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// ELISABETH MUELLER AND PHILIPP BOEING

Global Technological Impact in  
Cross-Country Comparison

# Global Technological Impact in Cross-Country Comparison

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## Abstract

We introduce a conceptual framework of global technological impact that assesses a country's unilateral impact on another country's knowledge base and, in turn, derives its bilateral and global impact. To implement this framework empirically, we develop novel measures of technological impact using citation data from International Search Reports (ISR) in the universe of Patent Cooperation Treaty (PCT) applications over the past two decades. For the leading innovating countries, we document substantial heterogeneity in positions along the spectrum from technological independence to dependence. The US exhibits the highest level of global technological independence, followed by Japan and Korea, while Europe and China are globally dependent. Over time, the US and Korea remain relatively stable, Japan declines after an earlier increase, Europe increases gradually, and China shows the largest increase from a low initial level. Additional analysis based on international trade data shows that China has reached a leading position, highlighting an important difference between innovation and production.

**Keywords:** bilateral and global technological impact, patents, citations

**JEL Codes:** O33, O34

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# 1 Introduction

The global economic landscape has shifted from a paradigm of globalization to a growing focus on the risks associated with economic integration and technological interdependence. Countries' technological capabilities are increasingly viewed through a geoeconomic lens, with policymakers striving to enhance technological sovereignty. In the literature, technological sovereignty is defined as a country's ability to provide technologies critical to its competitiveness, either by developing them domestically or acquiring them from abroad, without being unilaterally dependent on any particular country (Edler et al. 2023; March and Schieferdecker 2023). However, in a globalized world, no country can rely exclusively on its own knowledge base to achieve technological self-sufficiency; instead, it also relies on the knowledge bases of other countries (Crespi et al. 2021). In this context, we refer to technological impact as the extent to which one country's knowledge base influences the further development of another country's knowledge base. Despite mutual dependencies, a country may still be considered sufficiently technologically sovereign if its dependence on foreign knowledge is balanced by foreign dependencies on its own knowledge base.

Policymakers require an evidence-based assessment of technological impact and an understanding of how such impact shapes a country's technological dependence. This study introduces a conceptual framework of technological impact that covers the individual impact of a country's knowledge base as well as the impact at the bilateral and global level. Thus, our framework analyses the external aspect of access to technology within the concept of technological sovereignty. Specifically, our framework demonstrates how the measure of one-directional technological impact can be extended to evaluate a country's bilateral and global technological impact. By adjusting for bilateral technological impact between countries, our approach allows us to determine whether a country is in a situation of technological independence, reciprocity, or dependence with respect to another country, and, more broadly, with respect to all other countries. The measure of global technological impact provides a comprehensive indicator of a country's ability to access foreign knowledge bases without becoming unilaterally dependent on other countries. In addition, we contribute to an emerging literature that measures the technological impact of leading innovators. For example, recent work by Han et al. (2024) examines bilateral dependence between the US and China using patent citations. We make progress by enabling comparisons across any set of countries and by accommodating various data sources to study the phenomena of interest. While our main analysis relies on patent data to measure technological impact, we also provide a complementary analysis based on international trade data.

For the empirical implementation of our measure, we rely on patent data from 2000 to 2022. When one invention builds on another, the patent of the later inven-

tion cites the patent of the earlier invention. In this context, a citation indicates the technological impact of the cited patent (Hall et al. 2001), and the number of citations received is commonly used as an indicator of technological impact of an invention (Corredoira and Banerjee 2015; Jaffe and De Rassenfosse 2017). A core aspect of our approach is netting out of bilateral technological impact between two countries. In this respect, ensuring the cross-country comparability of patent citations is crucial because citations represent measurable units of technological impact. Following the approach of Boeing and Mueller (2016), we observe Patent Collaboration Treaty (PCT) applications and select International Search Report (ISR) citations to obtain a high degree of comparability across countries. We only consider non-self citations from abroad because we are interested in the degree to which the inventions of one country serve as the knowledge base for inventions in other countries. This approach also alleviates concerns about potential measurement bias due to domestic policy distortion, e.g. through pro-patent subsidies, as foreign citations are largely independent from domestic policies.

We briefly summarize our findings on the bilateral and global technological impact of countries,<sup>1</sup> focusing on the most recent period of our study. Among globally independent countries, the US exhibits consistent bilateral independence, resulting in the strongest global independence overall. Japan is bilaterally independent of all countries except the US and shows global independence as well. Korea, although bilaterally dependent on both the US and Japan, achieves moderate global independence. Among globally dependent countries, Europe depends bilaterally on all countries except China. China depends bilaterally on all countries and shows the most pronounced global dependence. Notably, all countries except Japan exhibit a long-term trend of increasing global independence in recent years, with China showing the highest growth.<sup>2</sup> We provide additional analyses based on key enabling technologies, alternative country selections, and international trade data. Interestingly, the analysis based on trade data shows that Europe and China are leading in global economic impact, whereas the US takes the last position. These results are opposite to the global technological impact based on patent data, highlighting important differences between innovation and production.

We highlight several implications for policymakers. The evolving geoeconomic

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<sup>1</sup>The term "country" refers to (i) Europe, (ii) the US, (iii) China, (iv) Japan, (v) and Korea, and the category of residual countries. We consider Europe as a whole because the European Union (EU) is increasingly governing geoeconomic and innovation-related issues of its member countries. One well-known example is the Horizon Europe research program and its predecessors (European Commission 2024). In this study, Europe comprises 30 countries: the EU-27 plus Norway, Switzerland, and the United Kingdom – which was an EU member country until January 2020.

<sup>2</sup>The literature has focused on more generally ranking the innovativeness of countries based on patent data, e.g. Bergeaud and Verluise (2022), Boeing and Mueller (2016) and Cerdeiro et al. (2021). Considering bilateral dependence, Han et al. (2024) show China's declining dependence on the US in the 2010s, which aligns with our finding of China's declining global dependence.

landscape has reinforced the use of innovation and industrial policy, underscoring the importance of ensuring the effective allocation of public funds. Our analysis can support policymakers in improving allocation efficiency by enabling them to monitor countries' bilateral and global technological impacts and make timely adjustments as needed. While the US currently maintains its global technological leadership, it is crucial for European policymakers to address Europe's global technological dependence. Europe may pursue less dependent bilateral partnerships with the US, Japan, and Korea while avoiding future dependence on other countries. Japan may aim to slow or reverse its recent decline in global technological independence by generating inventions that translate more effectively into technological impact. For Korea, relatively high R&D investment levels have likely supported its continued global independence, though questions remain about the long-term sustainability of this strategy. Although China shows the highest long-term growth in global technological impact, its ambitions to become a global innovation leader still exhibit some discrepancy with its current technological dependence.

The paper proceeds as follows. Section 2 introduces our conceptual framework as well as discusses the measurement of technological impact and the analysis of patent citation data in the literature. Section 3 explains the PCT system, our data, and our impact measures. Section 4 presents the empirical results, while section 5 discusses policy implications. Section 6 concludes.

## 2 A Framework for Global Technological Impact

This section presents the theoretical foundation of our approach. In 2.1 we introduce our conceptual framework, in subsection 2.2 we review the prior literature that measuring technological impact, and in subsection 2.3 we discuss the state-of-the-art in cross-country analysis using citation data.

### 2.1 Conceptual framework

The emerging literature on technological sovereignty recognizes that in a globalized world no country can rely solely on its own innovation capacity in an effort to achieve technological self-sufficiency (see Crespi et al. (2021) for a survey).<sup>3</sup> Edler et al. (2023) define technological sovereignty as "the ability of a state or a federation of states to provide the technologies it deems critical for its welfare, competitiveness, and ability to act, and to be able to develop these or source them from other economic areas without one-sided structural dependency." Concerning the

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<sup>3</sup>In an early discussion of technological sovereignty, Grant (1983, 239) defines this concept as "the capability and freedom to select, generate, acquire, apply, build upon, and exploit commercially technology needed for industrial innovation." This definition emphasizes the direct link between technological sovereignty and a country's ability to innovate.

provision of technologies, this definition foresees two mechanisms. Countries can provide the necessary technologies by developing them domestically or, and this is a crucial distinction from technological self-sufficiency, by acquiring them from abroad. Hence, this definition distinguishes between the domestic and international components of technological sovereignty.

Domestic R&D plays a crucial role for avoiding unilateral dependence on other countries. According to Griffith et al. (2004), domestic R&D fulfills both a supply and demand function. On the supply side, domestic R&D is essential for supplying the knowledge base on which a country builds for its own technological development and on which also other countries can draw. This latter use of the knowledge base increases the country's technological impact abroad. For our conceptual framework we define technological impact accordingly as the influence that the knowledge base of one country has on the further improvement of the knowledge base of another country. On the demand side, domestic R&D increases the absorptive capacity (Cohen and Levinthal 1989) of a country and thus facilitates the identification and use of technologies from foreign knowledge bases. Hence, domestic R&D allows a country to directly influence its own knowledge base, while the overall technological impact of a given country is also affected by the quality and further improvements of the knowledge bases of other countries, an aspect that is beyond its direct control.

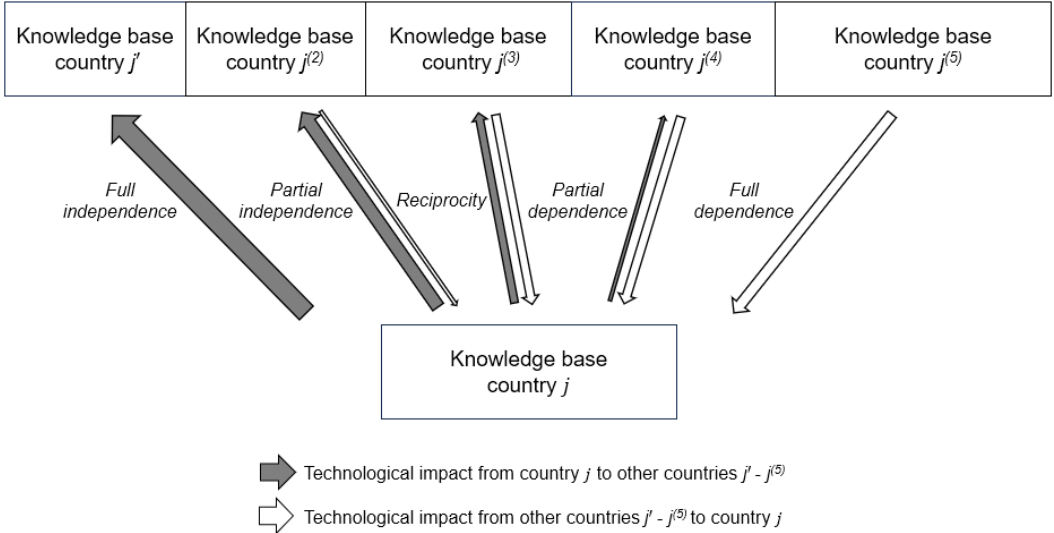
Our conceptual framework for global technological impact also answers the call by Edler et al. (2023, 7) for developing a model that allows for "an overarching assessment of a country's position regarding technological competitiveness and power relations." We argue that an important way to analyze a country's power relations—and thus to cover the external aspect of access to technology—is to examine the technological impact emanating from a country's knowledge base. We introduce a new approach of netting out the bilateral technological impact between two countries in order to understand their relative power position. Our framework has the added advantage that it is amenable to empirical measurement. Thus, we contribute to the literature by making the external aspect of technological sovereignty more concrete and empirically measurable.

We now introduce our framework, as visualized in the following figures. All subsequent analysis should be read from the perspective of focal country  $j$ . In Figure 1 the size of the knowledge base of each country is indicated by the size of the square. The variation in the size of the squares indicates variance in knowledge bases across countries. As a starting point, Figure 1 depicts the technological impact from country  $j$  to countries  $j'$  and  $j^{(2-5)}$  as gray arrows. Conversely, the returning technological impact is depicted by white arrows. The variation in arrow size indicates heterogeneity in the technological impact of countries.

In general, our framework uses the one-directional technological impacts as

shown in Figure 1 as a basis for evaluating the bilateral and global technological impact of country  $j$ . More specifically, despite an intensive recourse on foreign knowledge bases, country  $j$  can be considered sufficiently sovereign if its bilateral or global dependence is balanced, in other words, mirrored by foreign dependence on technologies originating in country  $j$ . Adjustment for reciprocal impact makes it possible to determine whether country  $j$  is in a situation of *independence*, *reciprocity*, or *dependence*. In our framework, reciprocity is given if the technological impact that country  $j$  and country  $j'$  have on each other is balanced. If the technological impact of country  $j$  on country  $j'$  is stronger than vice versa, country  $j$  is in a situation of partial or full independence whereas country  $j'$  is in a situation of partial or full dependence. These different situations are depicted in Figure 1.

Figure 1: One-directional technological impact

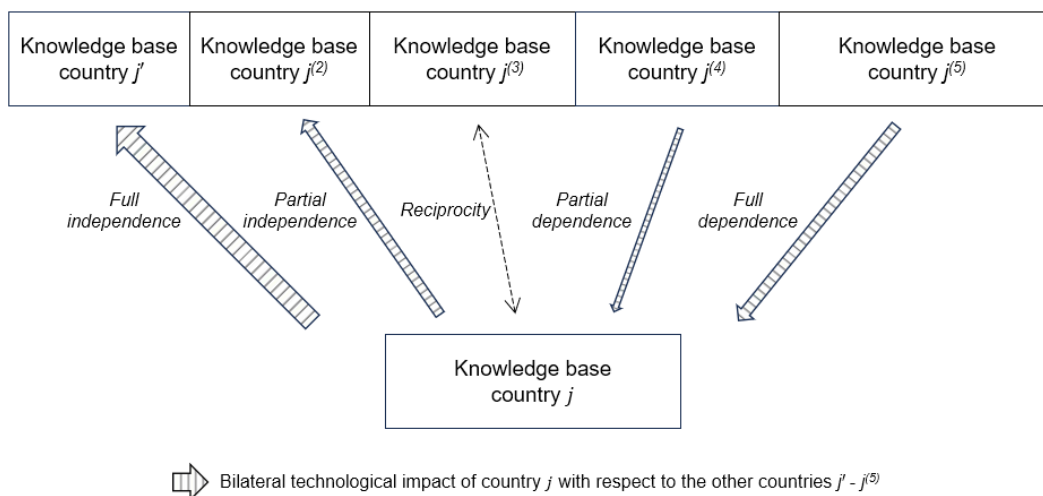


Notes: The labels on the arrows refer to the situation of focal country  $j$ .

In a next step, Figure 2 presents the bilateral technological impact of country  $j$  after netting out the respective one-directional technological impact of the other country. Therefore, the two-arrow linkages in Figure 1 are now displayed as single arrows. For instance, the arrow pointing from country  $j$  to country  $j^{(2)}$  indicates partial independence, the arrow between  $j$  and country  $j^{(3)}$  indicates reciprocity, and the arrow pointing from  $j^{(4)}$  to  $j$  indicates partial dependence.

Finally, Figure 3 represents the global impact of country  $j$  as the weighted average across all bilateral technological impacts. From a global perspective, country  $j$  is characterized by partial independence. While bilateral technological impact shows the situation of country  $j$  regarding a specific country, the global technological impact provides a summary measure of country  $j$ 's overall situation regarding all countries. Thus, the measure of global technological impact is an important summary measure for a country's ability of benefiting from technologies available

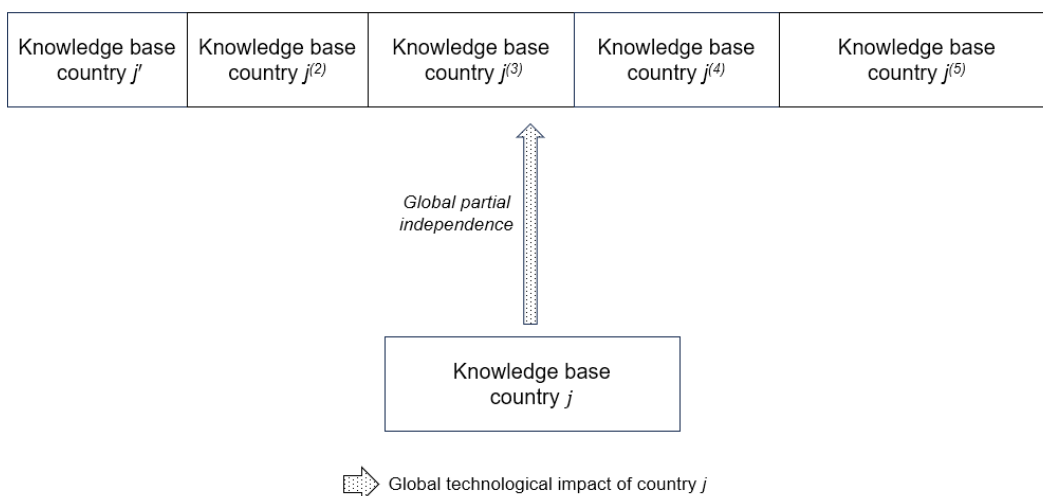
Figure 2: Bilateral technological impact



Notes: The labels on the arrows refer to the situation of focal country  $j$ .

abroad without being unilaterally dependent on other countries.

Figure 3: Global technological impact



Notes: The labels on the arrows refer to the situation of focal country  $j$ .

To complete the discussion of our framework of global technological impact, we address the influence of a country's size. In a setting without policy interventions and in which the quality of the knowledge bases is homogeneous, the relative

size of both countries is a neutral factor.<sup>4</sup> This insight emerges from the following rationale: if a country is large and has a large knowledge base, its knowledge is in general frequently adopted by other countries. However, a small country that adopts this knowledge develops itself only a limited amount of new knowledge and therefore also refers to the large country's knowledge base only to a limited extent. Conversely, the small country has a limited knowledge base and therefore influences a large country only to a limited extent. Hence, a small country has a more limited technological impact on others, and the impact that large countries have on it is also limited due to its small knowledge requirements. In conclusion, if the quality—and therefore the relative relevance—of a small and large country's knowledge bases are homogeneous, the two countries are in a situation of reciprocity.

## 2.2 Measurement of technological impact

Having introduced our conceptual framework of global technological impact, in this section we review the literature concerning the empirical measurement of technological impact and knowledge flows more generally. Knowledge flows, according to the definition of Peri (2005, 308), "occur whenever an idea generated by a certain institution is learned by another institution. These flows denote a process of learning from someone else's ideas". Compared to technological impact, the concept of knowledge flow does not contain a notion of effect. Technological impact implies that the knowledge that is learned is used to a certain effect, namely to improve the knowledge base of the learner.

The importance of knowledge flows was first recognized in the international trade literature (Grossman and Helpman 1991; Krugman 1979) and subsequently in the innovation literature, which introduced patent citations as an empirical measure of knowledge flows between inventors within and across countries (Jaffe et al. 1993; Jaffe and Trajtenberg 1996). To fix the empirical terms used throughout this paper, the citing patent *makes references* to the cited patent, while the cited patent *receives citations* from the citing patent. Specifically, the fact that patent  $i$  is referenced by patent  $k$  (i.e. receives a citation) indicates a flow of knowledge from  $i$  to  $k$ , corresponding with the technological impact of the cited patent  $i$  (Hall et al. 2001).

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<sup>4</sup>Note that in practice, countries may actively employ policies to strengthen their technological impact and thus to improve their technological sovereignty. Such policies can consist of holding back components that are critical to high-tech industries in other countries (Andrenelli et al. 2025), stopping the export of goods needed to build on a particular technology (Han et al. 2024), impeding the mobility of experts (Aghion et al. 2023), stopping the licensing of critical technology (Meschnig and Dubiel 2023), or imposing secrecy on future critical inventions (Glitz and Meyersson 2020). Additionally, the policies of larger countries may be more effective. For example, larger countries can generally invest in a wider variety of technologies, some of which may be strategically important to other countries (Hidalgo et al. 2007). Larger countries can therefore choose from a larger set of technologies with which they may threaten to exclude other countries. Also, larger countries tend to have stronger political relationships (Waltz 1979), which can be employed to the own advantage.

Likewise, the survey by Jaffe and De Rassenfosse (2017) interprets counts of citations as an indicator of technological impact. The literature has also considered citations and references from a supply and demand perspective. For example, much of the analysis in Jaffe et al. (1993) is concerned with observing citations received by patent  $i$  from patent  $k$ , with patent  $i$  being the source of knowledge supply. In contrast, MacGarvie (2005) considers the demand for knowledge by observing references made by patent  $k$  to patent  $i$ .

Concerning the measurement of technological impact of inventions across countries, the supply-side perspective of country  $j$ 's knowledge base provides a useful lens. The more influential the respective inventions are, the more dependent other countries  $j'$  are on the knowledge base of country  $j$ . Empirically, the citations that country  $j$  receives from country  $j'$  provide a measure of technological impact because they show that important prior knowledge for country  $j$ 's invention originated in country  $j'$ . Considering the timing of inventive activity, the technological impact of country  $j$  can be examined through the most recent inventive activity of country  $j'$ . Importantly, the period during which country  $j$ 's patent  $i$  can be cited by country  $j'$ 's patent  $k$  is usually limited to a fixed time interval to ensure comparability of patents filed at different points in time. Further, this approach is largely invariant to country  $j$ 's historical patent stock.<sup>5</sup>

A core aspect of our conceptual framework is the netting out of bilateral technological impact between two countries. For the empirical implementation of our framework we therefore need to adjust the typical measure of one-directional impact for the countervailing impact of other countries. This allows us to determine the bilateral impact of one country with respect to another country and, one step further, the global impact of a country with respect to all other countries. In this respect, ensuring the cross-country comparability of patent citations, which represent the measurable units of technological impact, is crucial for netting out the bilateral technological impact. However, this requirement poses an empirical challenge due to the considerable heterogeneity in the national legal frameworks and examination practices of patent offices, which affects the measurement of both patents and citations. In the light of these challenges, the next section discusses how the literature employs citation data in single and cross-country settings.

### 2.3 Analysis of citation data

Citation data has not only been used as a measure of technological impact (Corredoira and Banerjee 2015; Jaffe and De Rassenfosse 2017), but has often been inter-

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<sup>5</sup>In contrast, the demand-side perspective typically considers all references to prior art, some of which go back very far in time (Hall et al. 2001). This can make a difference in international comparisons, e.g., the US keeps patent records since 1790 but the China only since 1985. A related aspect is that within a fixed time interval of only a few years after filing (or publication), citations tend to be received by pending or recently granted patents, whereas it would not be uncommon for references also to be made to expired patents.

preted as an indicator of technical value (Trajtenberg 1990) and economic value (Harhoff et al. 1999; Lanjouw and Schankerman 2004), and exhibits a closer relationship to patents' actual economic value than references, claims, or family size (Gambardella et al. 2008). Recent studies also use citations in network settings to determine the centrality of specific patents (Funk and Owen-Smith 2017; Park et al. 2023). Nevertheless, working with citation data remains subject to empirical challenges as it is necessary to control for multiple, unrelated changes in patent and citation data-generating processes to obtain unbiased estimates of inventive activities. To address these challenges, Kuhn et al. (2020) recommend selecting appropriate patent and citation types and employing a fixed effects approach in regression analysis to control for remaining differences, especially across technology areas and over time. The remainder of this section discusses in detail the selection of patent and citation types that are appropriate for our conceptual framework.

A well-known challenge of using citations is their application to cross-country comparisons. This is because heterogeneity across national legal frameworks and patent examination practices leads to substantial variation in citations generated across patent offices. For a set of triadic patent families following national standards in examination, Michel and Bettels (2001) show that the United States Patent and Trademark Office (USPTO) applies three-times more patent references than the European Patent Office (EPO).<sup>6</sup> In addition, patent examiners are more likely to make references to patents from their home country, which is also known as "home bias" (Bacchiocchi and Montobbio 2010). Thus, naïve comparisons of international citation measures across countries may be misleading. To address this issue, several studies have used citations while attempting to control for potential differences in the data-generating process. A typical approach restricts the origin of citations to a single patent office. Lee and Yoon (2010) and Wu and Mathews (2012) compare USPTO citations received by USPTO applications filed by applicants from the US, Japan, Korea, and Taiwan. While focusing on a single patent office may increase the comparability of the citations generated, some limitations remain. First, the allocation of these citations may still be subject to the aforementioned home bias, favoring US patents. Second, applicants from other countries may select to only submit inventions of higher value because applications are more costly to file from overseas. A third limitation is the narrow empirical focus on patent data from only one country, which limits its global relevance (De Rassenfosse et al. 2014).

Naturally, the extension towards multiple patent offices permits a more comprehensive analysis of technological impact. At the same time, accounting for nu-

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<sup>6</sup>When examining international knowledge flows, some studies have therefore avoided citations altogether and instead relied on alternative measures, such as counting foreign patent applications (Eaton and Kortum 1999) or patents with international co-applicants (De Rassenfosse and Seliger 2020).

merous sources of heterogeneity in the data-generating process of patents and citations across countries becomes increasingly challenging. The literature has documented several country-specific issues related to patenting requirements, examination procedures, and pro-patent policies. A well-studied historical example is Japan's single-claim patent before 1989 (Goto and Motohashi 2007). Although the introduction of multi-claim patents subsequently increased the average number of claims per patent (Motohashi 2004), earlier regulations may have some persistence over time and can hence influence the the number of received citations per patent. Further, the USPTO requires applicants to cite all relevant prior art of which they are aware, whereas the EPO requires only the examiner, not the applicant, to cite prior art (Michel and Bettels 2001).<sup>7</sup> The distinction between citation types is important, because prior studies show that examiner citations have a stronger relationship with private value (Hegde and Sampat 2009), are more likely to refer to younger patents and foreign prior art (Thompson 2006), and are less affected by technology shocks influencing the search process for prior art, e.g. machine translation of Chinese patents (Büttner et al. 2022). While some studies emphasize that applicant references more closely track the actual knowledge flows between inventors, such citations may also be subject to strategic applicant behavior (Lampe 2012; Corsino et al. 2019).

Another concern regarding the international comparability of patents and citations is rooted in pro-patent policies, e.g. in China. National patenting targets (Sun et al. 2021), subsidies (Branstetter et al. 2023), and tax cuts (Wei et al. 2023) have all contributed to increased patenting, which makes the interpretation of domestic citations emanating from the Chinese patent office more difficult. China has led globally in patent output for both national applications by residents and PCT applications since 2011 and 2019 (WIPO 2023), respectively. On the downside, however, excessive workload, reduced examination time, and low examiner salaries can potentially degrade the quality of domestic patents' examination, subsequently introducing measurement error or bias regarding the references made by

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<sup>7</sup>Interestingly though, on average, patent examiner citations account for 63% of all citations at the USPTO (Alcácer et al. 2009).

such patents (Branstetter et al. 2023).<sup>8</sup> Several studies substantiate this concern.<sup>9</sup>

Notwithstanding such complications, a number of recent studies have conducted cross-country comparisons. Starting with a two-country setting, Han et al. (2024) observe patents filed in the US that cite patents filed in China and vice versa to measure decoupling and dependence. Examining 40 major countries, Liu and Ma (2023) analyze whether patents filed in a given country cite other patents filed in that country or abroad. Depending on the information available for a particular country, they assign patents to countries by the inventor, the applicant, or the patent office. Cerdeiro et al. (2021) follow a similar approach to study the impact of global knowledge flows on countries' economic performance.

Some studies adjust the selection of patents and citations to increase comparability. Eugster et al. (2022) only select patent families with at least two national applications for which the country is identified by the address of the first inventor. The authors also exclude self-citations between patents with the same inventors and set a fixed citation window.<sup>10</sup> Exploiting features of the PCT system, Bergeaud and Verluise (2022) observe citations originating from PCT applications and received by the top 10% most cited patents (considering all citation types) in each technology, year, and country. In an even more rigorous analysis, Boeing and Mueller (2016) observe the global population of PCT applications and select foreign non-self citations generated by examiners through International Search Reports (ISRs). While this selection ensures a homogeneous data-generating process of patents and citations (further details are provided in Section 3), the selection of foreign non-self citations imposes independence from domestic pro-patent policies. In this study, we build on the approach by Boeing and Mueller (2016) and select PCT applications as well as foreign non-self ISR citations for the measurement of technological impact.

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<sup>8</sup>Chinese examiners handled 47% more patents than US examiners and 136% more than European examiners in 2020, given a monthly salary of around 10,000 RMB, which is equivalent to 1,600 USD (Branstetter et al. 2023; Yin and Sun 2023).

<sup>9</sup>Yin and Sun (2023) show that citations generated by the China National Intellectual Property Administration (CNIPA) are not correlated with initial patent auction prices in China, which contradicts results in other countries. Wu et al. (2022) only find a significant relationship between citations and firms' total factor productivity after restricting their sample to patents that incurred higher filing costs at CNIPA, exceeding the threshold of 10 claims. Boeing and Mueller (2019) find that only foreign citations, but not domestic and self-citations (both may be partially driven by domestic policy), have a significant and positive relationship with R&D stocks of Chinese firms. Schmoch and Gehrke (2022) compare Chinese and non-Chinese PCT applications and show that after the international phase, only 66% of Chinese applications are transferred to the national phase (in patent families with three or more national applications), whereas the corresponding rate for non-Chinese applications is 79%, indicating lower average patent value for China.

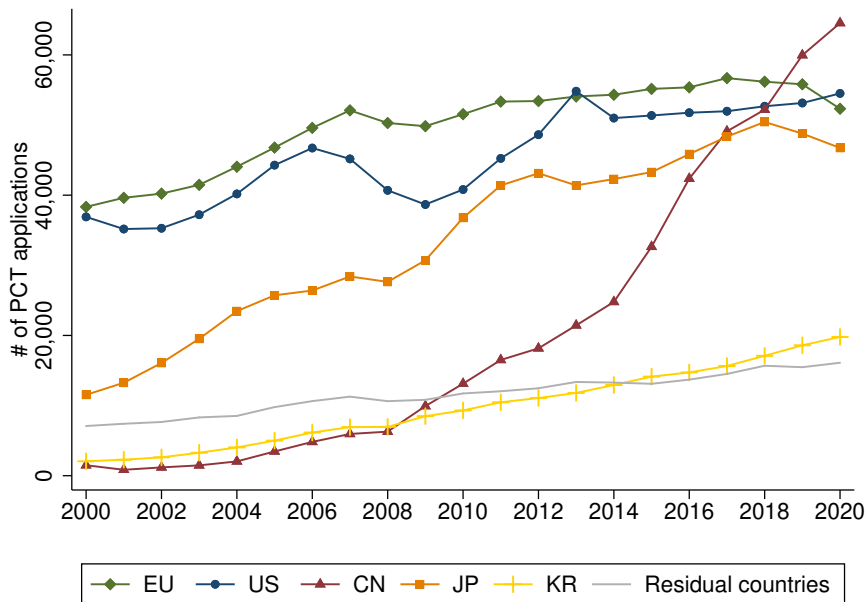
<sup>10</sup>Self-citations typically account for about 10% of citations received (Higham et al. 2021). They are often defined at the applicant level and their exclusion is common to avoid bias related to firm size.

### 3 The PCT System, Measurement and Data

#### 3.1 Usage of the PCT system

The PCT system, which is administered by United Nations' (UN) WIPO, allows applicants to simultaneously protect intellectual property in up to 158 countries. Figure 4 demonstrates that use of the PCT system has significantly expanded throughout the years, increasing from 97,414 filings in 2000 to 254,008 filings in 2020. Specifically, this growth is largely influenced by East Asian countries, particularly China, Japan, and Korea, which experienced larger growth rates than Western countries such as the US and European countries. China has been the number one ranked PCT applicant country since 2019, surpassing the US, Japan, Korea, and Germany. The shift in innovation activity from the West to the East is also reflected in Figure 5. In 2000, more than three-quarters of PCT applications originated from the US and Europe; however, the share of Western applications gradually decreased in the following two decades. By 2020, more than half of the global PCT applications originated from China, Japan, and Korea. In recent years, China and Korea's global shares have expanded, while those of the US, Japan, and Germany have contracted.

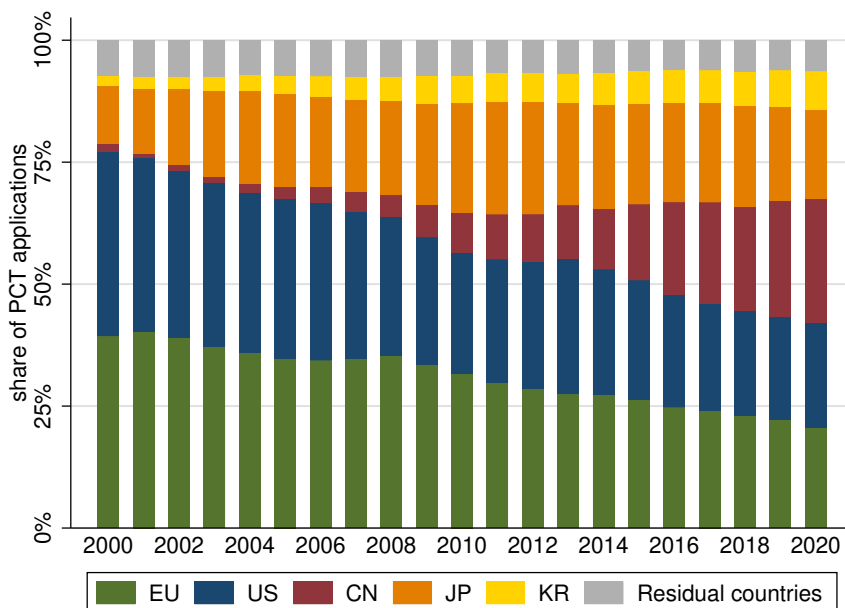
Figure 4: Number of PCT applications by countries



#### 3.2 Legal background of the PCT system

A PCT patent application passes first through the international phase. During the international phase the search authority is designated and the international search

Figure 5: Share of PCT applications by countries



report (ISR) is published. The ISR contains the prior art on which the technology in the patent application builds. Typically 30 months after the priority date the national phase starts. For this phase the applicant selects all countries or regions in which patent protection is sought. The designated national patent offices are then responsible for the grant decision (WIPO 2024).

The search for prior art of patent applications under the PCT system follows a strict legal framework. Prior art searches are conducted during the international search phase within 30 months of filing the application. Designated national patent offices act as International Searching Authorities (ISAs), with all examiners following the same WIPO examination rules when preparing an ISR (WIPO 2022a). Confirming the impact of identical regulations, Michel and Bettels (2001) provide empirical evidence of highly similar citation rates for the USPTO, the EPO, and the Japan Patent Office (JPO) when the patent offices prepare ISRs as ISAs. Regarding applicant citations, the rules of the PCT system state that the application should “indicate the background art which, as far as known to the applicant, can be regarded as useful for the understanding, searching and examination of the invention, and, preferably, cite the documents reflecting such art” (WIPO 2022b, Rule 5). Notably, the examiner ultimately decides which references are included in the ISR.

The selected references measure the technical and legal relationships among patents and are the appropriate measures of an invention’s impact for our analysis. Restricting our analysis to citations from the ISR offers several important advantages. The PCT system applies common standards for searching prior art, which

makes citations internationally comparable regardless of the nationality of the ISA conducting the search. The search guidelines explain in detail how citations should be selected by the examiners (WIPO 2022a, §15.63-§15.72). For example, examiners are encouraged to cite only the most relevant documents and to cite documents in the application's language, if several members of one patent family are available (WIPO 2022a, §15.69). As we aggregate citations at the family level, our measure is not influenced by which family member is actually cited.

International comparability is further enhanced because the search for prior art is highly concentrated among few ISAs. According to WIPO (2023, p. 75), the top-five ISAs were responsible for more than 90% of ISRs in 2022 (EPO, 37.8%; JPO, 21.1%; Korean Patent Office (KPO), 15.6%; USPTO, 9.7%; and CNIPA, 9.5%).

PCT applications move from the international to the national phase 30 months after priority. National patent offices conduct additional searches and examine the application prior to their grant decision. Citations in the national phase can differ from ISR citations as they follow national guidelines. To restrict the citations originating from only one data-generating process, we do not consider those generated during the national phase.

In international comparisons, it is essential to account for potential language barriers that deter patent examiners from identifying prior art from a specific country. Patent examiners typically begin their search for prior art with a keyword search in English. The PCT system provides an English translation of the main portions of PCT applications, including title, abstract, international search report, and any text related to figures for all PCT applications not published in English (WIPO 2022b, Rule 48.3 (c)). Abstracts have a key role in the search. According to Rule 8.3 (WIPO 2022b) "The abstract shall be so drafted that it can efficiently serve as a scanning tool for purposes of searching in the particular art, especially by assisting the scientist, engineer or researcher in formulating an opinion on whether there is a need for consulting the international application itself." Therefore, even if a PCT application is not originally published in English, it is easily identifiable as potentially relevant prior art.<sup>11</sup> To account for additional language heterogeneity across patents, in the empirical analysis we also control for the date when the English full text patent document becomes available.

According to further guidelines of the PCT system, patent examiners conducting the international search have access to the minimum documentation standard, which specifies which prior art needs to be searchable for examiners. Regardless of the publication language used, PCT applications are part of this minimum standard. As such, all PCT applications are fully available during the search process.

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<sup>11</sup>Büttner et al. (2022) show that citations by USPTO examiners are invariant to the implementation of Chinese-English machine translation provided by Google Patents, suggesting the prior existence of alternative translation services at the USPTO.

### 3.3 Development of our empirical measures of technological impact

Building on Boeing and Mueller (2016), we ensure comparability in the legal framework underlying the studied patent applications and citations by restricting our sample to PCT applications and citations generated in ISRs during the international phase. We only consider nonself-citations from abroad when measuring technological impact because we are interested in the degree to which the inventions of one country serve as the foundation for inventions in other countries. This approach also alleviates concerns about potential bias through domestic policy, because foreign citations are largely independent from domestic patent policies. The priority year indicates the year in which the first patent application for a given invention was filed. Country assignment of applications is based on the address of the first applicant, and we only consider citations from unique pairs of citing and cited patent families.<sup>12</sup> Self-citations are determined based on DOCDB standard names from PATSTAT and EEE-PPAT application name harmonization (Magerman et al. 2006). We set the citation window to three years to ensure comparability between patent families with different priority years and a high degree of timeliness.

We contribute to the literature by constructing empirical measures of technological impact that are calculated based on PCT filings with priority years between 2000 and 2017.<sup>13</sup> Consistent with the focus of our analysis, we first assign all filings to the world's five leading innovators, i.e. (i) Europe, (ii) the US, (iii) China, (iv) Japan, (v) and Korea, plus a residual (the rest of the world).<sup>14</sup> We also identify the main technology class of each application based on the International Patent Classification codes. Specifically, we use the classification by Schmoch (2008), which defines 35 technology classes. Finally, we quantify the number of citations a country receives from another country and vice versa and focus on three aspects of technological impact.

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<sup>12</sup>Because we use the address of the first applicant for the geographic assignment of the invention, our empirical measures are not influenced by the countries that are chosen for patent protection. E.g., if a Korean firm is only seeking protection in the US and in Europe, the invention would still be classified as belonging to Korea. When a patent is filed by applicants from different countries, we allocate the patent to the country of the first applicant. Because PCT rules do not stipulate a specific order, applicants may indicate the more important applicant first or choose a random order. In both scenarios the use of the first applicant will cover on average the impact that the countries receive from international co-applications.

<sup>13</sup>The inclusion of more recent years would introduce truncation to our citation measure. We cannot use PCT patents after 2017 as we require full data coverage for our three-year citation window. When considering the data availability for the citation count, we also need to take the publication lag into account, which influences when data becomes available in PATSTAT. Given the PATSTAT version from March 2021, with which we work, 2017 is the last year for which we have full citation data. We decided not to start our analysis before 2000 in order to have a meaningful minimum number of Chinese PCT applications. Even considering these restrictions, we can base our analysis on a long time period.

<sup>14</sup>Taiwan is excluded from the PCT system because it is not a member of the UN. Taiwanese applicants can only submit PCT applications indirectly through PCT member countries, which may involve additional administrative steps and costs compared to applicants from member countries.

First, we assess the *one-directional impact* of each invention at the patent level using ISR citations to measure the average one-directional technological impact of a country's inventions. Let  $i$  denote an individual invention, represented by a patent family, and  $K$  the set of PCT applications eligible to cite it (i.e., those with a priority date within three years of invention  $i$ 's priority date). The indicator ISR citation $_{i,k,j,j'}$  equals 1 if invention  $i$  from country  $j$  is cited by invention  $k$  from country  $j'$  within this window, and 0 otherwise, considering only non-self citations from abroad  $k \in K_{j'}$ , where  $j' \neq j$ . We omit the time dimension in the notation for brevity. The *one-directional impact* for invention  $i$  from country  $j$  is then defined as:

$$\text{One-directional impact}_{i,j} = \sum_{k \in K_{j'}, j' \neq j} \text{ISR citation}_{i,k,j,j'} \quad (1)$$

Second, we analyze each focal country's direction of *geographic impact*, assessing its impact on other countries' inventions within the PCT application universe  $K$ . To provide a complete picture, we include both foreign and domestic ISR citations  $k \in K$  for the calculation of this measure. By identifying the origin  $j'$  or  $j$  of each citing application  $k$ , we attribute citations to the focal country  $j$ , mapping the geographic distribution of ISR citations it receives. For example, for European patents, we calculate the percentage of ISR citations originating respectively from Europe, the US, China, Japan, Korea, and other countries. In equation (2) the denominator corresponds to all citations that the patents of country  $j$  receive and the nominator corresponds to the number of citations received from one of the six possible geographical origins.

$$\text{Geographic impact}_{j,j'} = \frac{\sum_{k \in K_{j,j'}} \text{ISR citation}_{i,k,j,j'}}{\sum_{k \in K} \text{ISR citation}_{i,k}} \quad (2)$$

Third, to quantify *bilateral impact*, we calculate the difference in citation counts between the focal country  $j$  and a partner country  $j'$ . Specifically, we compute the number of citations that country  $j$  receives from country  $j'$  (ISR citations $_{j,j'}$ ) and subtract the number of citations that country  $j'$  receives from country  $j$  (ISR citations $_{j',j}$ ). To ensure comparability across different country pairs, we scale this measure by the sum of the two citation counts. This metric ranges from -100 to +100, where 0 indicates reciprocal impact, positive values suggest independence from country  $j'$ , and negative values suggest dependence on country  $j'$ .

$$\text{Bilateral impact}_{j,j'} = 100 \times \frac{\text{ISR citations}_{j,j'} - \text{ISR citations}_{j',j}}{\text{ISR citations}_{j,j'} + \text{ISR citations}_{j',j}} \quad (3)$$

Furthermore, to calculate the *global impact* of a focal country  $j$ , we compute the weighted average of its bilateral impact with respect to the five other countries  $j'$ . The weights are derived from the time-variant global patent shares of partner countries  $j'$ , ensuring that countries contributing a larger share of global inventions have proportionally greater impact. This measure is also scaled between -100 and 100, where positive values indicate independence, negative values indicate dependence, and 0 represents reciprocity in global technological impact.

$$Global\ impact_j = \sum_{j' \neq j} \left( \frac{Patent\ share_{j'}}{\sum_{j' \neq j} Patent\ share_{j'}} \right) \times Bilateral\ impact_{j,j'} \quad (4)$$

The measure of *global impact* serves as our most comprehensive indicator of a country's technological impact. It captures the extent to which the inventions of a focal country receive more citations from all other countries than they provide in return. If a focal country's inventions are more frequently utilized by other countries than vice versa, it exhibits a higher degree of technological impact. Intuitively, this impact is expressed through technological relationships: a country whose inventions underpin subsequent inventions in other countries holds greater global impact.<sup>15</sup>

### 3.4 Descriptive statistics

We separate the time period 2000–2017 into three time spans of 2000–2005, 2006–2011, and 2012–2017. Table 1 presents the descriptive statistics for 1,252,148 PCT applications filed in the most recent period between 2012 and 2017. Among all applications, 10.1% received at least one and up to 68 ISR citations from other countries. Among all cited applications, the mean and median values are 1.477 and 1, respectively, indicating a right-skewed distribution, which is commonly observed for patent citation data. Citations are from up to five other countries, with mean and median values of 1.173 and 1, respectively, and from a maximum of 10 technology areas, with mean and median values of 1.098 and 1. The distribution of PCT applications by origin, in descending order, is as follows: Europe accounts for 26.3%, the US for 24.7%, Japan for 21.1%, China for 15.1%, Korea for 6.4%, and the remaining countries for 6.4%.

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<sup>15</sup>Following Griliches (1990), we acknowledge that not all inventions are patented nor are all inventions patentable. Since some crucial technologies are not patentable, our analysis may not capture the full picture of technological impact. In general, patents can be obtained for both product and process innovations (Nagaoka et al. 2010), but may be used to a lower extent for the latter. Govindaraju and Wong (2011) have shown that some countries are innovative but do not patent a lot. The authors demonstrate that local Malaysian firms engage in process technology and in product modification. These firms are building packaging and testing services for semiconductors of advanced design and have impact in global value chains. However, such an aspect of an innovative country would not be fully represented in our analysis.

Table 1: Descriptive statistics

	Mean	Median	Std. Dev.	Min.	Max.
ISR citations	0.152	0	0.653	0	68
ISR citations > 0 #	1.477	1	1.478	1	68
Citing countries	0.121	0	0.388	0	5
Citing countries > 0 #	1.173	1	0.473	1	5
Citing technology areas	0.113	0	0.352	0	10
Citing technology areas > 0 #	1.098	1	0.345	1	10
Europe (0/1)	0.263	0		0	1
US (0/1)	0.247	0		0	1
China (0/1)	0.151	0		0	1
Japan (0/1)	0.211	0		0	1
Korea (0/1)	0.064	0		0	1
Residual countries (0/1)	0.064	0		0	1

Note: PCT applications between 2012 and 2017 are observed. The number of observations is 1,252,148. #125,956 PCT applications receive > 0 citations.

Table 2 presents an overview of patent statistics by country and also by the three time spans of 2000–2005, 2006–2011, and 2012–2017. When observing the entire time period between 2000 and 2017, Europe contributed 31.1% of global PCT applications, closely followed by the US (28.0%), Japan (19.6%), China (9.0%), and Korea (5.2%). This emphasizes the traditional importance of European and US invention. However, contrasting the number of patent applications from 2000 to 2005 with those from 2012 to 2017 reveals that China’s contribution has increased 17.9-fold, while Korea and Japan experienced a 4.2- and 2.4-fold increase, respectively. In comparison, the US and European contribution increased only 1.3- and 1.4-fold. Notably, the strong rise in East Asia’s patent quantity has resulted in some decline in average ISR citations per patent: the US has the highest average overall, followed by Korea and Europe, with Japan and China coming last. Remarkably, average citations for China and Japan decreased by about a quarter or more, while those of Europe, the US, and Korea have remained stable. The average number of citing countries and technology fields follows a similar pattern, with Korea positioned in between.

Table 2: Invention characteristics by country

	Europe	US	China	Japan	Korea	Residual countries	Total
PCT applications (count)							
2000-2005	250,496	229,051	10,506	109,576	19,284	48,784	667,697
2006-2011	306,716	257,312	56,619	191,327	48,324	67,140	927,438
2012-2017	329,038	309,537	188,480	264,320	80,328	80,445	1,252,148
2000-2017	886,250	795,900	255,605	565,223	147,936	196,369	2,847,283
ISR citations (mean)							
2000-2005	0.134	0.237	0.115	0.128	0.244	0.269	0.181
2006-2011	0.120	0.219	0.103	0.101	0.218	0.238	0.156
2012-2017	0.128	0.242	0.084	0.083	0.230	0.215	0.152
2000-2017	0.127	0.233	0.090	0.098	0.228	0.236	0.160
Citing countries (mean)							
2000-2005	0.109	0.189	0.099	0.108	0.198	0.210	0.146
2006-2011	0.100	0.176	0.087	0.087	0.175	0.188	0.128
2012-2017	0.105	0.187	0.068	0.072	0.167	0.170	0.121
2000-2017	0.105	0.184	0.074	0.084	0.174	0.186	0.129
Citing technology areas (mean)							
2000-2005	0.110	0.188	0.095	0.107	0.183	0.207	0.145
2006-2011	0.098	0.168	0.079	0.084	0.157	0.183	0.123
2012-2017	0.101	0.174	0.063	0.069	0.145	0.163	0.113
2000-2017	0.102	0.176	0.068	0.082	0.153	0.181	0.124

Note: The absolute number of PCT applications and mean values of citations are displayed. Citations only consider ISR citations received from other countries.

## 4 Empirical Results

In this section, we first analyze the one-directional impact of each country's inventions at the patent level and provide a rigorous validation of this measure. Second, we examine the geographic impact for each country. Third, we calculate the bilateral impact between a specific set of two countries. Finally, we obtain each country's global impact as the average weighted bilateral impact for that country relative to the aggregate of all other countries.

### 4.1 One-directional impact

Our regression specification is depicted in Eq. (5). Let  $y_{it}$  represent patent  $i$  filed in year  $t$ . For each patent, the main outcome is the number of ISR citations received from other countries, as specified in Eq. (1). Variation in the outcome is assumed to depend on the country ( $j$ ) which the cited patent is originating from (e.g. the US, China, Japan, Korea, and residual countries), with Europe as the ref-

erence category. Additional variables that capture patent-specific heterogeneity are summarized in  $X_{it}$ . Unobserved time and technology-specific factors are controlled for through year ( $\varphi_t$ ), technology area ( $\varphi_a$ ), and year-technology area ( $\varphi_{ta}$ ) fixed effects.<sup>16</sup>  $\varepsilon_{it}$  is an i.i.d. error term with a mean of 0 and variance of  $\sigma_\varepsilon^2$ .

$$y_{it} = \alpha_0 + \gamma \sum_{j=1}^J \text{country}_j + X_{it}\beta + \varphi_t + \varphi_a + \varphi_{ta} + \varepsilon_{it} \quad (5)$$

The main parameter of interest in Eq. (5) is  $\gamma$ , which measures the average effect of a patent’s geographic origin on outcome  $y_{it}$ . In this setting, a significant  $\gamma$  would reject the null hypothesis of no correlation of patents’ geographic origin on the extent of impact of the focal patent to other countries. To broaden our analysis of impact, we also investigate two additional outcomes. First, we consider the number of citing countries to capture the spatial dimensions of impact. Second, we consider the number of citing technology areas to measure the technological diversity in a patent’s impact.

Table 3 presents our main regression results. We start by estimating Eq. (5) with the number of ISR citations as the outcome, considering the three time periods 2000–2005, 2006–2011, and 2012–2017 in columns, (1), (2), and (3), respectively. The number of ISR citations corresponds to our measure of one-directional impact in Eq. (1). In comparison to Europe, US patents receive significantly more citations. In contrast, Chinese patents are associated with fewer citations. The results for both countries remain relatively persistent over the three periods and become a bit more pronounced over time. Japanese patents initially start off similar to European ones, but weaken significantly over time. In contrast, Korean patents receive significantly more citations, albeit with some decrease over time.<sup>17</sup> The coefficient of 0.095 for the US in column (3) indicates a level of impact that is 62.5% higher than the mean of the dependent variable, which corresponds to 0.152 citations. In contrast, for China we calculate a level of impact that is 63.8% lower than the mean. The corresponding values for Japan and Korea are -26.3% and 48.7%, respectively. Thus, the average one-directional impact varies widely between countries. In column (4)–(7), we focus on the most recent time period and change the outcome to the number of citing countries and technology areas. The results reveal a similar pattern as that of the number of citations. Notably, the results also remain qualitatively robust to the inclusion of the number of citations as an additional

<sup>16</sup>The technology fixed effects control for differences between long- and short-cycle technologies (see, e.g., Lee (2024a)) in the time dimension in which citations accumulate. Within the 3-year citation window long-cycle technologies may receive fewer citations because their citations may be spread out over the longer time period during which the invention has economic value. The technology-year fixed effects control for time-variant differences in the average citation count by technology.

<sup>17</sup>Because residual countries collectively account for only 6.9% of global PCT applications, we omit them from the discussion.

control variable. This finding demonstrates that over and above receiving more citations, US patents also have a stronger impact across countries and technology areas. Overall, these results underscore that, in comparison to Europe, US and—to a lesser extent—Korean inventions, have a distinct impact through multiple channels. Conversely, the impact of China and Japan is shown to be weaker.

Table 3: One-directional impact

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Time period	2000-2005	2006-2011	2012-2017	2012-2017	2012-2017	2012-2017	2012-2017
Dependent variable	ISR citations	ISR citations	ISR citations	Citing countries	Citing countries	Citing tec. areas	Citing tec. areas
US (0/1)	0.089*** (0.002)	0.087*** (0.002)	0.095*** (0.002)	0.068*** (0.001)	0.023*** (0.001)	0.062*** (0.001)	0.024*** (0.001)
China (0/1)	-0.067*** (0.005)	-0.105*** (0.003)	-0.097*** (0.002)	-0.070*** (0.001)	-0.023*** (0.001)	-0.061*** (0.001)	-0.022*** (0.001)
Japan (0/1)	-0.003 (0.002)	-0.020*** (0.001)	-0.040*** (0.001)	-0.030*** (0.001)	-0.010*** (0.001)	-0.028*** (0.001)	-0.012*** (0.001)
Korea (0/1)	0.105*** (0.005)	0.072*** (0.003)	0.074*** (0.003)	0.044*** (0.002)	0.008*** (0.001)	0.030*** (0.002)	0.001 (0.001)
Residual countries (0/1)	0.131*** (0.003)	0.114*** (0.003)	0.085*** (0.003)	0.063*** (0.002)	0.022*** (0.001)	0.059*** (0.002)	0.025*** (0.001)
ISR citations					0.483*** (0.010)		0.402*** (0.009)
Year FE	Y	Y	Y	Y	Y	Y	Y
Technology area FE	Y	Y	Y	Y	Y	Y	Y
Year-technology area FE	Y	Y	Y	Y	Y	Y	Y
Observations	667,697	927,438	1,252,148	1,252,148	1,252,148	1,252,148	1,252,148
R-squared	0.034	0.029	0.029	0.038	0.681	0.031	0.571

Note: OLS regressions with robust standard errors in parentheses. \*\*\*p < 0.01, \*\*p < 0.05, \*p < 0.1. The reference category is “Europe (0/1)”.

We aim to estimate parameter  $\gamma$  (the relationship between a patent’s geographic origin and its impact), which is measured by the number of ISR citations received from other countries; however, bias may be introduced by omitted variables that confound origin and impact. To assess the robustness of our results, we compare our main results in column (1) of Table 4 which is identical to column (3) in Table 3, with results obtained after augmenting Eq. (5) with potential confounders. As a first step we control for the number of claims. While the average number of claims per patent may vary across countries; for instance, Japan is known to traditionally have fewer claims per patent (Goto and Motohashi 2007), the number of claims—and thus the inventive content of the patent—may positively influence the number of citations received. While a positive and significant relationship between claims and citations is confirmed in column (2), the magnitude of  $\gamma$  drops for Japan, confirming a lower average number of claims. Importantly, the baseline results remain robust. Second, we control for patenting by universities because the average number of citations received by science-oriented patents may be lower,

introducing a negative bias for countries with more patents coming from universities. Indeed, column (3) shows a negative correlation between patent applications by universities and the number of citations received; however, parameter  $\gamma$  remains virtually unchanged across countries.

Table 4: Robustness tests (2012-2017)

	(1)	(2)	(3)	(4)	(5)	(6)
	Comparison	Claims	Universities	Authority	English	All
Dependent variable	ISR citations	ISR citations	ISR citations	ISR citations	ISR citations	ISR citations
US (0/1)	0.095*** (0.002)	0.072*** (0.002)	0.096*** (0.002)	0.070*** (0.002)	0.078*** (0.002)	0.045*** (0.002)
China (0/1)	-0.097*** (0.002)	-0.072*** (0.002)	-0.096*** (0.002)	-0.044*** (0.001)	-0.065*** (0.002)	-0.014*** (0.002)
Japan (0/1)	-0.040*** (0.001)	-0.013*** (0.001)	-0.040*** (0.001)	-0.033*** (0.001)	-0.024*** (0.001)	-0.004*** (0.001)
Korea (0/1)	0.074*** (0.003)	0.093*** (0.003)	0.075*** (0.003)	0.031*** (0.003)	0.099*** (0.003)	0.058*** (0.003)
Residual countries (0/1)	0.085*** (0.003)	0.099*** (0.003)	0.086*** (0.003)	0.083*** (0.003)	0.078*** (0.003)	0.086*** (0.003)
Number of claims (log)		0.106*** (0.002)				0.087*** (0.002)
University applicant (0/1)			-0.032*** (0.002)			-0.010*** (0.002)
Chinese receiving office (0/1)				1.872*** (0.014)		1.855*** (0.014)
English full text (0/1)					0.105*** (0.001)	0.057*** (0.001)
Year FE	Y	Y	Y	Y	Y	Y
Technology area FE	Y	Y	Y	Y	Y	Y
Year-technology area FE	Y	Y	Y	Y	Y	Y
Observations	1,252,148	1,252,148	1,252,148	1,252,148	1,252,148	1,252,148
R-squared	0.029	0.037	0.029	0.213	0.033	0.219

Note: OLS regressions with robust standard errors in parentheses. \*\*\* p<0.01, \*\* p<0.05, \* p<0.1. The reference category is “Europe (0/1)”. In model (2) we include a dummy variable for missing claims information.

Next, in column (4) we control for ISR citations generated at the Chinese receiving office, which recently has become the largest ISA in terms of examined PCT patent applications (WIPO 2023). China introduced national subsidies for patenting through the PCT system in 2009.<sup>18</sup> Cost reductions from subsidies disproportionately incentivize the production of patents of marginal value and the

<sup>18</sup>In 2009 China’s Ministry of Finance introduced subsidies for PCT patenting. Applications in up to five countries are subsidized with a maximum of 100,000 RMB each (ca. 14,600 USD at an exchange rate of 31.12.2009) but more support is possible for projects involving significant innovation (Boeing and Mueller 2019).

additional citations generated by such patents may inflate the outcome variable.<sup>19</sup> By construction, our measure of one-directional impact prohibits patents receiving citations from their country of origin, but non-Chinese patents could still receive Chinese citations. Our results remain robust after including a dummy variable to control for citations of Chinese origin. In column (5), we address the concern that variation in the availability of a patent’s full text in English confounds the cited patent’s origin and the number of citations received by including a dummy variable that takes the value of 1 if the full text became available in English during the citation window. Unsurprisingly, the availability of a full text in English is associated with more citations received; however, our main results remain robust. Finally, in column (6) we include the full vector of control variables and once again obtain robust results.

## 4.2 Geographic impact

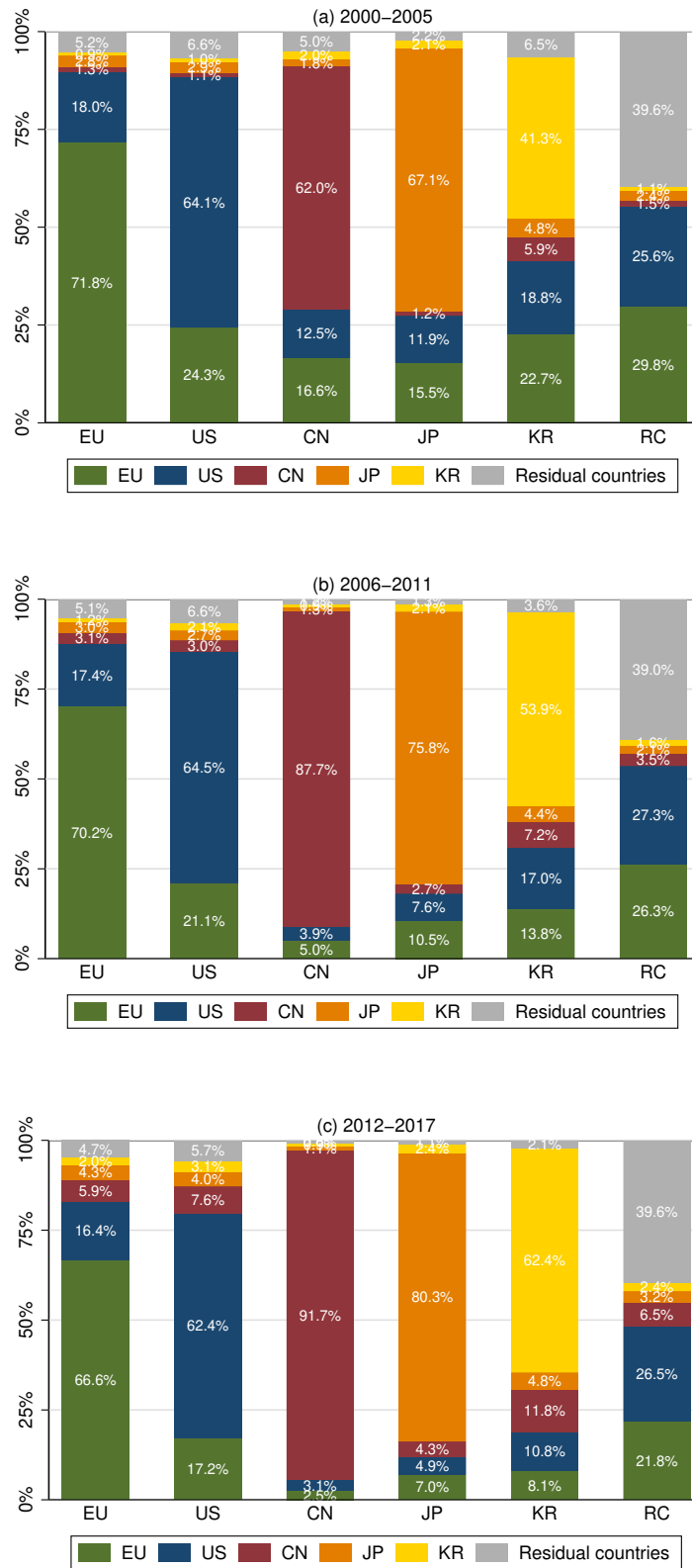
We proceed with our analysis by considering the geographic direction of impact, which allows us to assess one country’s specific impact on other countries. To analyze both the international and domestic dimensions of impact, in this section we relax our strict selection criteria and also include domestic ISR citations. Although such citations may be inflated by domestic policies, such as patent subsidies, this comparison is yet indicative of the level of take-up of domestic technology in a given country. To analyze changes over time, in Figure 6 we examine the periods 2000–2005, 2006–2011, and 2012–2017. For the early time period, Panel (a) shows PCT patents originating in Europe receive 72% of citations from within the immediate geographic area. European patents receive 18% of citations from the US, 1% from China, 3% from Japan, 1% from Korea, and 5% from residual countries. The economic implication is that European inventions are predominantly important for subsequent inventions in Europe. Despite a notable European impact on inventions in the US, the impact on other countries in the earlier years is more marginal.

Several insights stand out when focusing on Panel (c) for the time period 2012–2017. Building on self-generated inventions is critical, as demonstrated by the fact that between 62% and up to 92% of citations are of domestic origin. A notable degree of integration also occurs between Europe and the US, with 16% to 17% of citations coming from the respective partner, highlighting the depth of international cooperation. In addition, the share of citations from other countries to

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<sup>19</sup>We follow Abadie (2021) and employ a synthetic control group to assess the impact of China’s national PCT subsidies. The results show that subsidies not only increase the number of Chinese PCT applications after 2009, but also increase (decrease) the average number of domestic (foreign) non-self ISR citations received by Chinese PCT applications. This confirms that patent subsidies not only result in an disproportionate increase in the number of marginal patents, but also in an upward bias of domestic citations received by prior patents. Conversely, the reduction in foreign citations, which are independent of domestic policy, shows the expected inflation of Chinese patents.

Figure 6: Geographic impact



Note: The figure shows the geographic distribution of the origin of ISR citations received by the respective country.

Europe and the US grew from 10% and 12%, respectively, in the early time period to 17% and 20% in the late time period. The rationale for this increase is that the number of PCT applications strongly increased in East Asia; thus, these countries produced more inventions that refer to Western inventions. Overall, this illustrates that inventions from Western countries continue to exert broad international impact.

In contrast, the proportion of domestic ISR citations received in China and Japan increased to 92% and 80%, respectively. Although China's domestic ISR citations are biased upward by subsidy policy, our analysis still suggests an increasing degree of take-up of domestic technology combined with a declining international geographic impact of Chinese innovations in relative terms. In recent years, only 20% of citations in Japan and 8% in China came from abroad, compared to 38% in the US and 32% in Europe. These patterns highlight a strong domestic orientation of East Asia, with lesser impact on innovations developed elsewhere. As a noteworthy exception, Korea received 38% of its citations from abroad, confirming a stronger international geographic impact than Japan and China.

### 4.3 Bilateral impact

Technological impact positions countries heterogeneously in terms of dependence on other countries. Considering the time period 2012–2017, Table 5 presents the bilateral impact of the focal country indicated in the top row in relation to the countries noted in the column below. This measure considers both the quantity and the one-directional impact of inventions. A value of 0 indicates full reciprocity between the two countries, while an upper (lower) bound of 100 (-100) implies full independence (dependence) of the focal country in relation to the other country. For this measure, we quantify the number of ISR citations that the patents of one country obtain in one year from the other country. If the focal country obtains more citations than it gives to that country, then the focal country is deemed more independent.<sup>20</sup> For instance, a value of -22 for Europe suggests that Europe depends more on the US than the US does on Europe, whereas a value of 27 for Europe indicates that Europe depends less on China than China does on Europe. Europe's global impact has a value of -8 and indicates modest reliance on foreign innovation overall, placing the continent at a disadvantage in its global technological impact,

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<sup>20</sup>The measurement of bilateral impact is described in more detail in the Online Appendix, where the full details of our measure calculation are presented in Table A1.

except in comparison to China.<sup>21 22</sup>

Table 5: Bilateral impact (2012-2017)

	Europe	US	China	Japan	Korea	Residual countries
Europe		22	-27	16	9	6
US	-22		-48	-19	-21	-14
China	27	48		39	54	18
Japan	-16	19	-39		-11	-8
Korea	-9	21	-54	11		1
Residual countries	-6	14	-18	8	-1	
Global impact	-8	26	-37	8	3	-1

Note: Columns show the bilateral impact of the focal country with respect to the other country: 0 refers to reciprocity between two countries, 100 refers to full independence, and -100 refers to full dependence.

Notably, the US consistently shows higher levels of independence in relation to all other countries, as demonstrated by its global impact value of 26, and exhibits its strongest position in relation to China. Conversely, China has the weakest overall position, with an global impact of -37. At the country level, China exhibits significant dependence on Korea (-54), the US (-48), and Japan (-39), while its dependence on Europe is relatively lower (-27). Japan and Korea exhibit independence in relation to almost all other countries, as evidenced by a value of global impact of 8 and 3, respectively. While both countries are dependent on the US, Korea also depends on Japan.

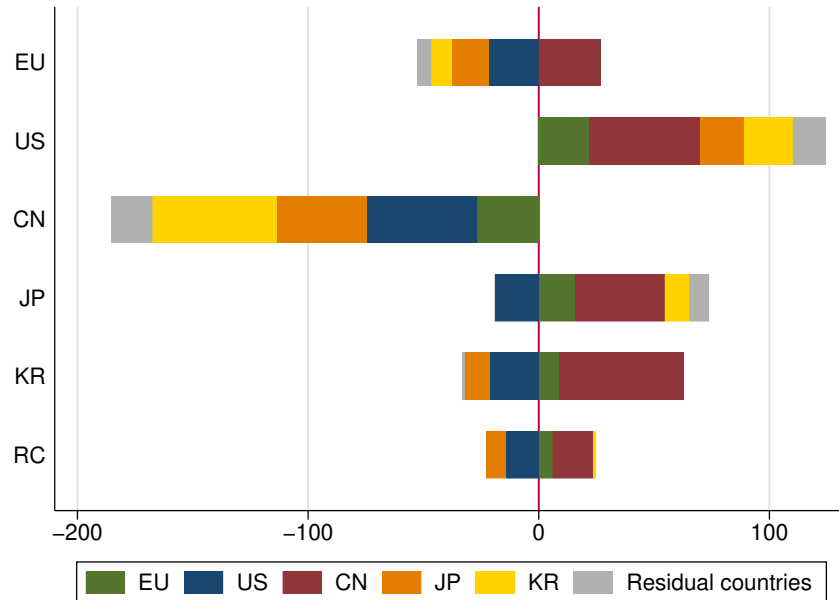
For a more comprehensive international perspective, Figure 7 illustrates the stacked bilateral impact for each country. Because we are quantifying the bilateral impact over all five partner countries, upper and lower bounds expand from 100 and -100 to 500 and -500, respectively. While Table 5 presents individual values for bilateral impact, Figure 7 allows for a more comprehensive representation, both indicating variation within and across countries. Notably, the US is the only country with consistent bilateral independence (124), while China is the only country with consistent dependence (-185). Europe (27 and -53), Japan (74 and -19), and Korea

<sup>21</sup>It can be numerically shown that our measure is not influenced by the size of a country. The intuition is that a smaller country would receive fewer citations from abroad but, because it has also fewer inventions, it would refer less often to the inventions of other countries.

<sup>22</sup>We tested whether our results are robust to the exclusion of patents with international co-applicants. On average only 7.1% of patent families entail international co-applicants in the period 2012-2017. The share ranges from 9.8% for the US to 1.8% for Korea. Our main results, see Tables 1-3 and Figure 6, remain robust if we exclude families with international co-applicants. Our calculations confirm that patents with international co-applicants have a higher one-directional impact as they receive more citations. Excluding patents with international co-applicants improves the position of Korea with respect to bilateral impact in Table 5, because the other countries lose relatively more patents with high citation counts. However, as patents with international co-applicants also belong to a country's invention base that confers technological impact, these patents are not excluded from our main calculations.

(63 and -33) have mixed accounts of stacked bilateral impact, with more moderate respective upper and lower values.

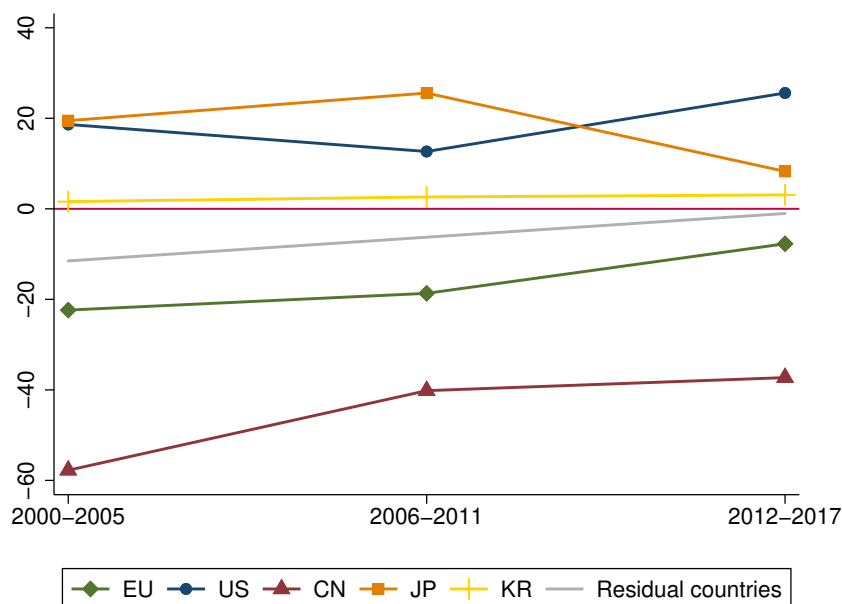
Figure 7: Stacked bilateral impact (2012-2017)



Notes: Each country's bar shows its stacked bilateral impact with respect to the other five countries. 0 refers to reciprocity, 500 refers to full independence, and -500 refers to full dependence.

Figure 8 displays each country's global impact over time. Global impact is calculated as the average weighted bilateral impact for each country with respect to all other countries. Again, a value of 0 indicates reciprocity, 100 indicates full independence, and -100 indicates full dependence. Notably, Europe and the US exhibit similar positive long-term trends. Specifically, the US fluctuates between 12.7 and 25.6, whereas Europe ranges from -22.4 to -7.7. Korea remains very stable between 1.6 and 3.1. Japan has first improved to 25.6 and then declined to 8.3. In contrast, China shows the greatest continuous increase from -57.8 to -37.3, which still positions it below other countries. In summary, the traditional innovation countries of Europe and the US have remained stable over the last two decades, considering both the impact and quantity of inventions; however, the rise of China and the recent decline of Japan are also evident. The decrease in the average impact of China's PCT applications is outweighed by increased quantity. In contrast, Japan is experiencing a decline in average impact without a sufficiently robust rise in patent quantity, leading to a decrease in its global impact. Korea accounts for the lowest number of PCT applications, however, its persistent and high rate of citations amounts to a modest but stable global impact.

Figure 8: Global impact over time (2000-2017)



Notes: Each country's global impact is displayed. 0 refers to reciprocity, 100 refers to full independence, and -100 refers to full dependence.

#### 4.4 Key enabling technologies

When analyzing technological impact, so-called key enabling technologies (KETs) may be of particular interest. These technologies have versatile applications across numerous technology fields and economic sectors, possess strong, nonsubstitutable complementarity with multiple other technologies, and have a considerable potential for performance enhancement (EFI 2022).<sup>23</sup> Therefore, we conduct an additional analysis focusing on KETs from 2012 to 2017. Empirically, we define KETs following the criteria outlined in Van de Velde et al. (2013), encompassing nanotechnology, photonics, industrial biotechnology, advanced materials, micro and nanoelectronics, and advanced manufacturing technologies.<sup>24</sup>

From 2012 to 2017, 17.8% of PCT patent applications were classified as KETs. Notable heterogeneity is evident in the share of KETs across countries. In decreasing order, Japan has 22.1%, the US 19.5%, Korea 18.4%, Europe 16.9%, and China 10.9%. Considering the one-directional impact based on average ISR citations received per patent (compare with Table 2), the US leads with a mean value of 0.257 for KETs, compared to a mean value of 0.242 for all PCT applications. The corre-

<sup>23</sup>Depending on differing comparative advantages and levels of development, countries may pursue different specialization patterns. For example, catching-up economies could transition from long-cycle to short-cycle technologies while moving up global value chains. Short-cycle technologies can provide valuable niches. As economies progress further, they can move back long-cycle technologies (Lee 2024b, 2021; Wong and Lim 2024).

<sup>24</sup>As the widespread use of artificial intelligence is still a very recent phenomenon, these patents are not considered separately.

sponding values are 0.171 and 0.128 for Europe, 0.167 and 0.230 for Korea, 0.099 and 0.084 for China, and 0.079 and 0.083 for Japan. Notably, Europe shows the highest positive difference for KETs patents (33.6%) whereas a negative difference is found for Korea (-27.4%) and Japan (-4.8%), suggesting disadvantages in these technologies. Regression analysis corroborates this finding. When we replicate our benchmark model (Table 3, column (3)) with a restriction to KETs and compare it to the original results, the more negative findings for Japan and Korea stand out. Japan's coefficient is -0.075 for KETs, while it is -0.040 for all technologies. For Korea, the coefficient for KETs turns zero and insignificant, compared to a positive and significant coefficient of 0.074 for all technologies. For the US, the respective coefficients are 0.066 and 0.095. These changes in coefficients confirm Europe's relative advantage in KETs towards the US, Japan, and Korea. Only for China we see a relative strengthening with respect to KETs with coefficients of -0.071 compared to -0.097.

The geographic impact reveals only minimal differences for KETs compared to all technologies (compare Figure 6). However, Japan and Korea substantially increase their share of own ISR citations, rising from 80.3% to 86.2% and 62.4% to 69.9%, respectively. This also suggests that these KET inventions have a lesser impact on other countries. Finally, replicating the results for bilateral and global impact restricted to KETs (compare Table 5), reveals the following notable results. Europe improves its global impact from -8 to -3, while Japan drops from 8 to -7 and Korea from 3 to -10. Japan and Korea show a lower bilateral impact in particular towards Europe (-3 for Japan, 0 for Korea) and the US (-29 for Japan, -35 for Korea). Japan's overall decline is attributable to a very low rate of foreign ISR citations, which cannot be compensated by the high absolute number of KET patents.

#### 4.5 Country and region

Technological impact is often understood as a national concept. In addition to the US, China, Japan, and Korea, we so far considered the whole of Europe as another country. In this section, we deviate from this perspective and include Germany as the single most important European country in terms of PCT patent applications. However, for measurement reasons, we also keep patents from Europe (without Germany) included, allowing for a comparison of Germany with the rest of Europe. Specifically, when counting ISR citations that build upon German inventions, we count only citations that come from outside Europe. We keep the citation measure as previously employed in the analysis but allow for a separation of European inventions into German and European but non-German. Hence, this setting

ensures direct comparability with our prior results.<sup>25</sup> Below we briefly report our findings for Germany in comparison to Europe. Between 2012 and 2017, Germany accounted for 105,923 patents, approximately one third of the 329,038 European patents. The average number of citations for a German patent is 0.077, about half of the average of 0.152 citations for the rest of Europe. The difference in citations may be due to the fact that Germany receives a significant portion of its citations from within Germany (59%) and other European countries (17%), amounting to 76% of internal citations from within Europe. The rest of Europe, on the other hand, receives 55% of its citations from other European countries and 7% from Germany, amounting to 62% of internal citations. The 14 percentage point difference in internal citations between Germany and the rest of Europe may be attributed to Germany's central geographic location in Europe as well as its high technological concentration, which conversely explains fewer citations from outside of Europe.

Following from this, Germany's global impact is about five times lower than that of the rest of Europe. Comparable to the rest of Europe though, Germany still shows bilateral independence with respect to China. The findings for Germany in comparison to the rest of Europe regarding KETs are consistent. Between 2012 and 2017, both Germany and the rest of Europe filed 16.9% of their PCT applications in KETs, resulting in Germany's patent count being approximately one third of Europe's. The average number of citations for a KET patent from the rest of Europe is 0.192, while the average number of citations for a German KET patent is 0.126, indicating a smaller relative citation gap for KET patents compared to all technologies.

#### **4.6 Global impact through international trade**

In addition to the concept of technological sovereignty, there is the related but broader concept of economic sovereignty. Crespi et al. (2021, 6) argue that technological sovereignty contributes to economic sovereignty, whereby the latter is defined as "the ability to generate value added and prosperity through independent

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<sup>25</sup>We use the same definition for ISR citations when evaluating inventions from other European countries excluding Germany. E.g., for inventions originating in France or in the Netherlands, we only count non-European ISR citations, which excludes German citations. There are potentially alternative settings that allow a separate analysis of Germany. Alternative settings could, for example, (i) allocate all remaining European countries to the residual country group or (ii) exclude all non top-five countries from the analysis altogether. However, results from these settings would not be directly comparable to our previous results. In alternative (i), Germany would receive foreign ISR citations from France, the Netherlands and other European and non-European countries. However, France, for example, would only receive German citations from the European countries but, for example, no Dutch citations. This different treatment of France and Germany seems implausible given that both countries often act in accord with the European Union. In alternative (ii), when excluding all non top-five applicant countries from the analysis, we would disregard 24.2% of PCT applications. With our chosen analysis we are able to cover all PCT applications and need only relegate 6.4% of PCT applications to the category "Residual countries", a category which isn't further analyzed.

activities or through a mutual exchange with other economies, avoiding unilateral dependencies." Technological sovereignty can support economic sovereignty, for example, by enabling the substitution of critical imports through domestic innovation, should the need arise.

Similarly to technological sovereignty, the concept of economic sovereignty also distinguishes between a domestic and an international component. In the domestic dimension, economic sovereignty is closely linked with domestic production. Goods and services produced domestically by country  $j$  can be directly used in this country and also help to reduce the reliance on imports from country  $j'$ . In the international dimension, domestic production can be supplied abroad as exports (which are imports from the perspective of country  $j'$ ), and thus determines the economic impact of country  $j$  abroad. Following our conceptual framework discussed in Section 2, we again calculate one-directional impact as a basis to evaluate the bilateral and global economic impact of country  $j$ . From the perspective of our framework, country  $j$  can be considered sufficiently sovereign if its bilateral or global dependence is balanced, i.e. mirrored by foreign dependence on imports originating in country  $j$ .

Just like technological impact is related to the supply of knowledge from country  $j$  to country  $j'$ , economic impact is related to the respective supply of goods and services.<sup>26</sup> At the broadest level, gross exports account for the total value of goods and services shipped from country  $j$  to country  $j'$ . However, this measure may be a noisy indicator of global economic impact because some of the value incorporated in gross exports originates from intermediate products imported by country  $j$  from other countries. Therefore, restricting the analysis to the volume of value added in exports could be more accurate because only the actual domestic production is considered. Thus, this measure allows to better capture the one-directional economic impact that country  $j$  has on country  $j'$ .

In order to establish an empirical measurement of economic impact, we access data for value added in exports that are embodied in the final demand of the recipient country and for gross exports from the OECD database "Trade in Value Added" (TiVA).<sup>27</sup> We observe the information for Europe, the US, China, Japan, Korea and residual countries between 2012 and 2017. The original values are in million USD at current prices. We deflate these values to 2015 prices using the US consumer price index and then calculate the average annual value over the time period 2012 to 2017. To arrive at the bilateral impact in trade, we calculate the trade flow from

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<sup>26</sup>We thank an anonymous reviewer for suggesting trade as an alternative measure for impact.

<sup>27</sup>The value added of country  $j$  embodied in the final demand of country  $j'$  corresponds to exports of country  $j$  to country  $j'$  in terms of value added. In the reverse perspective, this measure represents imports of country  $j'$  in value added terms. Our empirical measure only contains value added in final demand. This means that the import of intermediates that are not transformed within country  $j'$  into final goods are not included. In the definition of the indicator, value added in the final demand of country  $j'$  is traced back to the country of ultimate origin. This has the advantage that trade relationships from country  $j$  to country  $j'$  via third countries are included as well.

country  $j$  to country  $j'$  and subtract the trade flow from country  $j'$  to country  $j$ . Then we divide this difference by the sum of the two trade values and multiply by 100. The resulting measure is therefore scaled between 100 and -100.

Table 6 and Table 7 show the bilateral economic impact in value added in exports and gross exports, respectively, in the format of Table 5.<sup>28</sup> Interestingly, the correlation between technological impact (measured by patent citations) and economic impact (measured by trade) is negative:  $-0.34$  for value added in exports and  $-0.48$  for gross exports. In contrast, the correlation between both trade measures is  $0.95$ . This summarizes a substantial difference between the technological and economic dependence of countries. More specifically, the results in Table 6 show a positive bilateral impact of Europe on other countries, with the exception of China. Hence, the bilateral technological and economic impact work in different directions for Europe. This holds also true for the US, which shows economic dependence on all countries. China largely exhibits economic independence, and dependence only towards Korea. Japan's situation turns mostly towards dependence, except with respect to the US and Korea. Korea shows independence with respect to the US and China. Table 7 generally confirms these findings based on gross exports.

Table 6: Bilateral impact of value added in exports (2012-2017)

	Europe	US	China	Japan	Korea	Residual countries
Europe		-16	7	-6	-7	-13
US	16		35	14	18	7
China	-7	-35		-10	21	-6
Japan	6	-14	10		-7	11
Korea	7	-18	-21	7		-5
Residual countries	13	-7	6	-11	5	
Global impact	7	-18	7	-1	6	-1

Note: Columns show the bilateral impact of the focal country with respect to the other country: 0 refers to reciprocity between two countries, 100 refers to full independence, and -100 refers to full dependence.

<sup>28</sup>Details about the calculation of bilateral impact in trade can be found in the Online Appendix, specifically in Table B1 and Table B2.

Table 7: Bilateral impact of gross exports (2012-2017)

	Europe	US	China	Japan	Korea	Residual countries
Europe		-10	9	-5	-12	-11
US	10		36	12	10	6
China	-9	-36		-10	28	-4
Japan	5	-12	10		-15	9
Korea	12	-10	-28	15		1
Residual countries	11	-6	4	-9	-1	
Global impact	6	-15	6	1	2	0

Note: Columns show the bilateral impact of the focal country with respect to the other country: 0 refers to reciprocity between two countries, 100 refers to full independence, and -100 refers to full dependence.

According to both trade measures, Europe and China are leading in global economic impact, whereas the US takes the last position. Interestingly, these positions are opposite to global technological impact. In addition, note that the category ‘residual countries’ contributes a third of the value added of exports but only 6% of the patent citations. While a substantial part of the global inventive activity is highly concentrated, production is distributed across a larger set of countries.<sup>29</sup>

## 5 Discussion and Policy Implications

In the context of geoeconomic uncertainty, policymakers aim to balance economic efficiency with technological sovereignty. To achieve this, understanding both the technological impact of a country and its potential dependencies on others is crucial. In particular, domestic R&D allows to directly influence a country’s own knowledge base, while the overall technological impact of a given country is also determined by the further improvements of the knowledge bases of other countries, an aspect that is beyond the direct reach of domestic policies. To date, all countries have implemented policies that support domestic R&D activities, underscoring the importance of ensuring the efficient allocation of public funds. In Section 5.1, we first discuss our main findings that are a particularly insightful for evidence-based policy making. In Section 5.2, we go beyond the empirical results to discuss specific policy implications for each country.

<sup>29</sup>We interpret our trade measures as reflecting economic impact. We have chosen two comprehensive measures of trade that comprise all industries. Because trade typically includes goods and services that belong to the medium- and low-tech category, trade data is less related to the knowledge base of a country. We invite researchers to take up our framework for industry- or technology-specific analyses of trade data. Depending on the selection of industries, these measures could be interpreted as a reflection of technological sovereignty.

## 5.1 Discussion of results

Among globally independent countries, the US exhibits consistent bilateral independence, resulting in the strongest global independence overall. Japan is bilaterally independent of all countries except the US and also shows global independence. Korea, while bilaterally dependent on both the US and Japan, achieves moderate global independence. Among globally dependent countries, Europe is bilaterally dependent on all countries except China. China is bilaterally dependent on all countries and displays the most pronounced global dependence. Notably, all countries – except Japan – show a long-term trend of increasing global independence in recent years. Another key insight is the strong mutual relationship between the US and Europe regarding the direction of geographic impact. Despite this close integration, the US and Europe differ markedly in their respective global positions.

By comparison, East Asia – in particular China and Japan – shows an increasing internal focus over time. The results for China highlight that global leadership in patent quantity does not automatically translate into global technological impact. While China has overtaken the US, Japan, Korea, and Germany as the leading country in terms of PCT patent applications since 2019, our findings reveal China's continued dependence on all other countries. Nonetheless, China recorded the highest growth in global technological impact, albeit from a lower level. Japan's innovations are cited less frequently abroad, leading to a recent decline in its global technological impact. In contrast, Korea receives a larger share of citations from abroad than its neighbors Japan and China.

## 5.2 Policy implications

To date, all countries have implemented policies to support domestic R&D activities and, to varying degrees, to strengthen their technological impact abroad. Since the mid-2000s, China's policies have been explicitly focused on the long-term goal of reducing reliance on foreign technologies (Naughton 2021, 51). Key initiatives include the Mid- to Long-term Science and Technology Development Plan (2006–2020), Made in China 2025 (2015), and the recent 14th Five-Year Plan (2021–2025), all of which prioritize domestic invention and technological self-sufficiency. More recently, other countries have introduced similar policies, while continuing to emphasize international cooperation. For example, the US has launched the CHIPS and Science Act (2022) and the Inflation Reduction Act (2022); Japan has implemented the Integrated Innovation Strategy (2018); and Korea has pursued an Effective Strategy for Localization of Materials, Parts and Equipment (2019). The European Commission's 2024 report, *The Future of European Competitiveness – A Competitiveness Strategy for Europe*, highlights the need to invest in key technologies, reduce reliance on foreign supply chains, and foster cross-border

R&D collaboration among member states.

The global use of innovation and industrial policy underscores the importance of ensuring the effective allocation of public funds. Our analysis can support policymakers in improving allocation efficiency by enabling them to monitor their countries' bilateral and global technological impacts and make timely adjustments as needed. While the US currently maintains global technological leadership, it seems crucial for European policymakers to address Europe's global technological dependence. Europe could aim for more balanced, long-term bilateral relations with the US, Japan, and Korea while avoiding future dependency on other countries. Japan's recent decline in global technological impact parallels its economic decline — it now ranks fourth among the world's largest economies — and may be addressed by generating inventions that translate into stronger technological impact abroad.<sup>30</sup> For Korea, its relatively high levels of R&D investment may have contributed to its sustained global impact, but the question remains whether these high levels of R&D investment can be adequately maintained in the future.<sup>31</sup> Although China shows the highest long-term growth in global technological impact, its ambitions to become a global innovation leader still exhibit some discrepancy with its current bilateral and global technological dependence.

## 6 Conclusion

We develop a conceptual framework for the global technological impact of a country. A core element of this framework is netting out bilateral impact to understand the relationship between two countries. Using citations from the universe of PCT patent applications, we develop a novel empirical measure of technological impact that assesses the bilateral and global impact of a country's knowledge base. We examine the technological impact of Europe, the US, China, Japan, and Korea between 2000 and 2020.

Several directions for future research are promising. First, an important direction is studying specific technologies. Although our work starts by examining all technologies and KETs, future research may select specific technologies and examine them in detail, adding more detail on top of the average effects across technologies. Second, instead of studying global impact, analyzing technological impact within certain regions, e.g. an analysis for the individual countries of the European Union, may be insightful. Third, our approach to measuring the impact of patented inventions by using ISR citations to patents can be extended to using ISR citations to scientific publications. This will be helpful for examining the global

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<sup>30</sup>The 2023 GDP figures in current trillion USD are as follows: US (27.4), China (17.8), Germany (4.5), Japan (4.2), and Korea (1.7) (Worldbank 2024).

<sup>31</sup>Korea's R&D-to-GDP ratio of 4.9% in 2023 exceeds that of the US (3.6%), Japan (3.4%), Germany (3.1%), and China (2.6%) (Eurostat 2023).

impact of countries' basic research. Similarly, extending our analysis to measuring technological impact with non-patent indicators, such as survey evidence on process innovation, would be complementary. Finally, understanding how drivers of technological impact, e.g. domestic R&D, influence a country's global position will be helpful.

During the preparation of this work the authors used ChatGPT in order to check spelling and grammar in the text. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

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# Global Technological Impact in Cross-Country Comparison

## Online Appendix

### A Calculation of bilateral impact with citation data

Table [A1](#) contains the figures that underlie the calculation of the measure of bilateral impact as shown in Table [5](#). A value of 0 refers to reciprocity between two countries, 100 to full independence, and -100 to full dependence. The measure of bilateral impact is calculated as the total number of citations received by country  $j$  from country  $j'$  minus the total number of citations provided by country  $j$  to country  $j'$  divided by the sum of the two citation counts.

To illustrate the calculation, we provide two concrete examples. First, we explain the calculation of the value of bilateral impact of -22 that Europe (country  $j$ ) has with respect to the US (country  $j'$ ) as reported in the first entry of the first column of Table [5](#). The value of -22 marks a slight dependence of Europe on the US. The value is calculated by taking the total citations that Europe received from the US, 20,791, and subtracting the total citations that the US received from Europe, 32,384. Both values are displayed in Table [A1](#). The value of the obtained difference is -11,593. This value is divided by the sum of the respective citation counts, 20,791 plus 32,384, which equals to 53,175. The ratio of the two terms, -11,593 divided by 53,175, equals to -22%, which is the final measure of the bilateral impact of Europe on the US.

Second, when it comes to the bilateral impact of Europe with respect to China, the respective calculation is  $(7,788-4,505)/(7,788+4,505) = 27\%$ . The value of 27 can be found in the second entry of the first column of Table [5](#).

Table A1: Number of ISR citations received (2012-2017)

	Europe	US	China	Japan	Korea	Residual countries	Total
Europe	80,422	32,384	4,505	7,471	3,553	6,039	134,374
US	20,791	118,094	5,823	5,486	5,167	7,703	163,064
China	7,788	16,603	138,655	4,912	6,599	1,952	176,509
Japan	5,419	8,071	2,171	96,418	2,394	940	115,413
Korea	2,970	7,953	1,970	2,974	26,899	814	43,580
Residual countries	5,353	10,249	1,363	1,113	797	10,610	29,485
Total citations	122,776	193,433	154,567	118,380	45,416	28,073	662,425
Total citations (%)	18.5	29.2	23.3	17.9	6.9	4.2	100.0
Total patents	329,038	309,537	188,480	264,320	80,328	80,445	1,252,148
Total patents (%)	26.3	24.7	15.1	21.1	6.4	6.4	100.0

Note: The table shows the number of ISR citations received by a country, i.e. its impact. E.g., the US obtained 16,603 citations from China whereas China obtained 5,823 citations from the US.

## B Calculation of bilateral impact with trade data

The 'value added in exports' and 'gross exports' data used in this study are obtained from the 2023 edition of the OECD Trade in Value Added (TiVA) database.<sup>32</sup> Four key measures are employed: 'Domestic value added embodied in foreign final demand' (*FFD\_DVA*), 'Foreign value added embodied in domestic final demand' (*DFD\_FVA*), 'gross exports' (*EXGR*) and 'gross imports' (*IMGR*). All measures cover both goods and services and are reported in million USD in nominal terms. We use the USD CPI price index to deflate the current USD values to real values for the year 2015.

The information displayed in Table B1 provides the basis for our results shown in Table 6. To obtain the data for Table B1, we directly extract information for the indicator 'Domestic value added in foreign final demand' (*FFD\_DVA*) for the 20 pairs formed by our five individual countries for each of the years 2012-2017. We also extract information for this indicator for the 5 pairs of our individual countries with the world. This indicator covers the value added in exports that end up in the final demand of the recipient country. Because this indicator does not contain information on the flow of value added exports from the world to an individual country, we additionally extract information from the indicator 'Foreign value added in domestic final demand' (*DFD\_FVA*) covering the five individual country's imports from the world measured as value added that goes into the final demand of the five individual countries. This information corresponds accordingly to the world's value added part of exports to these five countries.

In order to calculate the residual countries' value added part of exports that

<sup>32</sup>The database is freely accessible via the following URL: <https://www.oecd.org/en/topics/sub-issues/trade-in-value-added.html>

goes to the five individual countries, which is reported in Table B1 in the column "Residual countries", we first use the world value of value added exports that goes to a focal individual country (e.g. the US) extracted from *DFD\_FVA*. We then subtract from this information the four values of value added exports that go from the other four individual countries (e.g., Europe, China, Japan, Korea) to this focal country (e.g. the US). Thus, we arrive at the information of the value added exports that go from the residual countries to the focal country (e.g. the US).

Next, in order to obtain the information for value added exports of an individual country to the category "Residual countries", which can be seen in the row "Residual countries" in Table B1, we start with an individual country's value added exports to the world taken from *FFD\_DVA* and subtract from this the value added exports of this individual country to the other four individual countries. E.g., from the value added exports of the US to the world, we subtract the value added exports of the US to the individual countries Europe, China, Japan, and Korea.

Finally, we deflate all annual nominal values to real values for the year 2015 and then average the six annual values.

Therefore, Table B1 contains the absolute volumes of value added in exports that ends up in final demand in the recipient country in real USD terms. E.g., the US had exports in value added to China amounting to USD 182,281 million.

Table B1: Value added in exports (2012-2017)

	Europe	US	China	Japan	Korea	Residual countries	Total
Europe		297,164	233,873	75,831	38,412	1,190,943	1,836,223
US	409,819		374,865	143,758	69,661	1,226,654	2,224,756
China	204,640	182,281		117,067	94,718	770,076	1,368,783
Japan	85,146	108,345	144,380		28,062	386,244	752,177
Korea	44,280	48,681	61,324	32,220		164,455	350,959
Residual countries	1,550,270	1,071,485	860,269	309,445	182,634		3,974,102
Total value added	2,294,154	1,707,956	1,674,710	678,321	413,486	3,738,373	10,507,001
Total value added (%)	21.8	16.3	15.9	6.5	3.9	35.6	100.0

Note: The table shows the value added of exports of a country that go to another country. E.g., the US has a value added of exports to China of 182,281 million USD whereas China has a value added of exports to the US of 374,865 million USD.

To obtain the data for Table B2, which is the basis for the results shown in Table 7, we proceed analogously. We directly extract the gross export data (*EXGR*) for the 20 pairs formed by our five individual countries plus for the 5 pairs of our individual countries with the world for the six years 2012-2017. Additionally, we extract the gross import data (*IMGR*) that covers the five individual country's imports from the world, which corresponds to the world's exports to these five countries.

In order to obtain the exports of the residual countries to a focal individual

country, we take the exports of the world to this focal individual country from *IMGR* and subtract the exports of the other four individual countries to the focal individual country. These latter values can be seen in Table B2 in the column "Residual countries".

Next, in order to obtain the information for gross exports from an individual country to the category residual countries as shown in the row "Residual countries" in Table B2, we use the gross exports to the world from the indicator *EXGR* of a focal individual country and subtract the gross exports of this focal individual country to the other four individual countries from this value. Finally, we deflate the nominal annual values to real values for the year 2015 and then average the six annual values.

Therefore, Table B2 contains the absolute volumes of gross exports in real USD terms. As an example, as shown in Table B2, the US had gross exports to China amounting to USD 192,700 million.

Table B2: Gross exports (2012-2017)

	Europe	US	China	Japan	Korea	Residual countries	Total
Europe		364,298	287,084	85,662	50,134	1,580,986	2,368,113
US	446,179		407,971	142,263	79,828	1,463,653	2,539,895
China	238,320	192,700		143,808	184,157	1,023,745	1,782,730
Japan	94,495	112,709	175,311		41,114	457,850	881,480
Korea	63,483	64,882	104,140	55,878		291,902	580,284
Residual countries	1,983,566	1,288,515	1,114,151	380,055	287,578		5,053,865
Total exports	2,826,044	2,023,095	2,088,657	807,625	642,811	4,818,136	13,206,367
Total exports (%)	21.4	15.3	15.8	6.1	4.9	36.5	100.0

Note: The table shows the value of gross exports of a country that go to another country. E.g., the US has a value of gross exports to China of 192,700 million USD whereas China has a value of gross exports to the US of 407,971 million USD.



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