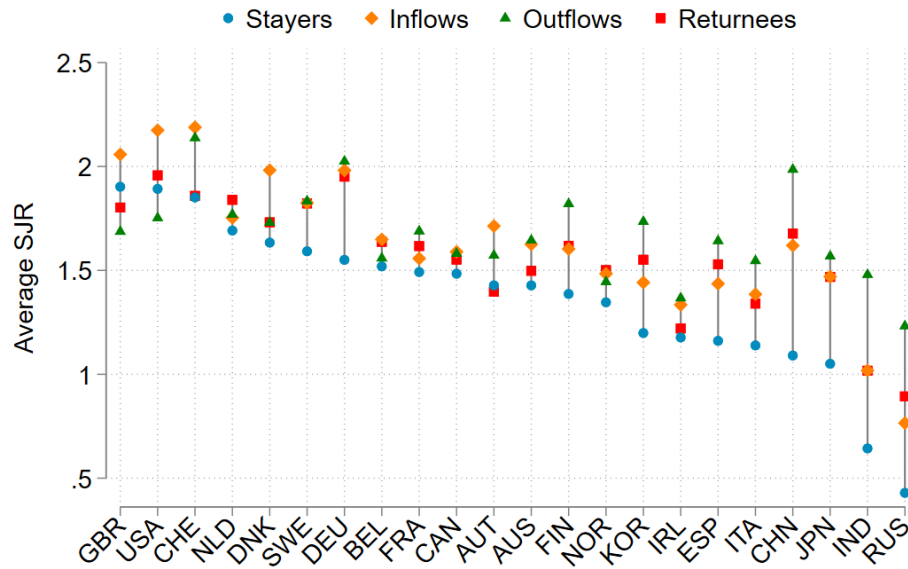


Figure 19 - Average SJR of scientific authors, by mobility type. International comparison (selected countries)

Notes: Data for comparative countries are sourced from OECD STI Scoreboard (OECD, 2017).

In Figure 19, besides the averages for inflows and outflows, we report also the values for “returnees” and “stayers”. The countries selected are arranged according to the quality of the latter category. On the left side of the graph, we observe countries where the quality of inflows surpasses that of the other categories. Notable examples include the United Kingdom, the United States (the only countries where the quality of outflows is lower than that of stayers), Switzerland, and Denmark.

Moving towards the right side of the graph, we encounter countries where the quality of outflows ranks the highest. This category prominently features Asian nations such as China, Korea, Japan, and India, alongside Finland and Spain. Germany also falls into this category, even if inflows and returnees exhibit comparable scores with respect to outflows. In particular, it is worth noting that Germany demonstrates a notably high quality score among returnees. This observation underscores the significant role that the mobility category holds within the German science system.

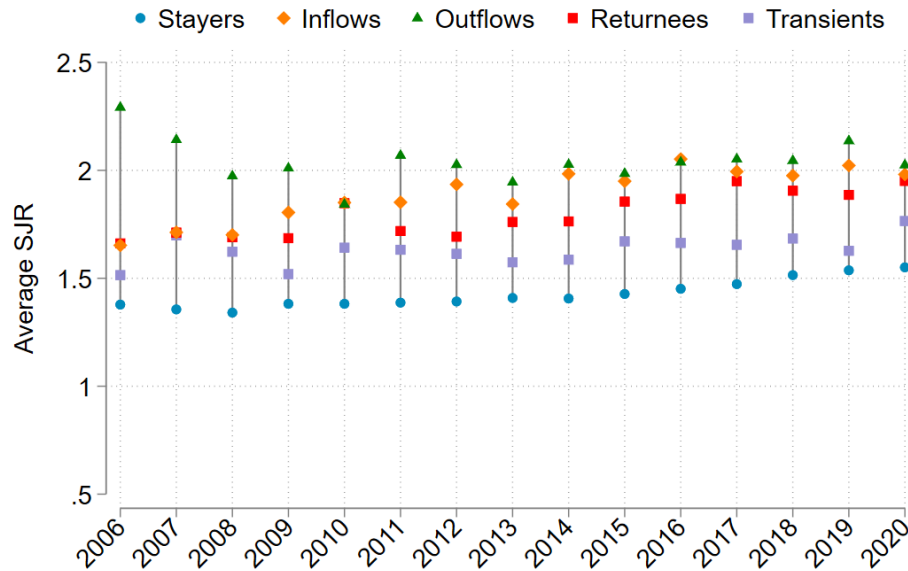


Figure 20 - Average SJR of German authors in 2006-20, by mobility type

Notes: Data for comparative countries are sourced from OECD STI Scoreboard (OECD, 2017).

Finally, in Figure 20, we recalculated the average SJR of German scientists based on their mobility types, including the “transients” category. We make a comparison with the average SJR values of German scientists in each year within the timeframe of our analysis (2005-2020). To achieve this, we categorized researchers according to their mobility typology, considering their publications throughout the entire period. For each mobile researcher, we identified the year when the mobility event occurred and determined the SJR of the publications they authored in that specific year.

The results indicate several relevant trends. First, the quality of outflows declined during the studied time span. Conversely, the quality of stayers demonstrates a clear upward trend, which might imply that over this period, Germany became more proficient at retaining high-caliber researchers. Moreover, the quality of both inflows and returnees also exhibited an upward trend, “closing the gap” with outflows, especially in more recent years. This might suggest that Germany evolved into a more appealing destination for accomplished researchers.

3.2.1 Focus: Exchanges with the US at the level of universities

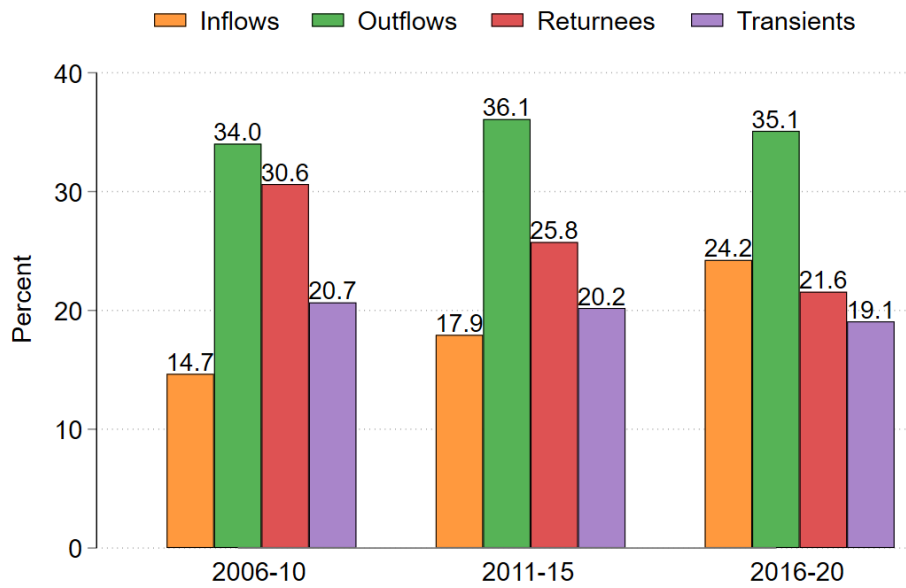


Figure 21 - Share of mobile scientists from/to US, by mobility type and time window

In Figure 21, we narrow our focus to mobile researchers engaged in movements to or from US institutions, considering the affiliation prior to or after the mobility event. We present the distribution of different mobility types within three distinct five-year time windows (2006-10, 2011-15 and 2016-20). To ensure the comparability among them, we categorize researchers into three groups. For each group, researchers must have completed their movement within the specified time window, and having their first documented publication spanning from the five years prior to the commencement of the time window up to the year just before the conclusion of the time window. As an example, researchers falling within the first group made their move during the period of 2006-2010 and had their initial recorded publication between 2000 and 2009.

Figure 21 reveals that the most substantial group of researchers consists of outflows, with both outflows and transients remaining relatively stable across the three time windows. Instead, there has been a notable rise in the percentage of inflows, climbing from 15% to 24%. Conversely, the portion of returnees has decreased from 31% to 22%.

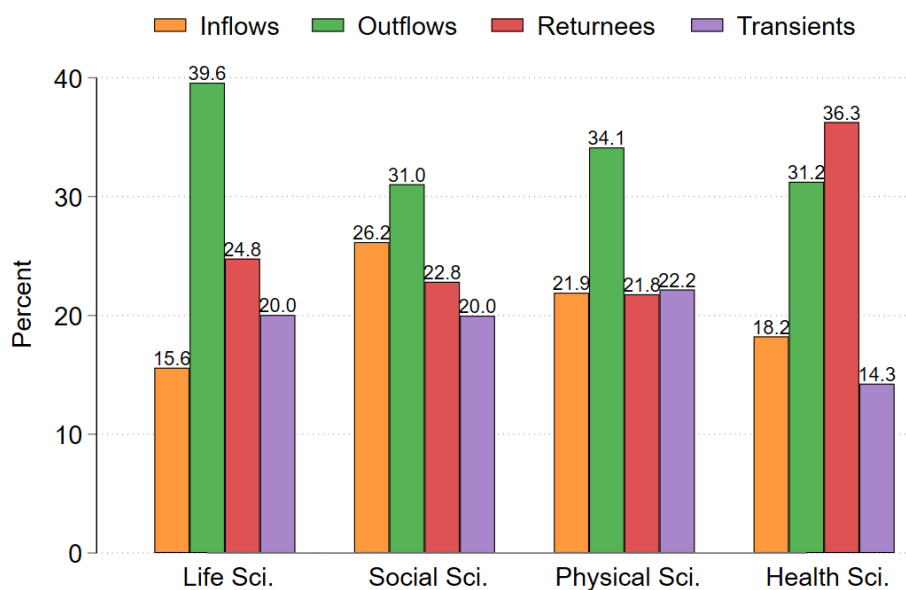


Figure 22 - Share of mobile scientists from/to US, by scientific field

Figure 22 provides an analysis by scientific field. Across all fields, the predominant portion is constituted of outflows, particularly noticeable in the case of Life Sciences where it constitutes nearly 40% of the mobile scientists. However, a noticeable exception is observed in Health Sciences, where the largest share is accounted for by returnees at 36.3%. The share of inflow scientists from the United States is most prominent in the domain of Social Sciences, accounting for 26.2% of the mobile researchers.

In Figure 23, our focus shifts to the analysis of the top 10 US institutions contributing to mobility in relation to Germany, encompassing all types of mobility (inflows, outflows, returnees, and transients). We maintain the same three time frames for evaluating mobility episodes as in the previous graph. In this representation, a clear pattern emerges: the first three positions remain consistently held by Harvard, Stanford, and Berkeley. However, MIT, Yale, and Princeton experience an increase in significance during the second time frame, and this trend becomes even more pronounced in the third time window. Notably, some universities lose positions, such as the University of California San Diego, San Francisco and Santa Barbara, while certain institutions that held relevance in the initial time frame, such as the University of Wisconsin-Madison and the University of Michigan Ann Arbor, drop out of the top 10 list in the subsequent time frames.

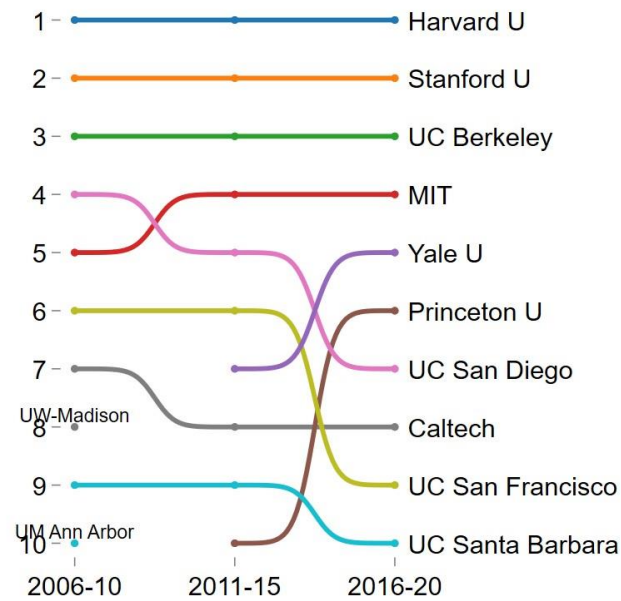


Figure 23 - Top 10 US universities by number of mobile scientists to/from Germany, by time window

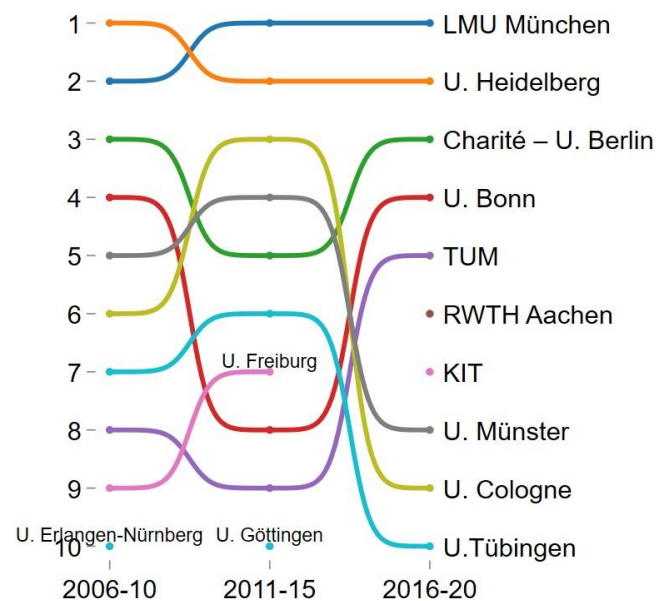


Figure 24 - Top 10 German universities by number of mobile scientists to/from the United States, by time window

Figure 24 displays the top 10 German universities in terms of mobility exchanges with the United States, encompassing all mobility types. Although LMU München and the University of Heidelberg firmly hold the first and second positions, the subsequent rankings in the top 10 exhibit more variability compared to the US universities in the previous figure. This variability indicates that the

pursuit of mobility exchanges with US counterparts is a common endeavour across a majority of major German universities.

Noteworthy is the ascension of technical universities like TU of Munich, RWTH Aachen, and the Karlsruhe Institute of Technology, especially in the most recent time frame. This highlights a growing trend in the significance of technical institutions in these exchanges. The third position occupied by Charité - Universitätsmedizin Berlin underscores a phenomenon observed in Figure 22, emphasizing the significance of returnees, particularly within the field of health sciences. Charité's third-place ranking is due to the substantial number of returnees from the United States, corroborating the prominence of return mobility in health sciences.

3.3 International collaborations

International collaborations play an important and increasing role in German science. As shown in Figure 25, in 2020 almost half of the multi-authored publications with at least a German author in the Social and Health sciences also had one or more international co-author, while in the Life and Physical sciences we observe shares of around 60%. These values result from a persistent and linear increase since at least 2005, when none of the four fields listed in Figure 25 exhibited shares of international publications higher than 50%. The most rapid increases are those of the Health and Life Sciences.

This increasing trend of international collaboration reflects the growing interconnectedness of the global research community. Advancements in communication technologies, easier access to research literature, and the recognition of the value of diverse perspectives and expertise from different regions have all contributed to the rise of international collaboration not only in Germany, but in all countries (see figure 56 in the appendix). However, compared to other big countries, such as the United States, China and Italy (but not France), Germany seems more affected by the phenomenon. Instead, smaller European highly open economies are more internationalized.

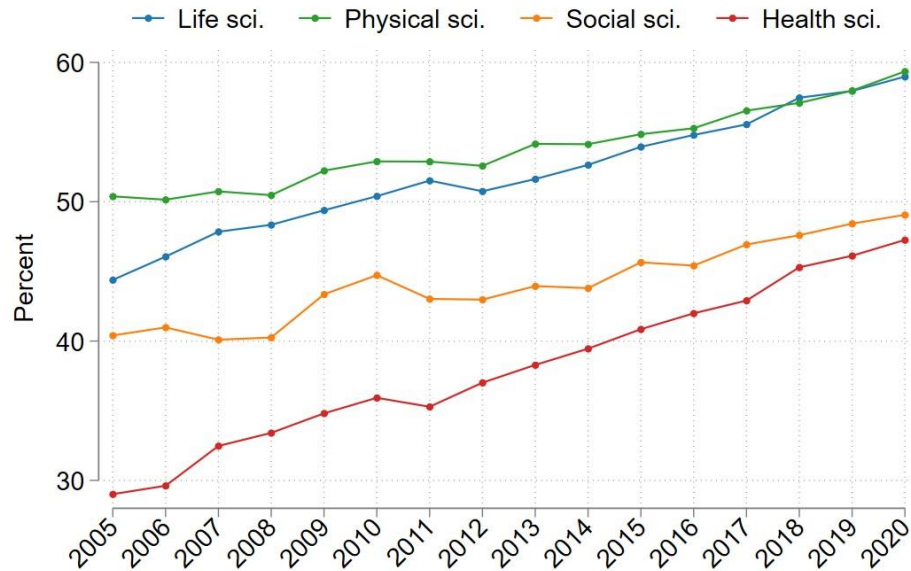


Figure 25 - Share of international co-authored publications with ≥ 1 German-affiliated author, by scientific field

Notes: Only co-authored publications. We use fractional count for articles associated to ≥ 1 ASJC.

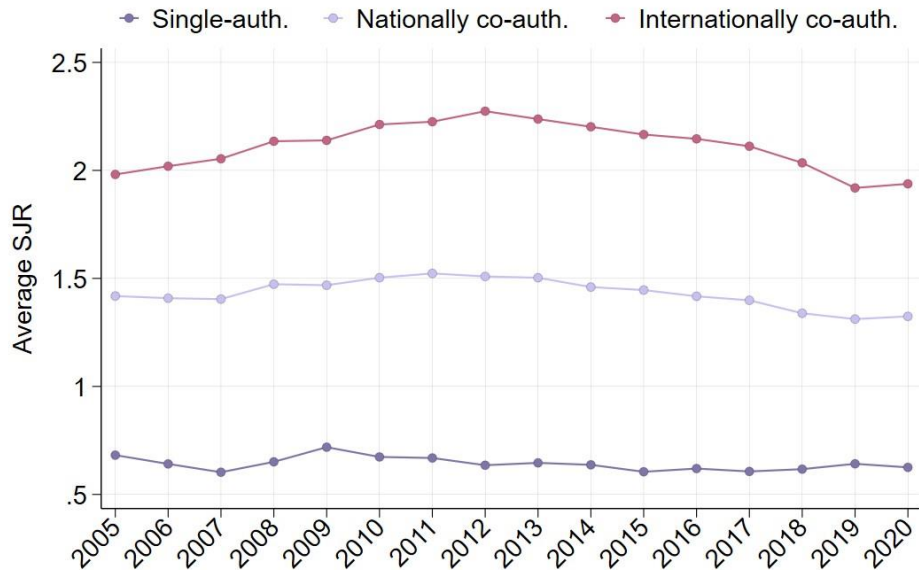


Figure 26 - Impact (SJR) of scientific publications with ≥ 1 German-affiliated author, by type of collaboration

Notes: Only co-authored publications. We use fractional count for articles associated to ≥ 1 ASJC.

Figure 26 highlights an important correlation between internationalization and quality of scientific articles, as measured by the SJR of the journals in which they appear. For multi-authored publications, we notice a persistent and stable quality gap between internationally and nationally authored ones, both of which appear of higher quality than single-authored publications.

Figures from 27 to 30 provide insights into the bilateral patterns of collaboration between Germany and other countries as well as on the level of internationalization of specific German institutions.

Figure 27 reports a map showing the collaboration intensity between Germany and all countries worldwide, based on the number of scientific articles co-authored. The most important partner countries are represented in shades of blue, and we can identify three distinct groups. In dark blue, we find the top partners, which include the United States and the United Kingdom. These are followed, in slightly lighter blue, by France and Italy. Finally, in light blue, we find both some small, but close countries such as Austria, Switzerland, Denmark, and Sweden, alongside larger, but far away ones such as Canada, Australia, and China.

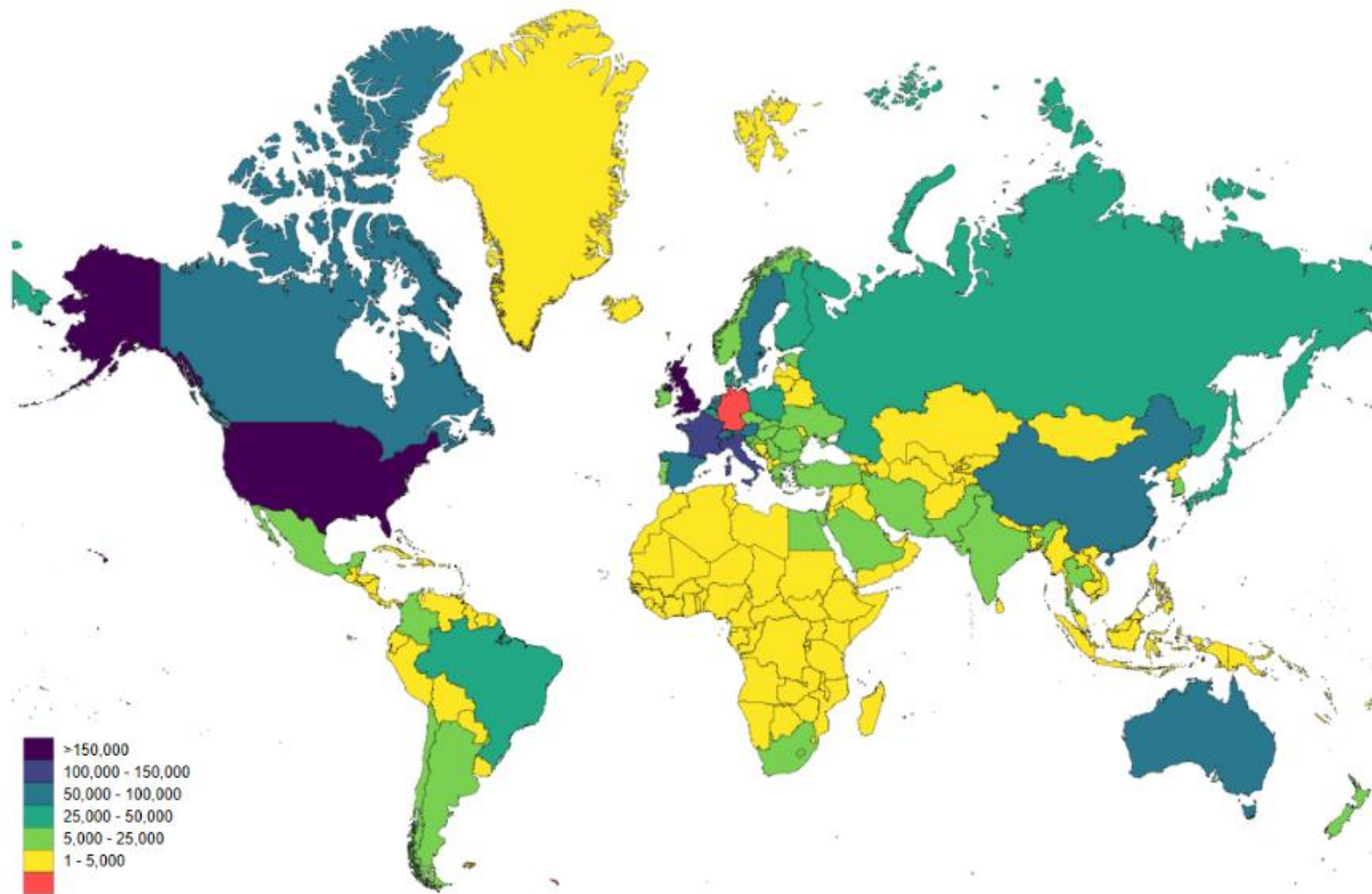


Figure 27 - Countries collaborating with Germany, by number of coauthored scientific articles (2005-2020)

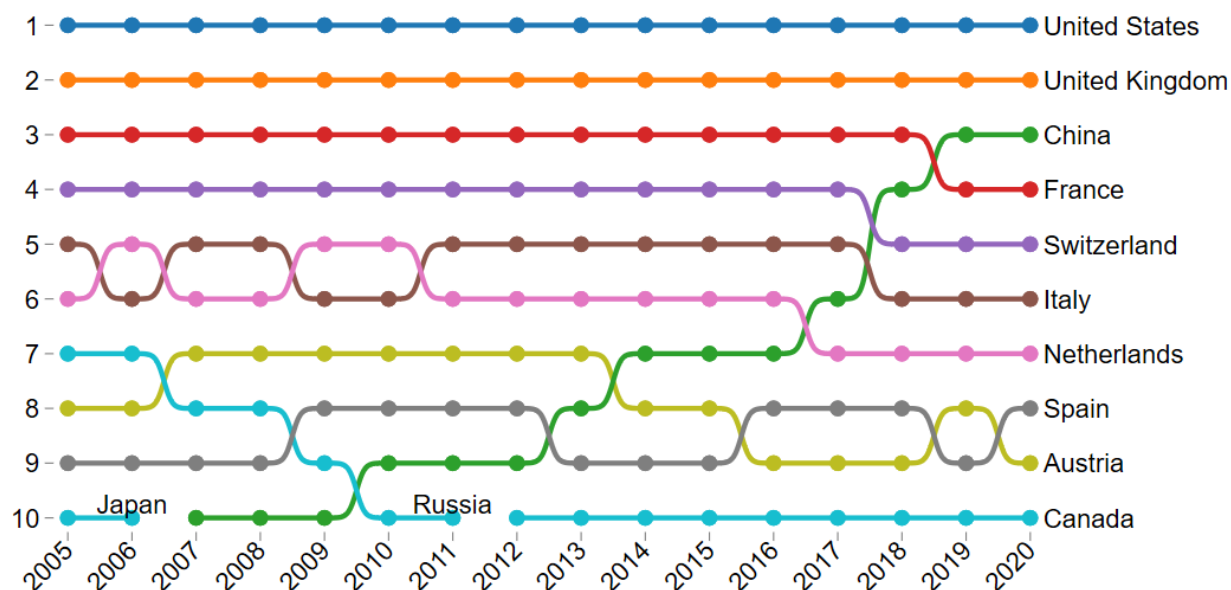


Figure 28 - Top 10 countries for number of co-authored articles with Germany (2005-2020)

In Figure 28, we observe the evolution of the top 10 ranking of countries with which Germany collaborates the most. The United States and the United Kingdom have consistently remained at the top of it as the two most important partners of Germany. France and Switzerland also persist as important partners, except for being both overtaken by China, whose weight on total collaboration has increased impressively in less than a decade. Conversely, it is worth noting the decline in collaboration with Russian science, which left the top 10 in 2011.

Figure 29 focuses on the most internationalized institutions in Germany, based on the number of internationally co-authored articles. When comparing this with Figure 30, which reports the evolution of the top 10 institutions for the number of inflow scientists, we notice a correlation. Institutions like LMU Munich and the University of Heidelberg rank high in both the inflow of scientists and international collaboration rankings, suggesting that their international openness contributes to their level of collaboration. In addition, in institutions like TU Munich and the University of Erlangen-Nuremberg correlates with an increase in international collaborations for these institutions. Similarly, the drop in inflows for the University of Bonn led to a significant reduction in international collaborations.

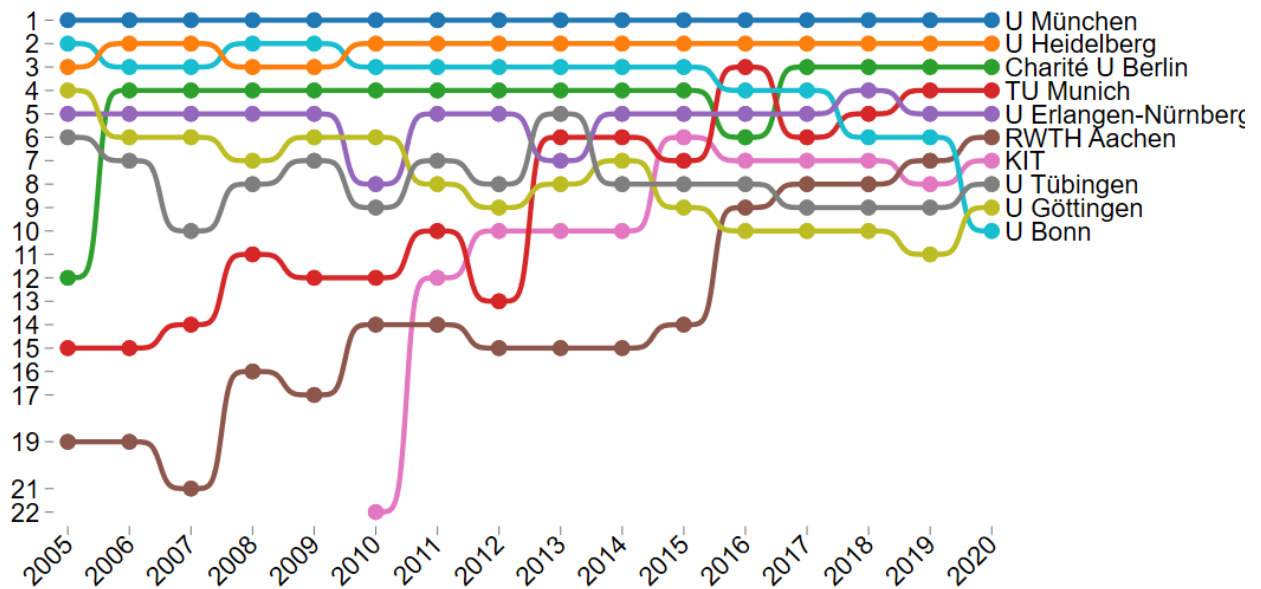


Figure 29 - Top 10 German institutions by number of international co-authored articles (2005-2020)

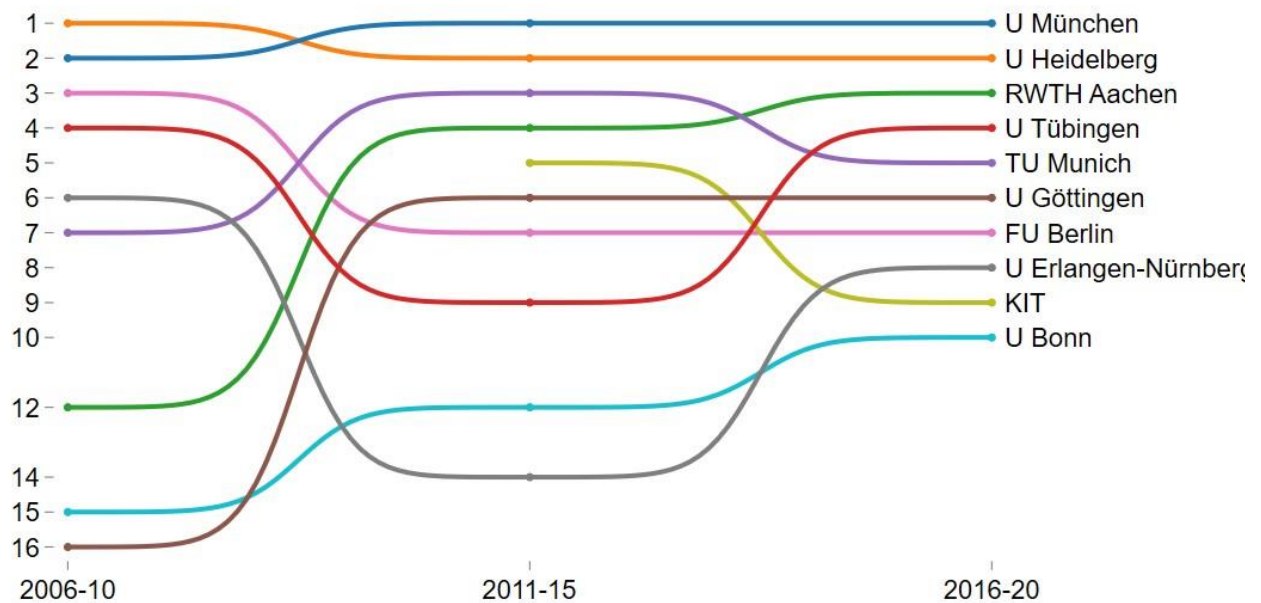


Figure 30 - Top-10 institutions for number of inflows

However, it is worth noting that the correlation may not always hold true for all universities. For example, the University of Tübingen increased the number of inflows and secured the third position in the ranking, but this did not lead to a significant increase in the internationalization of research conducted there.

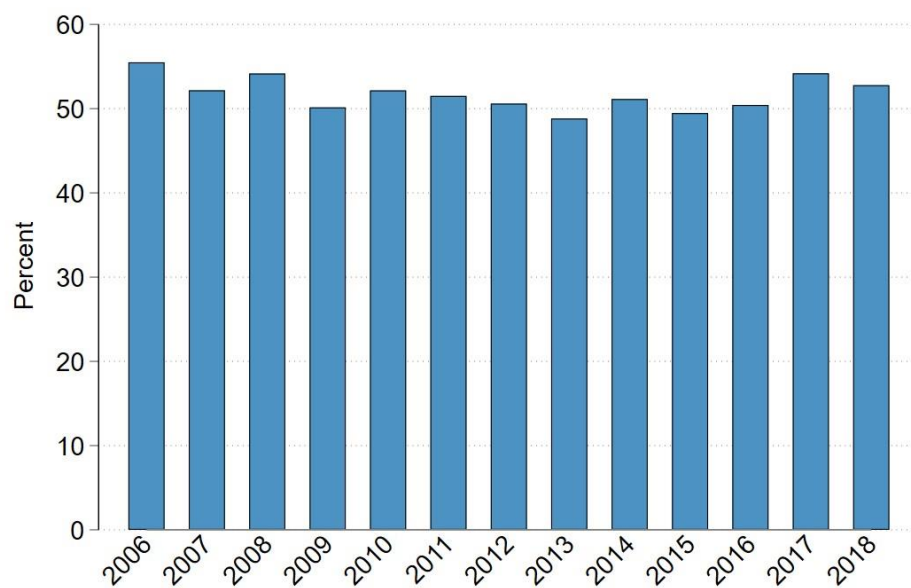


Figure 31 - Share of outflows collaborating with Germany 2 years after mobility, by year of mobility

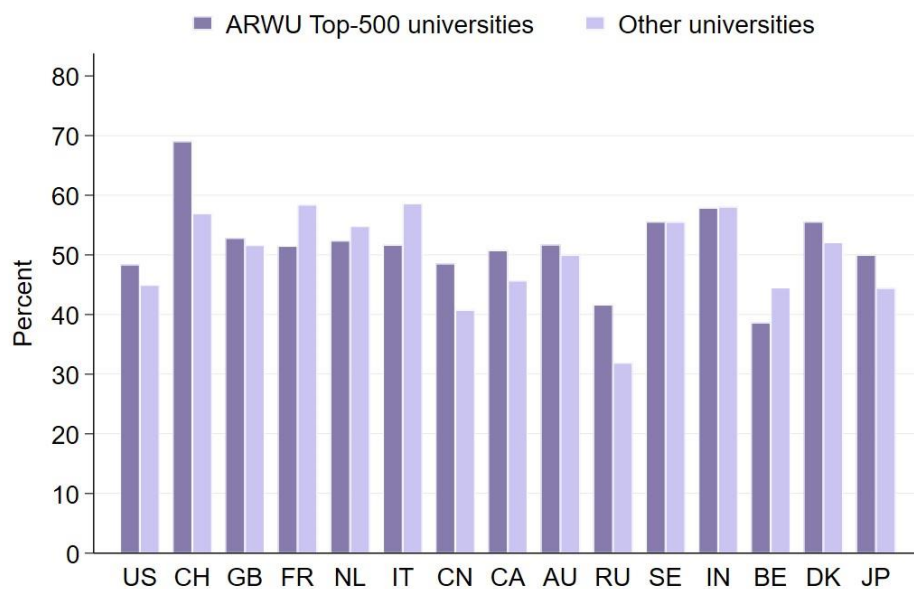


Figure 32 - Share of outflows collaborating with Germany 2 years after mobility, by country and institution rank

The analysis in Figure 31 and Figure 32 sheds light on the role of outflows in the internationalization of the German science system and the extent to which German scientists maintain connections with Germany after relocating to other countries.

In Figure 31, we observe that the share of outflow scientists collaborating with German-affiliated authors two years after the mobility event remains quite stable throughout the considered time period, hovering around 50% of outflows. This suggests that a significant proportion of German scientists who leave the country to work abroad continue to maintain connections and collaborations with researchers in Germany. These ongoing collaborations indicate that outflows can serve as conduits for knowledge exchange and scientific interactions between Germany and other countries.

Figure 32 further explores the relationship between destination countries and the rank of the university of destination for German outflows. The data examines whether German scientists who relocate to ARWU Top-500 institutions are more likely to maintain connections with Germany. The results show that the share of outflows maintaining connections with Germany two years after leaving is higher among those who go to top institutions in most of the popular destination countries. This difference in the likelihood of maintaining connections is especially pronounced in Switzerland, Denmark, and Japan. On the other hand, for countries like France, Italy, the Netherlands, and Belgium, the share of outflows maintaining connections with Germany is lower among movers towards top universities.

4 Fields focus

Using the methodology outlined in sections 2.2.3, we identified the articles and authors belonging to the three fields selected for in-depth analysis: Advanced Manufacturing (AM), Artificial Intelligence (AI), and Bioeconomy (BE).

Figure 33 displays the trend in number of scientific articles for the three fields during the period from 2005 to 2020. Observing the trends, we can see that the number of articles in the BE field increased at the beginning of the time period and then stabilized until the last recorded year (2020). On the other hand, AI experienced a more consistent and stable increase in the number of scientific articles throughout the entire period, with the yearly count more than doubling from the initial years to the end of the period.

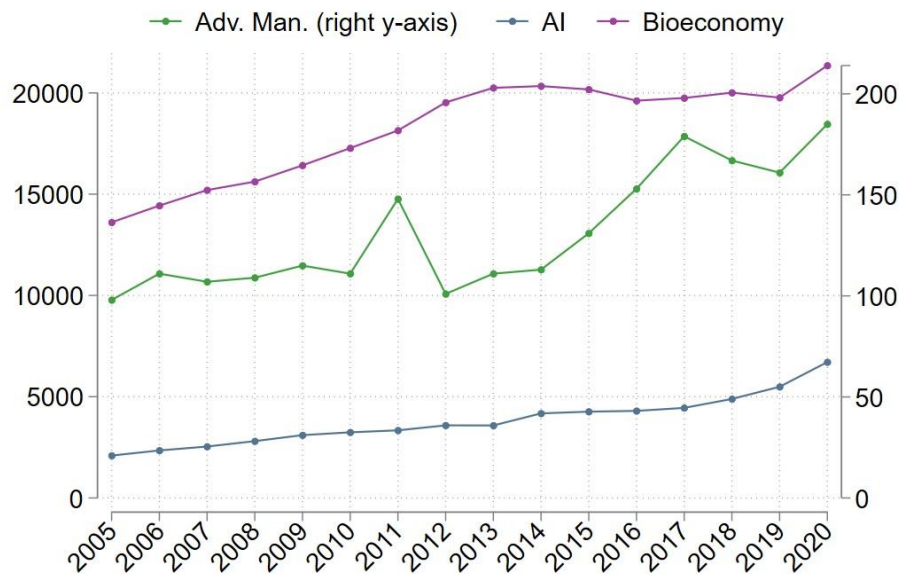


Figure 33 - Number of scientific articles in Advanced Manufacturing, Artificial Intelligence and Bioeconomy (2005-20)

Conversely, the field of AM identified the lowest number of articles among the three categories. This is mainly due to the more restrictive set of keywords used for this field compared to the other two, as explained in more detail in section 2.2.3 and Appendix B. The number of articles in AM nonetheless showed a growth during the analysed period, starting at 98 articles in 2005 and reaching 185 articles in 2020.

Figure 34 provides valuable insights into the internationalization of articles in the three subfields. It is evident that AI and BE are the most internationally collaborative fields, with over half of the articles in these two domains being internationally co-authored by the end of the observational period. On the contrary, AM stands out as a field with significantly lower levels of international collaboration, and even in recent years, the proportion of internationally co-authored articles remains below 40%.

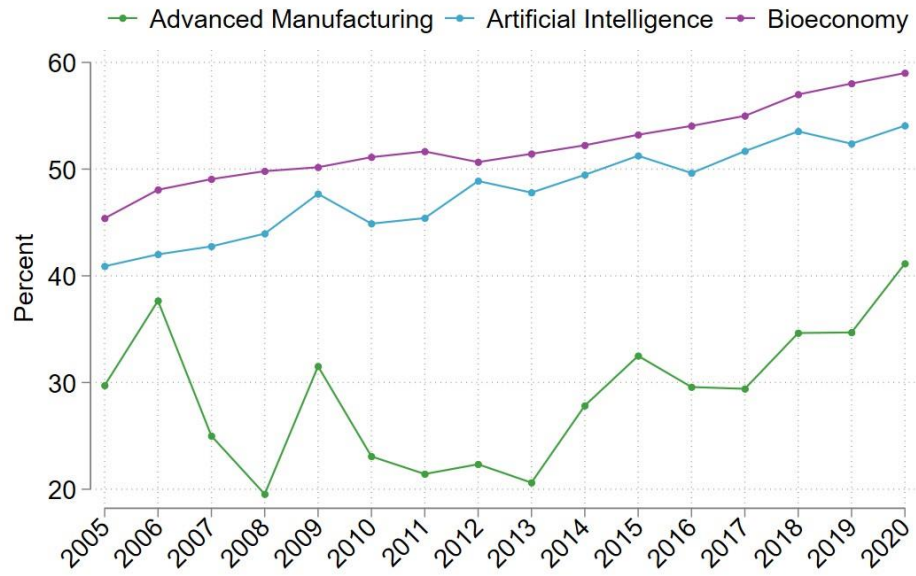


Figure 34 - Share of internationally coauthored articles in Advanced Manufacturing, Artificial Intelligence and Bioeconomy (2005-2020)

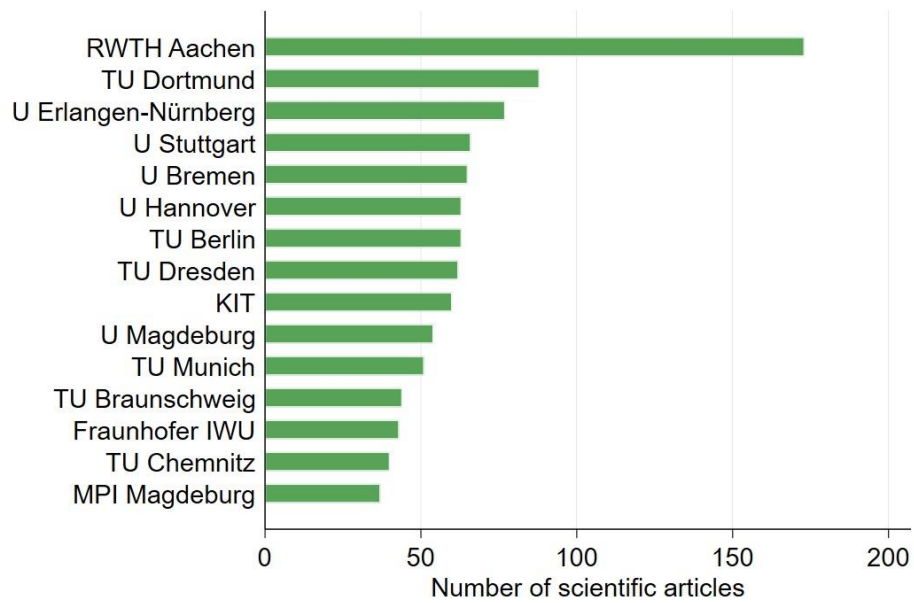


Figure 35 - Top 15 German institutions by number of scientific articles in AM (2005-2020)

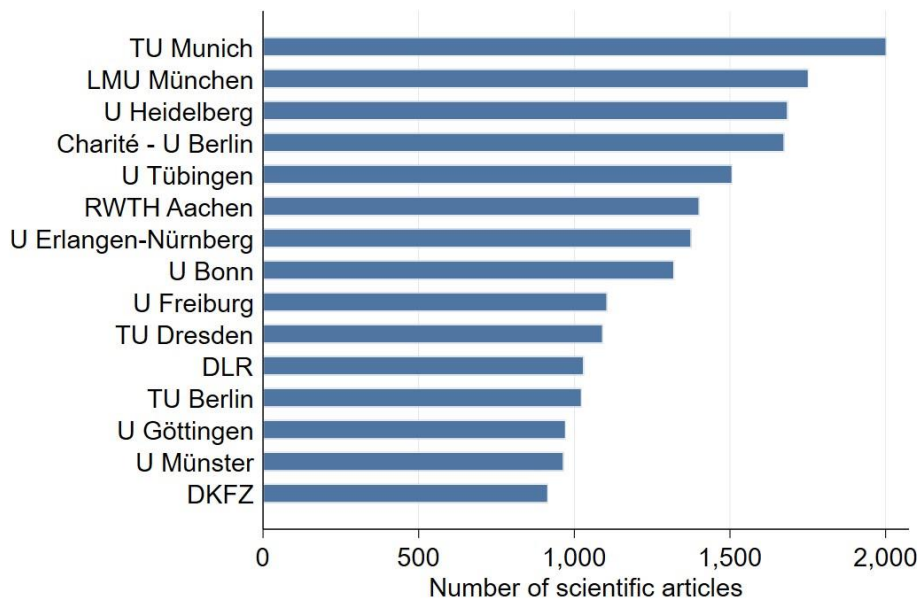


Figure 36 - Top 15 German institutions by number of scientific articles in AI (2005-2020)

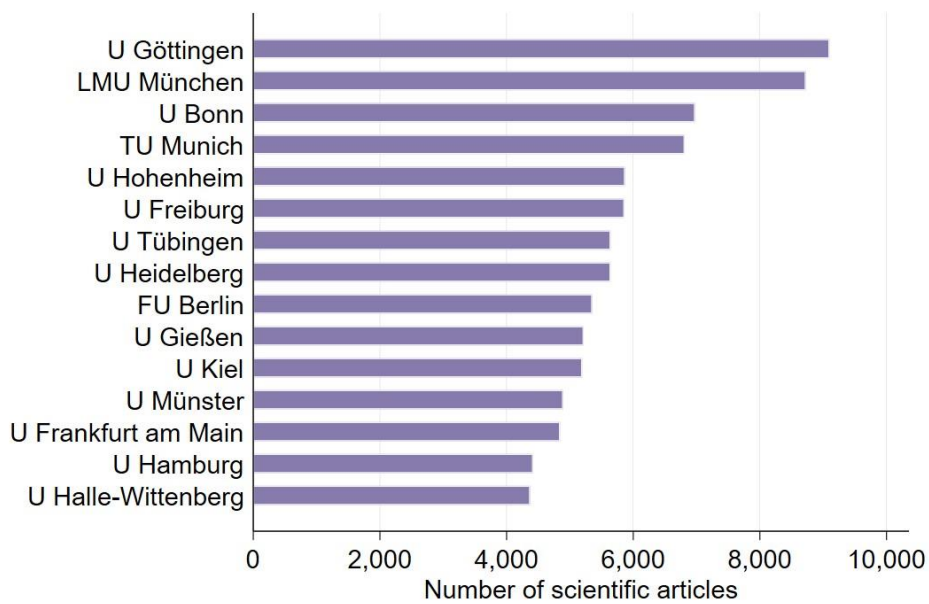


Figure 37 - Top 15 German institutions by number of scientific articles in BE (2005-2020)

Figure 35, Figure 36 and Figure 37 present the top 15 institutions based on the number of scientific articles in the fields of AM, AI, and BE, respectively. It appears that the number of scientific articles varies significantly across these scientific domains. Hence, in order to produce a meaningful comparison, Figure 38 normalizes both the number of scientific articles and the number of yearly

citations. The top right quadrant features institutions that exhibit relatively superior performance in terms of both the quantity of publications and the number of citations received—a proxy for research quality. Within the AM field, RWTH Aachen and TU Dortmund stand out. For AI, Berlin, Tübingen, and two universities from Munich (TU Munich and LMU Munich) emerge as top performers. These two Munich institutions also excel in the BE field, joined by Bonn.

In the top left quadrant, we find universities that publish fewer articles than the average but receive above-average citations. In particular, Stuttgart, Freiburg, and Heidelberg occupy this quadrant for AM, AI, and BE, respectively.

Finally, the bottom right quadrant encompasses universities that produce an above-average number of publications but receive fewer citations than average. Among them, Erlangen-Nuremberg represents AM, Heidelberg appears again this time for AI, and Göttingen in the case of BE.

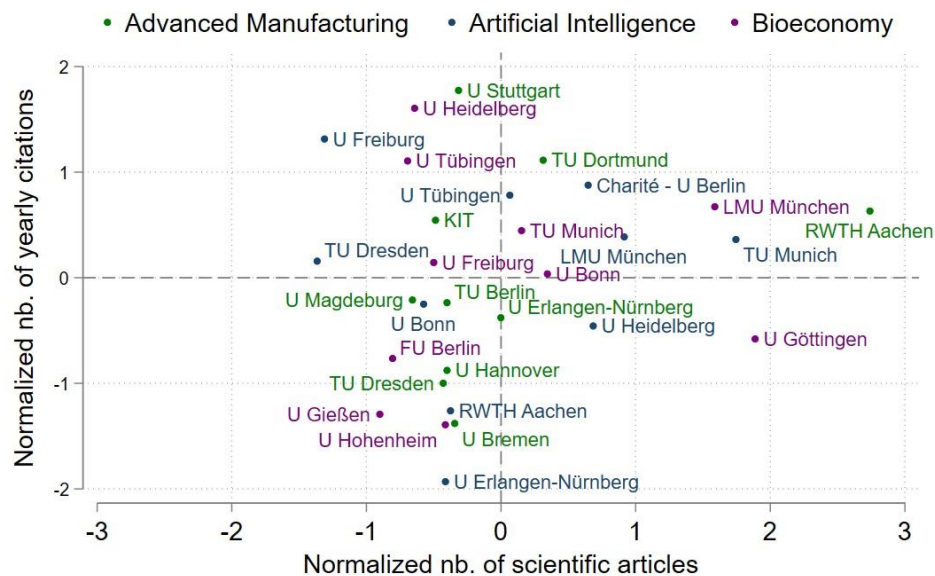


Figure 38 - Institutions' normalized number of scientific articles and yearly citations (AM, AI, BE) (2005-2020)

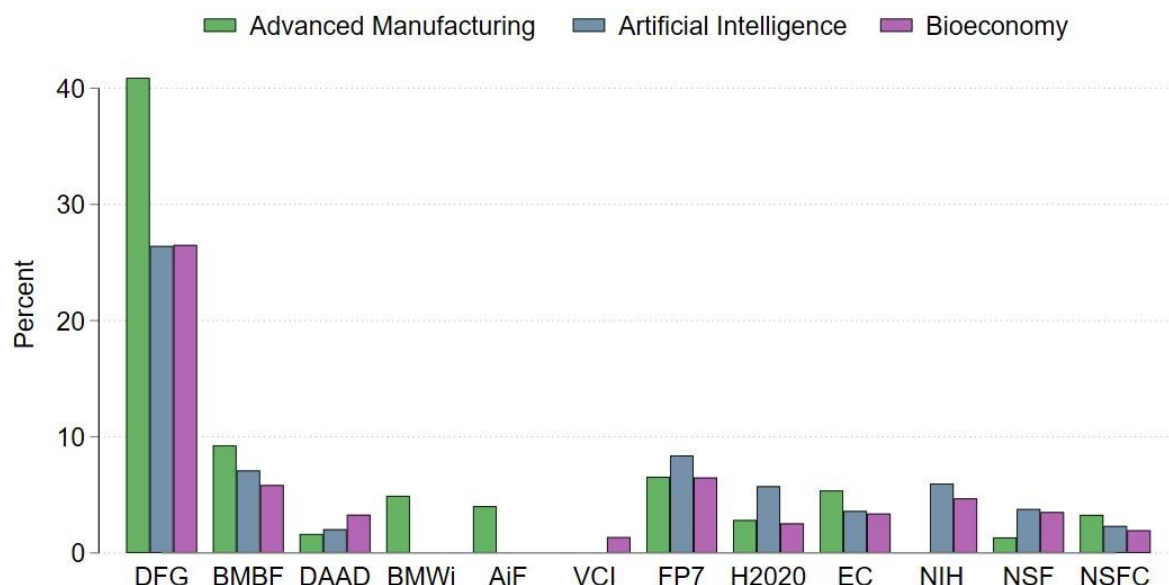


Figure 39 - Top funding sources mentioned in the acknowledgements, (AM, AI and BE) (2005-2020)

Figure 39 presents a breakdown of the top mentioned funding agencies or sponsors reported in the acknowledgments sections of scientific articles, categorized by scientific field. The figure displays the proportion of articles that reference each specific funding source out of all articles that acknowledge any form of funding within each scientific field. The detailed list of acronyms and funding names is reported in Table 4 in Appendix A. The funding agencies are divided into two categories within the figure: on the left, German funding agencies are listed, while on the right, the top international funding agencies are shown.

Research in the AM field predominantly receives funding from German agencies, particularly the DFG (German Research Foundation) and the BMBF (Federal Ministry of Education and Research). Interestingly, the DAAD (German Academic Exchange Service) is more frequently acknowledged in AI and BE funded research, indicating the greater international exposure of these fields.

AI shows a notable trend of acknowledging more funding from international sources, particularly European funding agencies such as the 7th Framework Programme and H2020 initiatives. An exception to the European and American funding agencies is the NSFC (National Natural Science Foundation of China), which is more frequently acknowledged in AM research compared to the other fields.

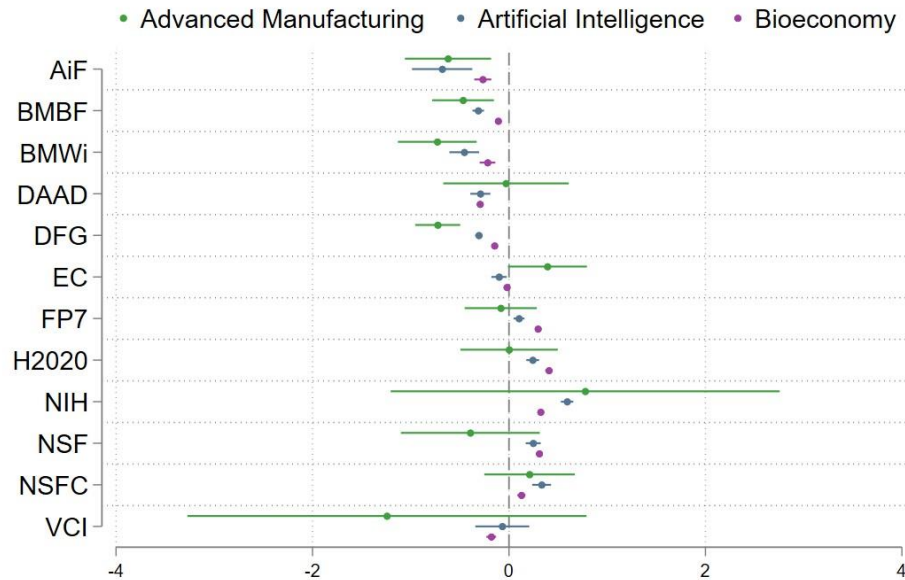


Figure 40 - Model coefficients for the different funding sources (AM AI, BE) (2005-2020)

Next, it is important also to investigate the impact that different funding sources can exert on the quality of publications. To achieve this, we performed a negative binomial regression for each scientific field, with the number of citations per publication as the dependent variable and the funding agencies mentioned in each publication as independent variables and additional controls for the publication year and the number of coauthors.

It is important to note that our data relies on acknowledgments within publications to identify the funding sources for specific research projects. However, not all funding sources are consistently acknowledged, which leads us to focus solely on publications that we can confirm have received funding. Consequently, our analysis does not distinguish between funded and non-funded projects, but only between different funding sources.

Figure 40 illustrates the outcomes of these regression models. It shows that publications funded by international agencies exhibit the highest citation counts. Notably, publications supported by sources like the National Institutes of Health (NIH) and European Union funding initiatives such as the 7th Framework Programme (7FP) and Horizon 2020 (H2020) get the most citations.

On the contrary, national funding sources like the DFG, BMBF, and DAAD attain lower scores in this indicator. Their relevance and significance predominantly lies in the context of AI research. Consequently, publications stemming from nationally funded research projects tend to attract a lower number of citations compared to those supported by international funding sources.

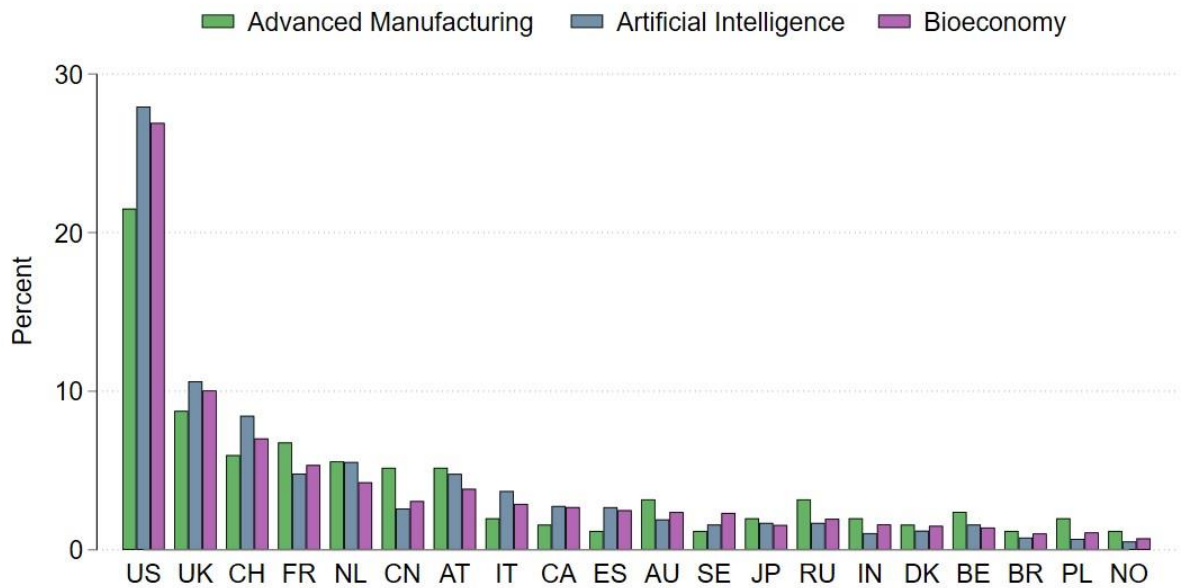


Figure 41 - Share of incoming (inflows and returnees) researchers from selected countries (AM, AI, and BE) (2005-2020)

Regarding the internationalization of researchers in the fields of AM, AI, and BE, Figure 41 and Figure 42 provide insights into the shares of incoming and outgoing researchers to/from specific countries.

From Figure 41, we see that the share of researchers coming from the United States, United Kingdom, and Switzerland is notably higher in the AI and BE fields. In contrast, when considering Western European nations such as France, the Netherlands, and Austria, as well as Asian countries like China, Japan, and Russia, the share of researchers from these regions is higher in AM compared to AI and BE.

Turning to Figure 42, we see that the shares of outgoing researchers to the top five countries for mobility (United States, United Kingdom, Switzerland, France, and the Netherlands) are most pronounced among AI researchers. In the BE field, a higher proportion of scientists are observed moving to China. On the other hand, the AM field exhibits a greater proportion of researchers moving to Australia and Brazil.

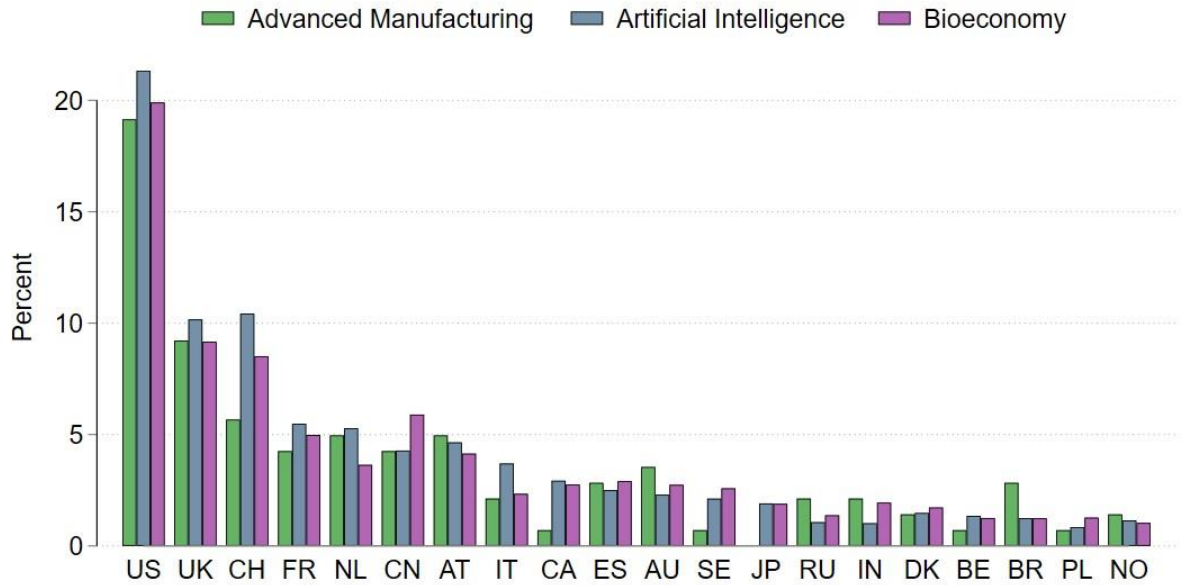


Figure 42 - Share of outgoing (outflows and transients) researchers to selected countries (AM, AI, and BE) (2005-2020)

For a more comprehensive analysis, we incorporate information sourced from the German EDT repository, so to identify those researchers who have obtained a PhD from a German university. The procedures used to match this data are presented in section 2.2.4.

This approach offers us the opportunity to provide an even more refined classification of the mobility typology than that of section 3. In particular, the inclusion of PhD information enables us to establish a chronological data point that predates the earliest recorded publication in our database. By adopting this framework, we reassign researchers with a German PhD previously classified as “inflows” to the “returnees” category. Similarly, we reassign the “transient” ones with a German PhD to the “outflows” category. This is because, in both cases, the information on the PhD allows us to correctly identify Germany as the first affiliation country, leading to adjustments in the identification based on the mobility taxonomy as presented in section 2.2.1.

The PhD data confirms the relative lack of internationalization in the field of AM (Figure 43), as compared to the baseline results discussed in section 3.1. While AI and BE exhibit similar or slightly higher shares of mobile researchers compared to the baseline case, AM shows a considerably higher share of stayers (84.4%). On the other hand, in all three subfields the proportion of returnees exceeds that of the entire sample, notably standing out in the case of AI, where it surpasses 15%. This is a relevant result for Germany, which has as the key objective of bolstering AI research (see section 5.1.3).

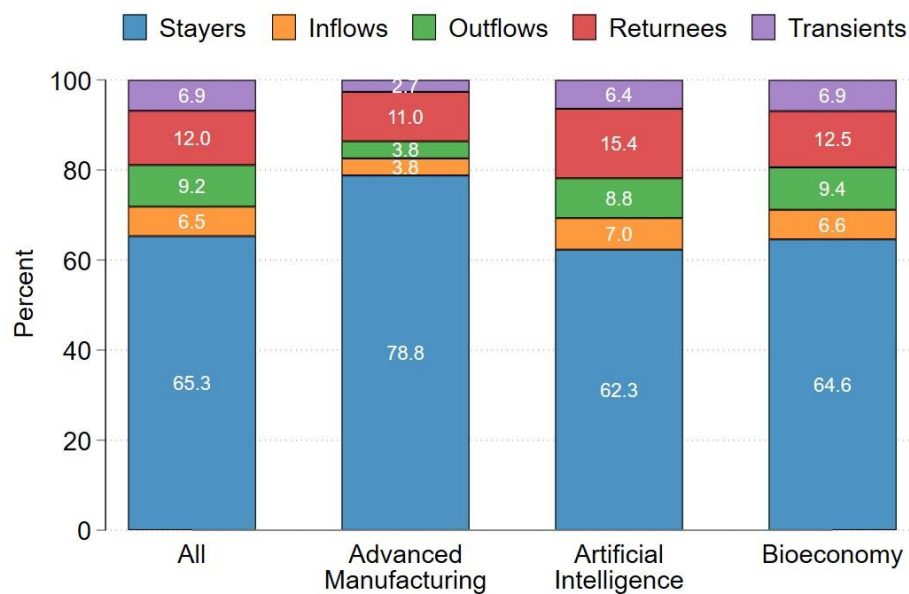


Figure 43 - Mobility type by scientific field (AM, AI and BE fields) (2005-2020)

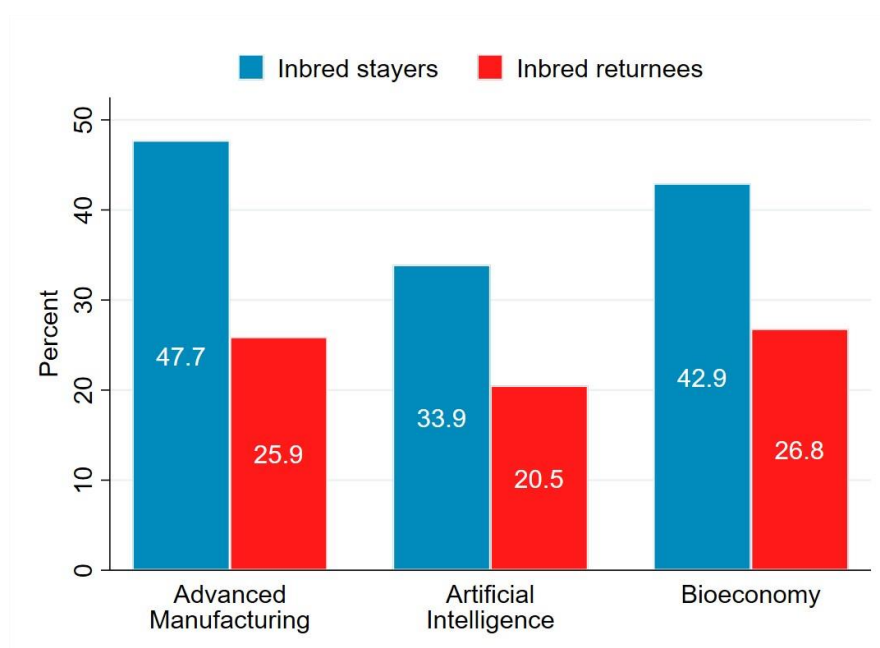


Figure 44 - Share of inbred scientists, by scientific field (AM, AI, BE) (2005-2020)

Notes: We classify scientists as “inbred” if their last registered affiliation coincide with their *alma mater*.

Utilizing the data sourced from the EDT repository, we can identify the researchers' *alma mater* information, which allows us to assess to what extent German PhD granting institutions contribute to the stock of scientists active in Germany. To investigate this, we focus on the subset of researchers who are matched to the EDT data. From this group, we assess the proportion of stayers and returnees who are affiliated with their PhD granting institution in their most recent publication.

We find that the prevalence of German doctorate holders is notably higher among stayers relative to returnees. Moreover, this phenomenon varies across scientific fields. Particularly, AM and BE exhibit a higher proportion of German doctorate holders among both stayers and returnees. On the other hand, the subfield of AI demonstrates the lowest incidence of German PhD granting institutions. This observation further confirms that AI, compared to other fields, experiences a higher level of mobility, even among German institutions. In fact, the share of researcher that did not go abroad but moved among German institutions at least once since the doctorate is 66%.

A relevant source of internationalisation of the science system is represented by the share of foreign PhD students. We measure the share of researchers holding a PhD obtained from a German institution (as matched with the EDT repository, see section 2.2.4) who do not present Germany in their list of CoAs, based on name analysis (see section 2.2.1.2). Once again, the field of AM emerges as the least internationalized, with merely 17.5% of PhD holders with non- or unfrequent German names and surnames. In contrast, the field of BE stands out as the most internationalized, with close to a quarter of PhD recipients from German institutions having foreign-origin full names. The field of AI occupies an intermediary position between these two extremes, with an approximate 22% of PhD recipients hailing from non-German origins.

Figure 45 provides a visual representation of the progression in the percentage of PhD holders without Germany listed as a CoA over the available time span (2000-2020). Across all three subfields, there has been a notable increase in the percentages during the analysed timeframe. Within this temporal context, the proportions for all three subfields have undergone a substantial transformation. Starting from levels below 10%, they have increased significantly, ultimately surpassing the thresholds of 30% for both AI and BE, and exceeding 20% for AM domain. This evolution signals a noteworthy trend of increasing internationalization of all subfields.

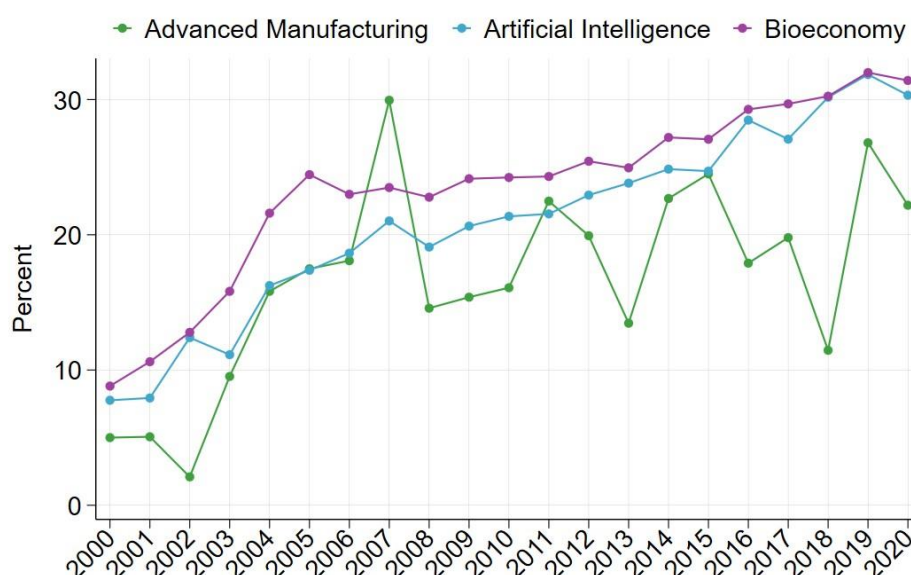


Figure 45 - Share of doctorate holders with publications in Germany without Germany as CoA (AM, AI and BE) by year of PhD

5 Funding programs and initiatives

5.1 Overview of selected funding programs

5.1.1 Excellence Initiative

In 2005, the German Federal and State Governments launched the Excellence Initiative (EI)⁹, a significant effort aimed at promoting high-quality research at German universities and institutions to enhance the country's global attractiveness and competitiveness in the field of research. The initiative was organized by Deutsche Forschungsgemeinschaft (German Research Community or DFG) and the German Council of Science and Humanities (WR).

During the first phase of the EI, which spanned from 2006 to 2012, German universities were invited to submit draft proposals to compete for funding. In total, the German Federal Government provided 1.9 billion euros to support selected projects. The funding supported 47 projects across 28 different universities, which included 21 Graduate Schools, 20 Clusters of Excellence, and six Institutional Strategies.

⁹ See: https://www.dfg.de/en/research_funding/funding_initiative/excellence_initiative/ (last visited on 23/08/2023).

Following the success of the initial phase, the second phase of the EI commenced in 2012. During this phase, another round of proposals was submitted by German universities, and the DFG managed 2.7 billion euros in funding. This larger pool of funding supported a total of 99 projects at 44 separate universities, encompassing 45 Graduate Schools (33 extensions and 12 new projects), 43 Clusters of Excellence (31 extensions and 12 new projects), and eleven Institutional Strategies (six extensions and five new strategies).

The funding for the second phase of the EI came to an end in 2019, marking a significant contribution to fostering research excellence and international collaboration in Germany's academic landscape.

The EI encompasses three distinct lines of funding, each with specific objectives to enhance research and academic competitiveness in Germany:

1. Graduate Schools: The graduate school funding line aims to provide support to promising and talented young researchers at top universities within Germany. By offering funding to these graduate schools, the initiative seeks to nurture a new generation of researchers and scholars, fostering their academic growth and contributing to the overall research excellence in the country.
2. Clusters of Excellence: The clusters of excellence funding line is designed to capitalize on the "research potential" present at various university locations in Germany. These clusters aim to promote collaboration and networking among researchers working in key scientific fields. By providing financial backing to these clusters, the initiative encourages interdisciplinary research, innovation, and the establishment of cutting-edge research centers.
3. Institutional Strategies: The institutional strategies funding line focuses on strengthening entire universities as entities, making them more competitive on the international stage. This line of funding is intended to support universities in enhancing their research infrastructure, facilities, and overall academic environment. By bolstering the universities as a whole, the initiative seeks to increase their international attractiveness and reputation.

The selection process for entities of excellence is carried out by a committee of experts. These experts evaluate the applicants based on a set of criteria, which include the quality of research produced by the institution. For the Cluster of Excellence, the assessment also considers the quality of the research environment or community fostered within the cluster. Through a rigorous evaluation process, the most promising and impactful projects and institutions are chosen to receive funding, enabling them to achieve higher levels of research excellence and international recognition.

In 2016, during the second phase of the EI, the German Federal and State Governments reached an agreement to launch the new Excellence Strategy¹⁰, aimed at continuing the objectives of its predecessor. The Excellence Strategy began funding projects in 2019 and introduces two lines of funding: Clusters of Excellence and Universities of Excellence.

Under the Excellence Strategy, a total of 57 Clusters of Excellence and 11 Universities of Excellence were selected to receive funding during the first stage of the competition, which started with calls for proposals in 2016. These selected projects were granted a combined annual funding of 533 million euros, demonstrating the government's commitment to supporting outstanding research and academic institutions.

In 2022, the DFG issued a new brief, announcing the initiation of another round of proposals for funding under the Excellence Strategy. This new competition invites applicants to vie for funding opportunities set to commence in 2026, fostering continued growth and development in research excellence and academic competitiveness in Germany.

5.1.2 Alexander von Humboldt Professorship

The German Federal Ministry of Education actively contributes to strengthening the country's research competencies through the Alexander von Humboldt Professorship (AvH)¹¹. Established in 2008 as part of the International Research Fund for Germany, the AvH Professorship provides annual funding to global scholars, inviting them to come to Germany to teach and conduct research in their respective fields.

In 2020, as part of the AI Strategy, the AvH Professorship was expanded to include additional professorships specifically for scholars specializing in AI. Both the regular AvH Professorship and the AvH Professorship in AI offer funding of up to 5 million euros over a 5-year period, with the possibility of a 2-year extension. These professorships are highly competitive and serve as prestigious opportunities for outstanding scholars to further their research and academic careers in Germany.

The selection process for AvH Professors involves a nomination in collaboration with a university sponsor, followed by a rigorous evaluation based on the nominee's academic excellence and the research plan proposed by the sponsoring university. The selected AvH Professors then integrate

¹⁰ See: https://www.dfg.de/en/research_funding/funding_initiative/excellence_strategy/ (last visited on 23/08/2023).

¹¹ See: <https://www.humboldt-foundation.de/en/apply/sponsorship-programmes/alexander-von-humboldt-professorship> (last visited on 23/08/2023).

themselves into the local research community, fostering international collaboration and knowledge exchange.

Eligible researchers for the AvH Professorship may be of German nationality, but they must have received their academic education and formation outside of Germany. This requirement aims to attract talented international scholars, contributing to Germany's competitiveness on the international stage by enriching its academic landscape with diverse perspectives and expertise.

The inclusion of the AvH Professorship in AI aligns with this goal, but with a particular focus on enhancing Germany's reputation in the field of AI technology and research. By inviting top AI researchers from around the world, Germany aims to strengthen its position as a leading hub for AI research and innovation.

As of 2023, a total of 118 scholars have been awarded the AvH Professorship, out of which 18 are specialized in AI. These scholars play a crucial role in advancing research excellence and promoting Germany's global standing in academia and cutting-edge technologies like AI.

5.1.3 AI Strategy

In 2018, the German Federal Government unveiled its "AI Strategy"¹² to address the growing significance of artificial intelligence and to ensure that Germany remains competitive with other global leaders in AI, like the United States. The primary goal of this strategy, as outlined in the document "Artificial Intelligence Strategy Status: November 2018" is to establish a strong foundation for the development and implementation of AI in Germany.¹³

To achieve this, the federal government committed an initial investment of 500 million euros, with the intention of increasing this amount to 3 billion euros by 2025, in order to bolster the AI Strategy. The document highlights three main objectives of the AI strategy:

1. **Becoming the European Center for AI:** The government aims to position Germany as the leading hub for AI research and implementation in Europe. To achieve this, they plan to develop a network of 12 clusters dedicated to AI research and application. Additionally, the strategy seeks to support the education and training of young AI experts, create 100

¹² See: <https://www.de.digital/DIGITAL/Redaktion/EN/Standardartikel/artificial-intelligence-strategy.html> (last visited on 23/08/2023).

¹³ See: https://www.ki-strategie-deutschland.de/home.html?file=files/downloads/Nationale_KI-Strategie_engl.pdf (last visited on 30/07/2023).

professorships specifically focused on AI, and establish a collaborative Franco-German AI research and development network.

2. **Promoting Responsible AI Use:** The strategy emphasizes the responsible use of AI in society. To accomplish this, the government intends to establish a German Observatory for AI, which will monitor and assess AI's impact on various sectors. Furthermore, the government aims to initiate dialogues at both the EU and transatlantic levels to discuss the ethical and safe implementation and development of AI technologies.
3. **Ethical and Legal Integration of AI into Society:** The AI Strategy acknowledges the importance of ethical and legal considerations in AI implementation. To address this, the government plans to introduce specific data protection guidelines and actively shape policies to ensure AI integration aligns with societal values and norms.

By pursuing these three overarching goals, the German Federal Government seeks to position Germany at the forefront of AI innovation in Europe and beyond, promoting responsible AI use and ensuring that the ethical and societal implications of AI are carefully considered and appropriately managed.

Indeed, the AI Strategy in Germany recognizes the importance of retaining and attracting top AI experts to strengthen the country's position as an AI leader on the global stage. One of the significant challenges is competing with other countries, like the United States, that already have substantial numbers of international AI experts.

To address this challenge, Germany aims to establish "AI made in Germany" as a recognized seal of approval, indicating high-quality AI research and development. The strategy focuses on actively attracting international AI experts to reside and conduct research in the country. The creation of 100 new professorships in AI is a crucial component of this effort, as these positions offer prestigious opportunities for experts to lead research and academic initiatives in the field of AI in Germany.

In addition to the professorships, the strategy also emphasizes the importance of facilitating the mobility of AI experts within the European Union (EU). By enabling seamless mobility within the EU, Germany aims to create an attractive environment that encourages top AI researchers to choose Germany as their destination for conducting research and contributing to the country's AI ecosystem.

By actively seeking to retain its own AI talents and attract international experts, the AI Strategy aims to build a thriving AI community within Germany, fostering collaboration, innovation, and advancements in the field. This concerted effort to bolster the presence of AI experts in the country

plays a vital role in achieving the broader goal of making Germany a leading center for AI research and development in Europe and beyond.

In 2020, the German federal government released an update to the AI Strategy titled "Artificial Intelligence Strategy of the German Federal Government - 2020 Update - Status: December 2020."¹⁴ This update showcased the government's commitment to further strengthen its efforts in AI development and research.

A key highlight of the update was the decision to increase funding for the AI Strategy from 3 to 5 billion euros by the year 2025. This substantial increase in funding underscores the government's dedication to advancing AI initiatives in Germany and remaining competitive on the global stage.

Part of the increased funding is planned to be allocated to create additional professorships in AI. The strategy aims to achieve this through various programs, including the AvH Scholarships and the German Academic Exchange Service (DAAD). These initiatives will support the establishment of more professorships in AI, further attracting top AI experts to conduct research and contribute to the development of AI within the country.

Additionally, the update emphasized the importance of continued support for international AI networks within the EU and other major AI research hubs, such as Silicon Valley. Collaborative networks with these global partners play a vital role in knowledge exchange, research collaboration, and staying updated with the latest advancements in the AI field.

By increasing funding, promoting professorships, and fostering international AI networks, the German federal government aims to solidify its position as a leading player in the AI landscape. These efforts will contribute to making Germany an attractive and innovative destination for AI research and development, furthering its goal of becoming a European and global center for AI expertise and excellence.

¹⁴ See: https://www.ki-strategie-deutschland.de/files/downloads/Fortschreibung_KI-Strategie_engl.pdf (last visited on 19/08/2023).

5.2 Evaluation of funding programs' effectiveness

5.2.1 Comprehensive documentary review

The evaluation of the EI, conducted by the German Council of Science and Humanities (WR) and the Institute for Information Research and Quality Assurance (iFQ), provides valuable insights into the impact of the program on its recipients.¹⁵

One of the significant findings of the evaluation was the successful recruitment of new personnel under the funding of the EI. This suggests that the program effectively facilitated the expansion of research teams and the creation of new academic positions at universities and clusters of excellence.

However, the evaluation also identified challenges related to this recruitment process. It highlighted that there might have been a shortage of suitable candidates for some of the newly created positions. Additionally, the report pointed out that the salaries offered for these positions remained uncompetitive compared to those offered by non-academic and private research institutions. This finding highlights the importance of addressing salary competitiveness to attract and retain top talent in academia.

On the positive side, the evaluation revealed that the EI played a significant role in fostering both domestic and international cooperation between universities. Much of this collaboration occurred within the regions of the Cluster and Universities of Excellence themselves. Furthermore, the program facilitated exchange programs with international partner universities, promoting research collaboration and knowledge exchange on a global scale.

Moreover, the evaluation looked into the program's impact on promoting young scientists and researchers, increasing interdisciplinarity, and addressing gender equality. While the report did not provide specific details on these aspects, it suggests that the program was designed with these goals in mind.

The second internal evaluation of the EI, conducted by an independent panel of experts and published in 2016 by the German Council of Science and Humanities, provided a comprehensive assessment of the program's impact over its entire duration.¹⁶

One aspect of the evaluation focused on using bibliometric data to observe the impact of the funding on publications from the funded institutions. While the report noted an overall increase in publications

¹⁵ See: https://www.wissenschaftsrat.de/download/archiv/ExIni_BLK-Vereinbarung_91b.pdf?blob=publicationFile&v=1 (last visited on 30/07/2023).

¹⁶ See: <https://www.gwk-bonn.de/fileadmin/Redaktion/Dokumente/Papers/Imboden-Bericht-2016.pdf> (last visited on 30/07/2023).

over the funding period, it did not explicitly attribute this increase solely to the funding provided by the EI. The evaluation suggests that various factors, including the researchers' efforts, institutional support, and external collaborations, could have contributed to the observed increase in publications.

The report found that the EI had a positive impact on the integration of universities into national research structures. The funding likely facilitated closer collaboration and engagement with other research institutions and organizations within Germany, strengthening the overall research landscape in the country.

Additionally, the evaluation highlighted the positive influence of the EI on the internationalization of German universities. The funding likely fostered increased collaboration and partnerships with international universities and research institutions, contributing to a more globally connected and diverse research environment.

However, one concerning finding of the evaluation was the potential counterproductive impact on the goals of young doctoral researchers. The report suggests that despite the overall positive outcomes, there might have been challenges or unintended consequences for young researchers under the program. It would be important to further investigate and address these issues to ensure the program's effectiveness in supporting the career development and opportunities for young researchers.

In conclusion, the second internal evaluation of the EI, while it showcased several positive outcomes in terms of research integration and internationalization, it also raised important questions about the support and opportunities provided to young researchers.

In addition to these reports, a number of academic articles evaluating various aspects of the EI provide valuable insights into the program's impact on research productivity, collaboration, and citation performance of funded institutions.

Bornmann (2016) conducted a network analysis of Clusters of Excellence funded by the initiative. The paper offers a deeper understanding of the networking patterns within these clusters. The study, based on bibliometric data from the Web of Science (WoS), reveals an increase in networking within the clusters, particularly in the natural sciences. The formation of new networks under the Clusters of Excellence resulted in a more consolidated and coherent structure, reflecting the positive impact of the initiative on research collaboration and integration.

Möller et al. (2016) also use WoS data to examine changes in publication counts within the Clusters of Excellence. Their findings indicate that the majority of high-cited publications (top 10%) during

the funding period were attributed to the Clusters of Excellence, highlighting the program's role in boosting research output and quality in the university sector.

The more recent study by Carayol & Maublanc (2022) provides a comprehensive assessment of the impact of funding under the Excellence Initiative over its entire lifespan. The study compares the program with similar initiatives in France using data from the CWTS Leiden Ranking, ETER (European Tertiary Education Register) and EUMIDA (EUropean MIcroDAta). Their difference-in-difference estimation and matching approach reveal significant positive effects of the funding. Universities that received funding under the initiative demonstrated increased research productivity, with more scientific articles, particularly stemming from international collaborations and collaborations with industry. Furthermore, the study found a higher proportion of top-cited papers (top 10% and top 1%) among the publications from the funded universities, emphasizing the positive influence of the initiative on research quality. Specifically they find that “one Million euros in excellence policy leads to 22.5 more scientific articles (that means a paper costs less than fifty thousand euros), among which 19 are out of an international collaboration, 2.5 are produced in collaboration with industry, 3.7 are top 10% cited papers and 0.6 are top 1% cited papers” (Carayol & Maublanc, 2022, p. 16).

Overall, these articles provide robust evidence of the positive impact of the Excellence Initiative on research productivity, collaboration, and citation performance of funded institutions. The findings not only showcase the program's effectiveness in enhancing academic outcomes but also underscore its importance in fostering international collaboration and industry partnerships, further solidifying Germany's position as a leading research hub.

Regarding the Alexander von Humboldt (AvH) Professorship, an independent evaluation was conducted by the Technopolis Group in 2017¹⁷, which analysed AvH Professorships between 2008 and 2015. The evaluation focuses on 50 recipients of the AvH Professorship, selected from over 200 nominated scholars, and examines various aspects of the program's effects.

One significant achievement of the AvH Professorship program, as indicated by the evaluation, is its success in attracting international scholars to Germany, even if some of them were German nationals. The program played a crucial role in bringing talented researchers from around the world to contribute to the academic landscape in Germany.

¹⁷ See: <https://www.technopolis-group.com/es/evaluation-of-the-alexander-von-humboldt-professorship-programme/> (last visited on 30/07/2023).

The surveys conducted as part of the evaluation reveal positive outcomes in terms of increased cooperation and networking. The recipients reported that their collaboration with scholars, both within and outside of Germany, intensified after the start of their professorship. This finding highlights the program's role in fostering international research partnerships and knowledge exchange.

An intriguing observation from the evaluation is that all recipients whose financing had already ended at the time of the study chose to remain in Germany. This indicates that the AvH Professorship not only successfully attracted scholars to Germany but also contributed to their continued presence and integration within the German academic community.

According to respondents, their appointment to positions at German universities would not have occurred without the AvH Professorship. This suggests that the program has been instrumental in recruiting and retaining top-level researchers, bolstering the research capabilities and reputation of German universities.

The evaluation also includes individual case studies of 14 recipients, utilizing bibliometric data from the WoS to assess changes in their publishing activities after receiving the professorship. The network analysis conducted in the evaluation demonstrates how the researchers' networks become more connected with colleagues from their respective universities and other researchers in their field as the professorship progresses. This finding indicates that the AvH Professorship not only benefits individual researchers but also contributes to enhancing the overall research environment and collaboration within the academic community.

In conclusion, the Technopolis Group's evaluation highlights the success of the AvH Professorship program in attracting international scholars to Germany and fostering increased collaboration and research productivity. The program's impact extends beyond individual recipients, benefiting the research community as a whole and reinforcing Germany's position as an attractive destination for top-level researchers from around the world.

Regarding the AI Strategy, while the program's impact cannot be assessed using the collected data due to its recent implementation, it is evident that Germany is dedicating substantial effort and resources to the field of AI. As part of this strategy, the AvH Foundation established specific AvH Professorship positions to attract research scientists in the AI domain. By 2024, 30 additional AvH Professorships are being created in the AI field. Researchers from various disciplines who investigate AI and its societal impact are eligible for nomination.

Insights into the mobility of AI scientists can be gleaned from recent work by Zwetsloot et al. (2021). Their survey of 524 AI researchers' immigration preferences and motivations reveals that the United States is the most favoured destination, followed by the United Kingdom, Canada, Switzerland, and France. Factors influencing these decisions include professional opportunities, lifestyle, culture, political climate, and personal relationships. Notably, the United States, the United Kingdom, China, Canada, Germany, Switzerland, and France stand out in attracting top-tier AI talent and exhibiting high AI research output at relevant conferences.

Interestingly, the study by Zwetsloot et al. (2021) indicates that Germany has a relatively high rate (23%) of AI researchers who do not intend to move. A mere 14% of respondents from Germany considered visa and immigration issues to be a significant concern for high-quality AI research in their country of residence.

Furthermore, another study (Aiken et al., 2020) focused on migration decisions for AI PhD graduates in the United States, highlights that Germany, along with the United Kingdom, Singapore, and France, is among the prevalent work locations outside the United States for AI PhDs. Around 8-11% of respondents considered Germany as an alternative to a US PhD program, and 35% reported being somewhat likely to move to Germany in the short term. This underscores Germany's appeal as a destination for AI researchers and suggests that it has successfully positioned itself as an attractive environment for AI-related research and work.

5.2.2 Empirical assessment

In the context of the EI, we assess the proportion of researchers with international experience – namely those now active in Germany but with previous publications abroad. In particular, we are interested into those who are currently employed within the universities designated as Graduate Schools (GS), Clusters of Excellence (CoE), and Institutional Strategies (IS). In Figure 46, we calculate the share of inflows over the total number of authors affiliated to a GS, CoE, or IS during each of the two implementation phases of EI and for the specific fields for which the universities were granted GS or CoE status (in the case of IS, all fields can be considered).

The figure illustrates a rise in the proportion of inflows across all categories of institutions. The most pronounced is the trend within GS, with an increase from a 3.8% share in the first phase to 6.9% afterwards. This is only marginally better than what observed for IS, but far more remarkable than CS.

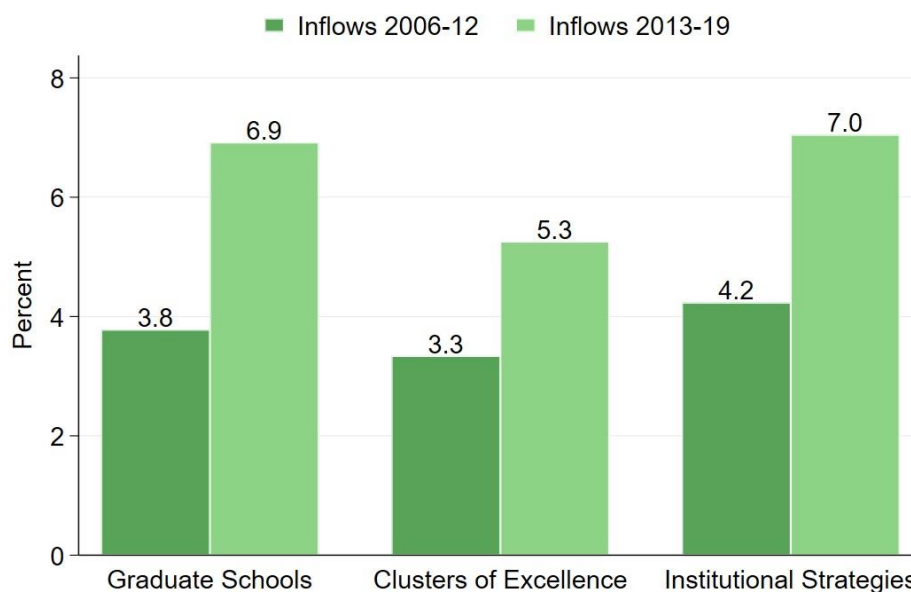


Figure 46 – Share of inflows in EI's Graduate Schools, Custer of Excellence and Institutional Strategies, by implementation phase (2006-12 and 2013-19)

During the initial EI phase, the most significant sources of inflows were the United States and Western Europe, in particular countries like Switzerland, France, the United Kingdom, and Austria. In the following one, the United States maintains their prominence, but we observe a clear rise of Asian countries, notably China and India. Conversely, the role of Russia has diminished. Also, Southern European countries have gained importance as origin countries for inflows, in particular Italy and Spain. This suggests a diversification in the geographic sources of researchers entering the German scientific system during the second phase of the EI implementation. This is in line with general trends discussed in section 3.

The Institutional Strategies, or “Universities of Excellence,”¹⁸ hold a significant place within the academic landscape. These institutions are frequently referred to as “elite universities” and have earned comparisons to the Ivy League institutions in the United States (Vogel, 2006). These institutions play a pivotal role in Germany's scientific system and are recognized both nationally and internationally for their academic excellence.

¹⁸ As mentioned in section 5.1.1, the original name for these universities is "Institutional Strategies." However, in the context of the Excellence Strategy launched in 2019, the name was changed to "Universities of Excellence." For simplicity, we will refer to them as "Universities of Excellence" throughout, even when discussing the previous "Institutional Strategies" within the context of the Excellence Initiative.

In Figure 47 we compare the average SJR for inflow scientists joining institutions selected as Universities of Excellence from the German Science Council to that of inflow scientists in other German universities, not selected neither as GS nor part of CoEs. The analysis considers universities that were awarded in the first two rounds of the EI competition in 2006-2012 and 2013-2019. In total, 14 universities received awards, with 6 of them being awarded in both periods. The average SJR is calculated for inflows based on the articles they published before moving to Germany.

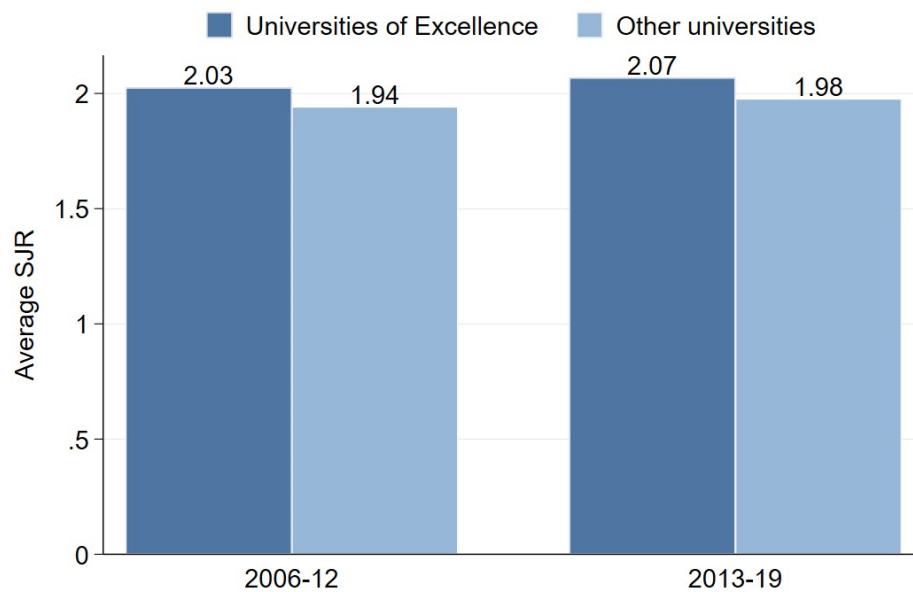


Figure 47 - Average inflows' SJR, Excellence Universities vs. other universities

The figure shows that the average quality of inflows going to universities of excellence is higher for both periods, but only slightly. In addition, the difference is more pronounced in the first period, which may indicate that already in the second period, the overall quality of German universities had improved, leading to an enhanced ability to attract international talent.

The Universities of Excellence award recognizes outstanding research and academic institutions in Germany and signifies their exceptional quality and prominence in the global academic landscape. The higher average SJR of inflows towards these universities highlights their strong reputation and ability to attract high-quality researchers from around the world.

Additionally, the graph suggests that the EI has had a positive impact on the internationalization of German universities, as evidenced by the higher status of researchers being drawn to these institutions. The initiative likely played a significant role in enhancing the research environment and

resources available at these universities, making them more appealing to top talent in the global scientific community.

If the goal of the EI is to raise the overall excellence of the German science system, there is also a range of mobility programs that have been established with the specific objective of attracting foreign scientists, with a special emphasis on recruiting top-tier researchers. These initiatives encompass various programs, including the Heisenberg program, the Emmy Noether program, and notably, the AvH Professorship.

Over the period spanning from 2009 to 2020, a total of 80 AvH Professorships have been conferred upon distinguished scientists. Fifty out of eighty (62.5%) of these academic positions have been awarded to German academics. These professorships symbolize a concerted effort to bring in exceptional international talent, further enhancing the scientific landscape within Germany. The recognition of these scholars through these programs underscores Germany's commitment to fostering a diverse and world-class academic environment, facilitating collaboration, and strengthening the nation's position in the global research community.

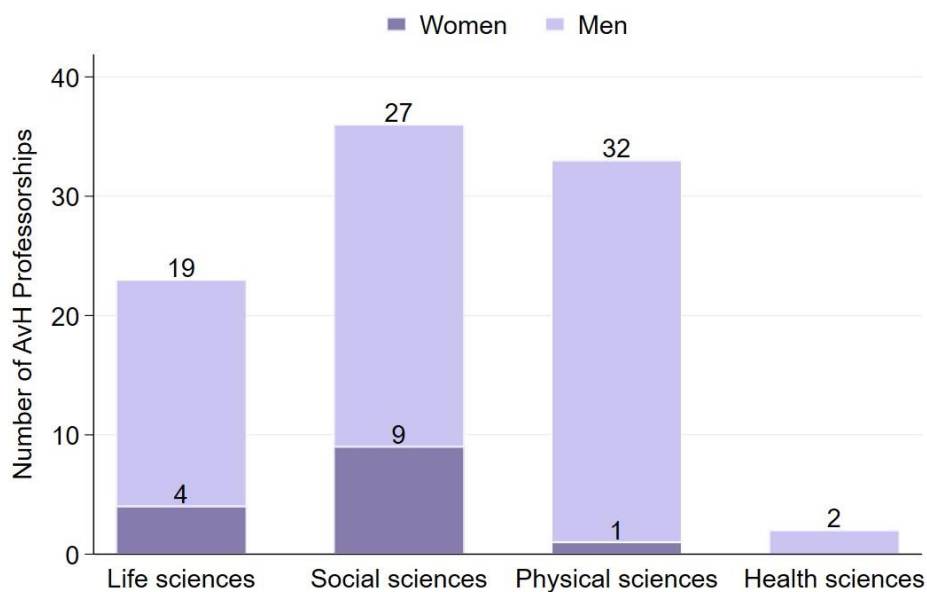


Figure 48 - Number of AvH Professorship (2009-2020), by scientific field and gender of recipients

Figure 48 shows the distribution of AvH professorship positions across different academic disciplines. We notice that Social Sciences and Physical Sciences emerge as the fields with the most significant number of professorships awarded. In contrast, Health Sciences received a comparatively lower

number, with only 2 AvH professors in this category. It is relevant to point out that the representation of women at this stage is relatively limited, with an overall share of 17.5% women researchers that have been awarded the AvH professorship. Additionally, all these women researchers were selected starting from 2014, hence no female scientist received AvH professorships within the first five years of the program's existence.

Furthermore, the gender distribution exhibits variations among the different research domains. The share of female AvH professors is higher within the field of Social Sciences, where one-third of the AvH professors are women. In contrast, the representation is particularly low in Physical Sciences, with only one female researcher (3% of the total) being granted the AvH professorship in the period considered.

The AvH Foundation and the grant committee are aware of this gender disparity and have undertaken efforts to address the issue. There has been a concerted focus on increasing the allocation of AvH professorships to women academics, aiming to foster greater gender diversity and inclusivity within the program. This reflects the commitment to promoting gender equity and ensuring that talented women researchers are appropriately recognized and supported within the academic community.

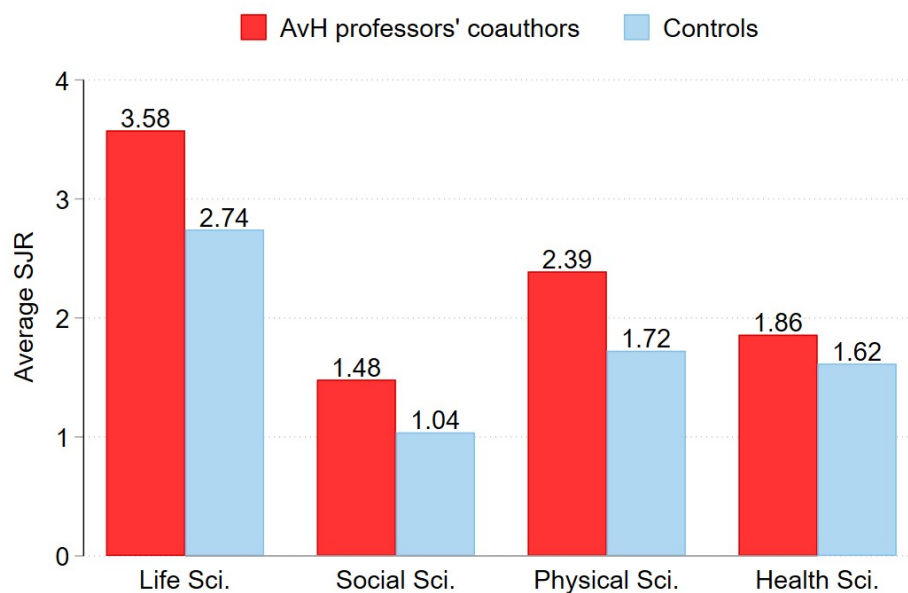


Figure 49 - Average SJR for AvH professors' coauthors and control researchers

Notes: We do not consider articles coauthored with the focal AvH professors."

An interesting aspect of consideration pertains to the effectiveness of programs designed to attract distinguished foreign scientists, particularly regarding their influence on resident researchers at the host institution. This subject has been explored in previous works, such as Yadav et al. (2023), whose methodological approach we adopt in Figure 49 to shed light on this matter within our own study. In there we delve into the productivity of coauthors of AvH Professors following their arrival, drawing comparisons with similar scientists based on pre-arrival attributes. In particular, we systematically identified all coauthors of AvH Professors who remained active at the host institution after the professor's arrival. Employing a 1-to-1 matching process, we paired them with comparable researchers active in the same university and field prior to the AvH Professor's arrival, using observable metrics such as publication record, citation count, field of study, and scientific age (i.e., years since their first publication) at the time of the AvH Professor's appointment. The detailed characteristics of this matched sample are presented in Table 5 in Appendix A. Subsequently, we examined the publications produced by the two groups of researchers after the arrival of the AvH Professor, calculating the average SJR while excluding articles coauthored with the AvH Professor. The figure depicts the average SJR of the two groups of scientists across four scientific fields, indicating a higher quality of publications among the coauthors of AvH Professors.

Figure 50 on the other hand, explores the impact of AvH professors on the scholarly output of their host departments. This phenomenon has been analysed in earlier literature, such as in Agrawal et al. (2017), who look at influence of recruiting star scientists on the output of their respective host departments. To conduct this analysis, we begin by collecting publications within specific “departments”, which we identify as university-field combinations, focusing on universities that have welcomed at least one AvH Professor. We calculate the average SJR for all articles published by each university within a particular field. Our focus is on comparing the average SJR before and after the introduction of the AvH Professor. It is important to note that articles co-authored by the focal AvH professor are not included in this exercise. To establish a baseline, we consider the SJR of articles published in the year just before the AvH Professor's arrival (referred to as $t-1$).

We then perform a simple regression analysis, using the average SJR of each given year as the dependent variable. We incorporate a series of dummies as independent variables, taking on the value of 1 from the year of the AvH Professor's arrival onward. Furthermore, we introduce control variables for the department (i.e., university+field pairs) and fixed effects for each year. As depicted in Figure 50, the average quality of articles published by universities that have hosted at least one AvH Professor in the years leading up to their arrival does not exhibit a significant deviation from the

quality of articles published in the year before the arrival ($t-1$). Nevertheless, starting from year t onward, a noticeable improvement in the quality of publications appears.

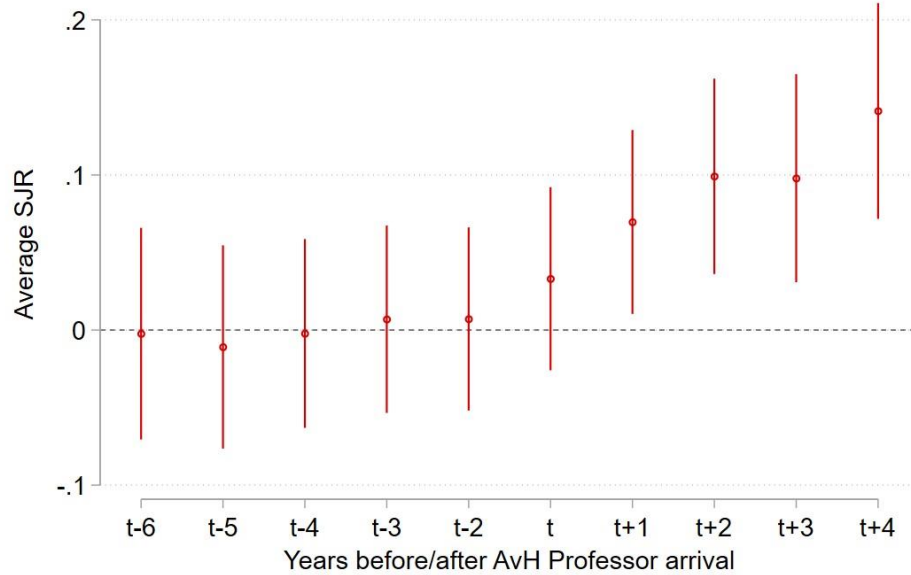


Figure 50 - Departments' SJR before/after AvH Professor arrival

Notes: The figure plots the regression coefficients.

To be more precise, the output during the period of $t-6$ to $t-2$ exhibits no statistically significant variance from the output in the year directly preceding the arrival of the star professor ($t-1$), which is the reference category. The bars in the figure represent the 95% confidence intervals. However, there is an increase in output quality during the year of the star professor's arrival compared to $t-1$. This suggests the absence of any pre-existing trend leading up to the professor's arrival (in other words, AvH Professors do not seem to choose universities “on the rise” as host institutions). The higher output compared to $t-1$ persists throughout the entire duration of the AvH professorship, which spans five years.

6 Conclusion

This report combines empirical evidence and a comprehensive literature review to evaluate Germany's standing within the global landscape of scientists' mobility and collaborative activities. The empirical analysis utilizes an extensive dataset sourced from Scopus, which encompasses over 5 million articles authored by researchers affiliated with German institutions during the period from

2005 to 2020. To enhance the dataset's depth and scope, we incorporated diverse supplementary data, including doctoral theses conducted in Germany from 2000 to 2020, and an ethnic analysis of scientists' names and surnames.

Building upon this data, the report introduces a novel taxonomy of internationally mobile scientists, delineating five categories: stayers, inflows, outflows, returnees, and transients. Utilizing this taxonomy, the report focuses on the evolution of mobility and collaboration patterns among German scientists and research institutions, comparing them over time with analogous countries and global leaders.

Several notable findings emerge from this study. First of all, while Germany is not among the few most advanced countries attracting large inflows of scientists from abroad, the country has performed well, especially compared to similar countries, and compared to previous years. Over the analysis period of 2005-2020, compared to the prior timeframe of 1996-2011, there is a shift in the trend of mobile scientists. From being negative in the earlier period, Germany has transitioned to a positive net inflow of over 5,000 scientists in the subsequent period. This shift is particularly pronounced in recent years, with decreasing outflows and rising inflows. In particular, the share of inflows has almost tripled within the considered time span, signifying the growing attractiveness of the German science system in more recent years.

Researchers leaving Germany demonstrate higher quality than those coming in, across all disciplines. The consistent pattern shows that outflows have the highest SJR, followed by inflows, while stayers exhibit the lowest value. This suggests that on average, departing researchers are of higher quality than incoming ones. However, Germany also demonstrates a significantly high quality among “returnees” researchers. Furthermore, the temporal inspection reveals that the gap between the research quality of outflows and inflows has been progressively narrowing over time.

The report also delves into international collaborations, highlighting Germany's active participation in global scientific partnerships, a trend comparable to that of the United States. Over time, the percentage of international collaborative research has been on the rise, highlighting Germany's increasing engagement in the global research landscape. Notably, certain institutions have demonstrated a noteworthy correlation between an upsurge in the influx of mobile researchers and heightened levels of international collaborations.

Moreover, the report conducts a comprehensive evaluation of several German funding programs, shedding light on their effectiveness in talent attraction and fostering collaborative endeavours. The Excellence Initiative, Humboldt Professorship program, and Artificial Intelligence Strategy have each

yielded significant outcomes. These initiatives have contributed to heightened research output, facilitated international cooperation, and bolstered collaborations with international partners.

In conclusion, while Germany still has a long way to go to be member of the selective group of countries attracting the best and brightest scientists in the world, mainly the Anglo-Saxon ones, notable progresses have occurred in recent years, in terms of attraction and retention of talent, that we have tried to highlight in our report. Moreover, the different initiatives aimed to insert Germany and its scientific institutions in the global landscape of scientists' mobility and collaborations seem to have worked relatively well.

Consequently, our primary recommendation stemming from our results, particularly considering the evolution of these findings over time, is that Germany has been gradually and consistently enhancing its position in attracting talented individuals. Therefore, Germany needs to maintain its current policies and continue this positive trajectory. The programs and initiatives that we evaluated have demonstrated a relatively effective track record, making it advisable to continue them, potentially with some refinements in their design.

For instance, an important aspect that requires attention is the gender balance within these programs. We have observed significant gender disparities, with women being notably underrepresented. This gender gap presents a clear area for improvement that could not only increase the quantity of candidates but also enhance the overall quality of the talent pool. Our own analysis has indicated that women are also less prevalent among returnees and tend to exhibit less mobility compared to men. This emphasizes the importance of actively involving women in the pool of attracted talent.

Moreover, it is worth noting that these programs heavily rely on returnee scientists and tend to prioritize them over foreign individuals. While returnees certainly bring valuable expertise, it is also essential for Germany to tap into a broader spectrum of new and foreign talent, even if it is unrelated to the German scientific ecosystem. To enable this, complementary policies should be considered that do not solely hinge on the willingness of Germans to return home, often in exchange for financial incentives. These complementary policies could address bureaucratic challenges associated with obtaining visas or securing tenure positions at universities, making it easier for foreign talent to contribute to Germany's scientific landscape.

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Appendix A

All Science Journal Classification (ASJC) codes and keywords use to identify the articles belonging to the subfields for the in-depth analyses.

Table 1 - List of keywords used to retrieve scientific publications in Artificial Intelligence

Keywords		
human action recognition	high-dimensional data	natural language understanding
generative adversarial network	image classification	neural network
artificial intelligence	image processing	artificial neural network
human aware artificial intelligence	image recognition	convolutional neural network
artificial bee colony algorithm	image retrieval	deep convolutional neural network
brain computer interface	image segmentation	deep neural network
cluster analysis	intelligent software agent	neuromorphic computing
cognitive computing	intelligent classifier	object recognition
computational intelligence	machine intelligence	pattern recognition
computer vision	machine learning	reinforcement learning
cyber physical system	extreme machine learning	robot
data mining	machine translation	human-robot interaction
deep learning	machine vision	industrial robot
evolutionary algorithm	markovian	rule-based learning
evolutionary computation	hidden markov model	self-organising map
fuzzy logic	memetic algorithm	semantic web
genetic algorithm	meta learning	speech recognition
genetic programming	motion planning	swarm intelligence
gesture recognition	multi-agent system	swarm optimisation
gravitational search algorithm	natural language generation	text mining
hierarchical clustering	natural language processing	unsupervised learning

Table 2 - List of ASJC codes and keywords used to retrieve scientific articles in Bioeconomy

ASJC codes		Keywords
11XX	1501	NOT tissue*
1301	1502	NOT extracell*
1303	1508	NOT implant*
1304	2305	NOT cancer*
1305	2402	NOT tumor*
1307	2404	NOT clinic*
1311	NOT 27XX	
1312		

Notes: “11XX” and “27XX” mean all codes starting with 11 and 27, respectively.

Table 3 - List of ASJC codes and keywords used to retrieve scientific articles in Advanced Manufacturing

ASJC	Keywords in title and abstract
2209	control* AND process*
	measure* AND electric* AND variable*
	sensor system* OR sensor tech*
	measur* AND instrument* AND (electrical* OR height* OR pressure* OR angle* OR depth* OR profile* OR gyroscope* OR distance*)
	measur* AND instrument* AND (transducer OR force* OR power* OR fluid* OR torque* OR vacuum gauge* OR velocity* OR wave)
	measur* AND instrument* AND (transponder OR reflection OR reradiation OR nuclear* OR gravitation OR gravity* OR optical*)

Table 4 - Top funding sources mentioned in the acknowledgements

Fund acronym	Fund name
AiF	Allianz Industrie Forschung
BMBF	Bundesministerium für Bildung und Forschung
BMWi	Bundesministerium für Wirtschaft und Technologie
DAAD	Deutscher Akademischer Austauschdienst
DFG	Deutsche Forschungsgemeinschaft
EC	European Commission
FP7	Seventh Framework Programme
H2020	Horizon 2020
NIH	National Institutes of Health
NSF	National Science Foundation
NSFC	National Natural Science Foundation of China
VCI	Verband der Chemischen Industrie

Table 5 - Treated and control characteristics after CEM

	Controls					Treated			
	Mean	SD	Min	Max		Mean	SD	Min	Max
Publications stock	11.13	28.63	1.00	275.00		11.62	30.65	0.00	325.00
Citations stock	222.11	817.29	0.00	12835.34		254.15	831.59	0.00	13563.71
Scientific age	5.28	6.16	1.00	47.00		3.99	6.79	0.00	47.00
Nb. Life Sciences	515					515			
Nb. Social Sciences	213					213			
Nb. Physical Sciences	1127					1127			
Nb. Health Science	60					60			
Total	1915					1915			

Appendix B

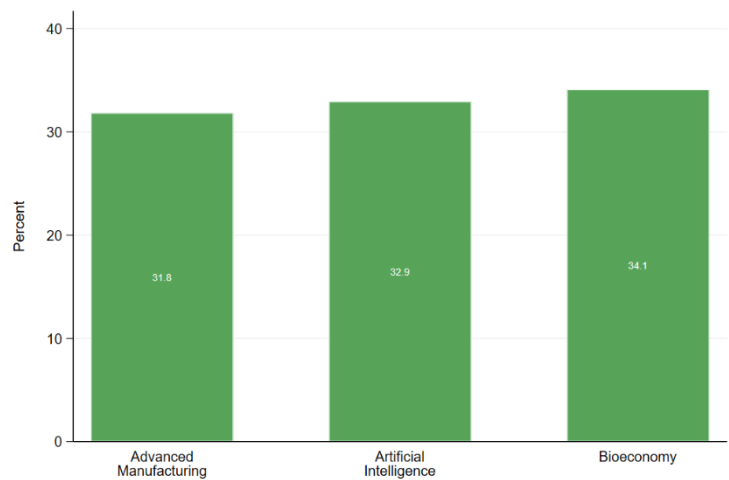


Figure 51 - Share of researchers with a PhD from a German university, by field (AM, AI and BE)

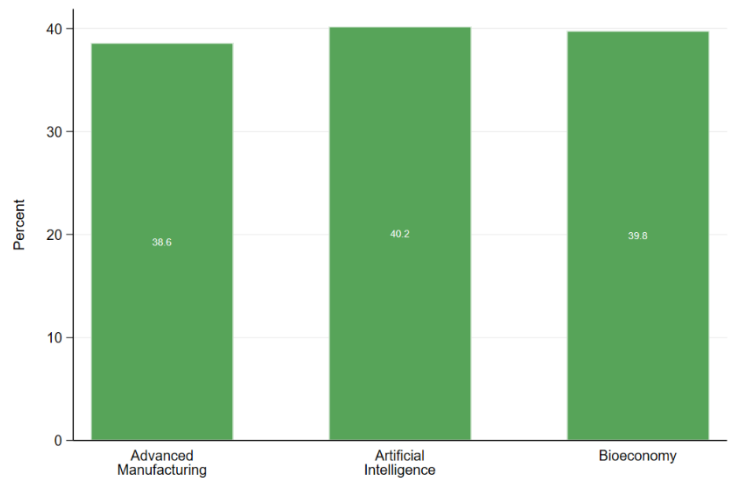


Figure 52 - Share of researchers with a PhD from a German university, by field (AM, AI and BE). Only resercher who published the first article from 2000 onwards

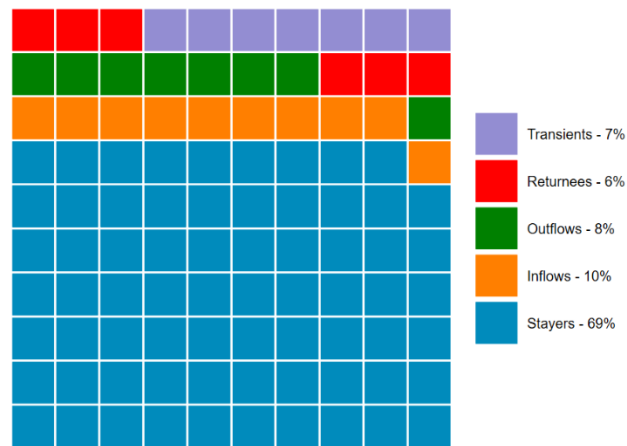


Figure 53 - Researchers by mobility type (2005-20, affiliation information only)

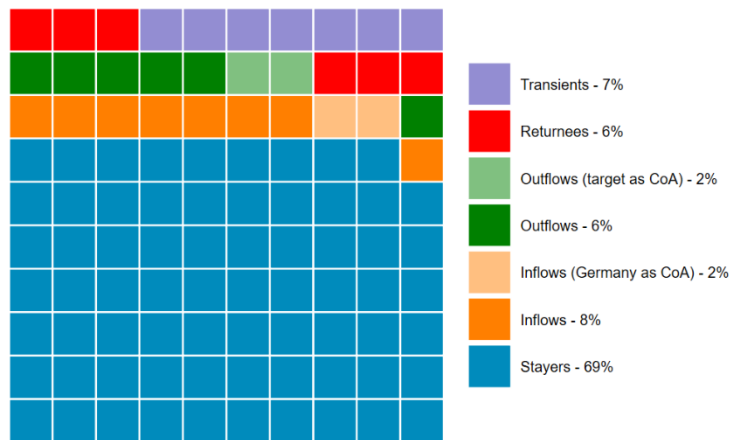
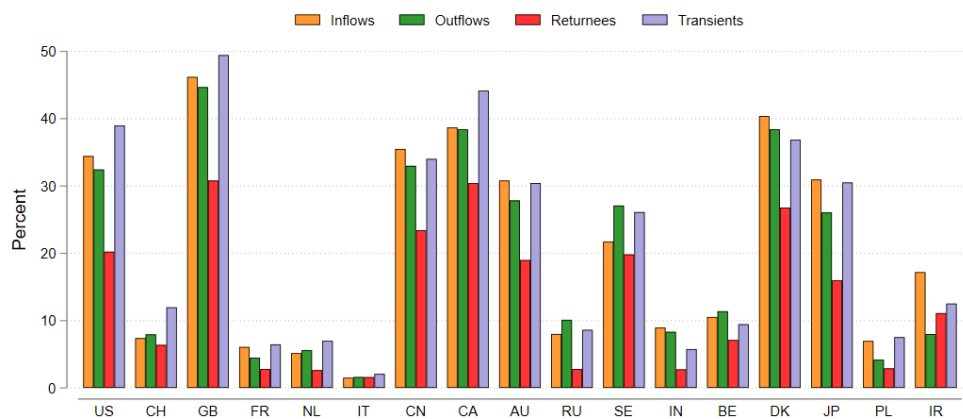
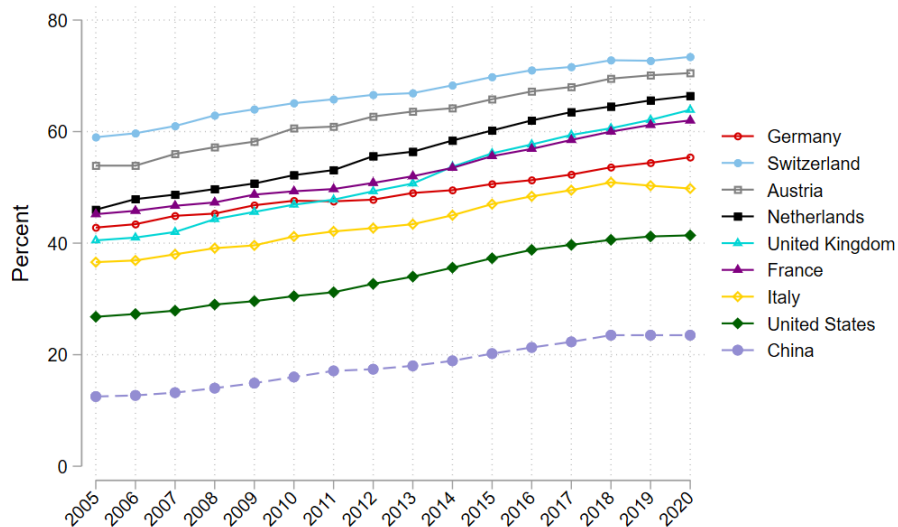


Figure 54 - Researchers by mobility type (2005-20, Affiliation information & name analysis)



Notes: We take into account the rank and the country of the affiliation immediately before/after the mobility event.

Figure 55 - Share of scientists in ARWU Top500 institutions



Notes: Only co-authored publications.

Figure 56 - Share of international co-authored publications, international comparison (selected countries)

Notes: Data for the comparison countries are sources from Elsevier's SciVal.