Global Influence of Inventions and Technology Sovereignty

Elisabeth Mueller* Philipp Boeing◊

Abstract

We study the technology sovereignty of Europe, the US, China, Japan, and Korea. By examining citations from PCT patents filed from 2000-2020, we assess the bilateral and global influence of inventions. We highlight four insights. First, the US shows superior technology sovereignty through its leadership in bilateral and global influence. Second, the US and Europe are highly integrated, but their global positions differ due to Europe's bilateral dependence on all countries except China. Third, while Japan has shown a recent decline from its former leading position, Korea has maintained its global influence. Finally, although China has filed the most patents in recent years, its dependence on all other countries amounts to the highest global dependence.

Keywords: technology sovereignty, bilateral and global influence of inventions, patents and citations
JEL Codes: O33, O34

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*IESEG School of Management, Univ. Lille, CNRS, UMR 9221 - LEM - Lille Economie Management, F-59000, Lille, France; ZEW – Leibniz Centre for European Economic Research, Mannheim, Germany. E-mail: e.mueller@ieseg.fr

◊Goethe University Frankfurt, Frankfurt am Main; ZEW – Leibniz Centre for European Economic Research, Mannheim; IZA – Institute of Labor Economics, Bonn, Germany; Tsinghua University, Research Center for Technological Innovation, Beijing, China. E-mail: philipp.boeing@zew.de

1 Introduction

The global economic landscape has fundamentally shifted from the paradigm of globalization to renewed concern regarding the risks and rewards of economic interdependence. This shift has sparked critical discussion of technology sovereignty, a concept at the crossroads of geoeconomics and innovation studies. Technology sovereignty differs from national autarky or technological self-sufficiency. It refers to a country's capacity to provide essential technologies for its competitiveness and welfare, and to develop them domestically or acquire them from abroad without being unilaterally dependent on any particular country (Edler et al. 2023). Since new innovations and technological regimes develop globally, technology sovereignty and international cooperation are not antagonistic, but mutually dependent. However, if there is no reciprocal interdependence ensuring access to foreign knowledge, unilateral dependence can erode the technology sovereignty of more dependent countries.

Recent technological competition and geoeconomic disputes, particularly between China and the West (Lee 2021), have compelled policymakers to balance efficiency and risk reduction strategies. In general, countries aim to collaborate with like-minded and geoeconomically reliable partners while reducing unilateral dependence on less reliable countries. Therefore, it is increasingly necessary to provide policymakers with measures of economic influence and dependence that allow for evidence-based decision making. Because understanding the bidirectional nature of knowledge flows is essential, this requires nuanced measures to assess how countries mutually influence one another's innovations. Our study presents a novel empirical approach to measure the influence and dependence of the leading global innovators, rendering the concept of technology sovereignty empirically assessable.

From an empirical perspective, the prior literature has mainly focused on onedirectional knowledge flows, i.e. this literature has considered the extent to which a country benefits from the knowledge generated in other countries (e.g. see Eaton and Kortum (1999); Liu and Ma (2023); Melitz and Redding (2022)). To extend this literature, we measure bidirectional knowledge flows based on patent citations. In particular, we evaluate how two countries build on each other's inventions. Ensuring the comparability of the units of knowledge flow, i.e. citations, is crucial to netting out bilateral influence and accurately measuring a country's technology sovereignty. This presents an empirical challenge due to considerable heterogeneity across national data generation processes, which is evident not only for patents but also for citations.

Building on an approach that was first presented by Boeing and Mueller (2016), we ensure the comparability of the data generation process of patent applications and citations. This is achieved by restricting to patent applications filed through the World Intellectual Property Organization's (WIPO) Patent Cooperation Treaty (PCT), and citations generated in the corresponding international search reports (ISRs) during the international phase of PCT applications. In measuring influence, we consider only nonself-citations from foreign countries and are interested in the extent to which inventions in one country provide the basis for inventions in other countries. This approach also ensures that our measure is unbiased and independent of potential distortions through domestic policy.

We contribute to the existing literature by introducing empirical measures of technology sovereignty. Our analysis is based on the entire universe of global PCT filings between 2000 and 2020. In line with the focus of our study, we initially allocate all applications to one of the top five global innovators, i.e. Europe, the United States (US), China, Japan, and Korea, along with a residual category (covering the residual countries). Subsequently, we compute the number of citations that a country obtains from another country – and vice versa.[1] In our empirical analysis, we examine three important aspects. First, we analyze the strength of influence at the patent level for each country, and provide rigorous validation of our measure. Second, we explore the geographic direction of influence and how it changes over time. Third, to calculate bilateral influence, we add up all inventions from a country during a specific time frame and determine if the focal country shows either independence or dependence with regard to the other country. Finally, we compute global influence as the average bilateral influence for each country and again analyze changes over time.

Throughout our findings, it is clear that the US has maintained its influential position as the world's technological superpower. Not only does the US possess the strongest global influence, but it also exceeds all other countries in its respective bilateral relationships, thereby establishing remarkable technology sovereignty. Nevertheless, this conclusion is far from obvious when looking at simple patent counts. Since 2019, China surpassed the leading US, Japan, Korea, and Germany in PCT patent applications, making it the top-ranking country. However, based on our analysis, China's innovation policy emphasizing quantitative patent targets, in conjunction with industrial and R&D policies and periodic moonshot projects, has not yet resulted in inventions with overwhelming global influence. On the contrary, although China shows the greatest increase in global influence, our research reveals that China remains dependent on all other countries. This dependence is evident on average across all technologies, as well as when considering specifically future-oriented key enabling technologies (KETs).

[1] The term "country" refers to (i) Europe, (ii) the United States, (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 topics of their member countries. One well-known example is the Horizon Europe research program and its predecessors (European Commission 2024). In this study, Europe includes 30 countries: the EU-27 plus Norway, Switzerland, and the United Kingdom – which was an EU member country until January 2020.

Another important insight is the strong integration between the US and Europe. In contrast to the West, East Asian countries rather show a growing internal focus over time. This is the case not only in China, where innovation policy is explicitly aimed at reducing foreign dependence, but also in Japan and—to a lesser extend—in Korea. Strikingly, Japan has witnessed a recent decrease in its global influence, despite previously holding the highest position, thus making Japan the only country exhibiting a recent downward trend. In contrast, Europe, the US, and China are able to improve their positions while Korea has maintained a stable position over time. The cases of China (for all PCT applications) as well as Japan (for KET PCT applications) also show that leadership in application numbers does not necessarily equate to a higher technological influence. For example, while Europe files a relatively lower quantity of PCT applications in KETs, its respective influence is actually stronger than in overall technologies.

There are various considerations relevant to policymakers. While Western countries remain stable and integrated amidst a changing global geoeconomic landscape, the US and Europe differ considerably in their respective positions. The US has achieved outstanding technology sovereignty, whereas Europe is dependent on all countries except China. In terms of innovation policy, it is desirable for Europe to cooperate with technology leaders such as the US, Japan and Korea and yet reduce dependencies. Policymakers should focus on promoting KETs, as Europe has already gained advantages in these technology areas. At the same time, Europe should avoid a future dependence on Chinese innovations given the current geoeconomic environment.

Although Japan carries significant global influence and depends solely on the US, the country has recently experienced a gradual decline, albeit from a high level. While Japan has made significant contributions to global innovation for several decades, and is also heavily involved in future-oriented innovations related to KETs, this inventive activity has not been adequately translated into international influence. Inventions from Japan receive fewer foreign citations over time, not just from fewer countries and technology areas, resulting in a decline in their overall influence. It is crucial for policymakers to address this downward trend. Korea, on the other hand, has the lowest number of PCT applications among the leading innovation countries, but its patents receive the second highest average number of citations. Overall, this amounts to a modest but stable global influence, consistent with its bilateral independence from China and Europe. Finally, Chinese policymakers face a challenging situation. Due to systemic rivalry, other countries are seeking long-term technology sovereignty that goes beyond recent de-risking strategies in commodity trade and foreign direct investment. However, such circumstances pose a challenge for China, as it has made significant progress in both the number and influence of inventions, but remains more dependent on other countries than vice versa.

The paper proceeds as follows. Section 2 reviews the literature on technology sovereignty, patent citations, and measures of influence. Section 3 introduces our data and measurement. Section 4 presents the empirical results, while section 5 discusses policy implications. Section 6 concludes.

2 Literature

2.1 Technology sovereignty

In recent years, the global economic order has undergone a fundamental transformation. The paradigm of globalization has given way to new perspectives regarding the risks and benefits of economic interdependence. The world is shifting away from a market-based regime in which economic integration was seen as an end in itself to one in which strategic actors exploit economic openness and vulnerabilities to pursue independent geopolitical objectives. In response, governments are attempting to make their economies more resilient. Policymakers increasingly require measures of economic impact and dependency to make informed, evidence-based decisions. Located at the intersection of geoeconomics and innovation studies, the concept of technology sovereignty has received considerable attention; however, empirical measures related to technology sovereignty are urgently needed to advance such evidence-based policymaking.

According to March and Schieferdecker (2023), technology sovereignty is distinct from national autarky or technological self-sufficiency. The authors define technology sovereignty as a country's capability to self-determine the development and use of technologies and innovations that affect its political and economic sovereignty. Similarly, Edler et al. (2023) define technology sovereignty as the capability to offer the necessary technologies for the competitiveness and welfare of a country and to develop or acquire them from other countries without being unilaterally dependent on a particular source.

Hence, access to the outcomes of research and development (R&D) that is conducted domestically and internationally has a crucial role in establishing technology sovereignty. Since new innovations and technological regimes develop globally, technology sovereignty and international cooperation are not antagonistic, but mutually dependent. As documented in Griffith et al. (2004), domestic R&D serves at least two functions from this perspective. First, it facilitates the identification and adoption of R&D outcomes from international sources, which is also referred to as absorptive capacity (Cohen and Levinthal 1989). Second, it is essential for generating research outcomes that other international actors can use and build upon. Overall, domestic R&D is crucial for benefiting from international knowledge and avoiding unilateral dependence.

Within the concept of technology sovereignty, so-called key enabling technologies (KETs) play a crucial role in contributing to economic growth and development while also promoting dynamic application of other technologies. KETs exhibit three defining features (Commission of Experts for Research and Innovation (EFI) 2022). (1) They have various applications in different technological fields and economic sectors. (2) They exhibit strong, non-substitutable complementarity with multiple other technologies. (3) Both the KET itself and its application areas have a high potential for performance enhancement. Interpreted from a global perspective, economies could specialize in specific KET areas and develop comparative advantages over other economies. This portfolio perspective suggests that economies may specialize in certain KETs, leading to mutual dependence on one another, which makes unilateral dependence less probable. From a development perspective, economies that are catching up may benefit more from pursuing long-term rather than short-term innovation strategies (Lee 2021). For example, such economies can focus on certain KETs that require more substantial upfront investments but will enhance comparative advantage and technology sovereignty in the future. This approach still emphasizes the importance of global integration, which significantly differs from technological self-sufficiency strategies.

However, in the absence of reciprocal interdependence ensuring access to foreign knowledge, unilateral structural dependence can erode the more dependent country's technology sovereignty; therefore, a country's strategic placement between complete global integration and national self-sufficiency is crucial to defining the limits of reliance and autonomy (Eaton and Kortum 1999). Recent technological competition and geoeconomic disputes, particularly between the US and China, but also between Europe and China, compelled a balancing act between prioritizing efficiency and implementing risk mitigation strategies, which could also necessitate the development of domestic redundancy. Overall, policymakers are now attempting to transition collaborations toward like-minded and geoeconomically reliable partners, while seeking to reduce unilateral dependence on less reliable countries. At the global level, this involves navigating technological influence and dependence among countries and regions (Van der Pol and Virapin 2022).

Notably, technology sovereignty is distinct from the interdependencies between countries that can be observed through commodity trade; for example, when considering global value chains (Felbermayr et al. 2023). The flow of commodities represents trade in semi-finished or finished products, whereas the production of knowledge precedes that of commodities and is often an early determinant of subsequent product specialization. Against this background, we are particularly interested in examining the degree to which the knowledge of one country is taken up elsewhere. In this sense, both phenomena are related but distinct. For instance, Gong et al. (2023) investigate the patenting and exporting activities of Chinese firms in the US, determining that the first US patent grant has a positive impact on the Chinese companies' subsequent export performance, demonstrating that knowledge creation and the protection of inventions precede the production and shipment of goods. Similarly, Liu and Ma (2023) measure the correlation between knowledge flows and input-output production networks across industries in 40 countries, revealing these activities are only moderately correlated. Specifically, knowledge spillover from upstream industries is more influential than that from within a given industry or this industy's international commodity trade to advance innovation in the focal industry. Han et al. (2023) show that domestic upstream innovation is important for counteracting negative sanction-induced shocks to a downstream industry because it is possible to substitute the required intermediates through domestic production. In general, upstream innovation capacity is crucial for mitigating downstream geoeconomic risks. It follows that KETs, which are often in upstream sectors, are of considerable strategic importance.

Our work is also related to the previous literature on knowledge spillovers. This literature attests to the longstanding acknowledgment that inventions do not just take place within national boundaries but are dependent on knowledge flow from abroad. Prior research shows that such knowledge spillovers can directly affect countries' productivity and output growth (Melitz and Redding 2022). Whereas the literature on knowledge spillover concerns access to international knowledge and its economic consequences, our study is interested in measuring the influence that the inventions of one country have on other countries. From an empirical perspective, previous research on knowledge spillovers primarily focuses on onedirectional knowledge flows, only considering the extent to which one country benefits from the knowledge generated by other countries. More specifically, a country's patent citations of inventions from another country are a measure of the latter country's technological influence in the first country (Aghion et al. 2023). We extend this approach by measuring knowledge flows as bidirectional by examining patent citations to measure how a pair of countries builds on one another's inventions. Importantly, ensuring comparability between the units of knowledge flow (citations) is crucial for determining bilateral dependence and accurately measuring countries' technology sovereignty. This endeavor poses an empirical challenge due to considerable heterogeneity across national data-generating processes, which is true for patents and citations. The next section elaborates on the issues surrounding the use of citations in cross-country analyses and our approach to addressing them.

2.2 Citation-based measures

Forward citations of a published patent are a well-established measure of the cumulative nature of inventions (Jaffe et al. 1993). This measure is observable since subsequently filed patents refer to prior art (Higham et al. 2021). As such, forward citations are an appropriate measure for the global influence of inventions, and are often used to measure economic value (Harhoff et al. 1999; Lanjouw and Schankerman 2004). Gambardella et al. (2008) show that forward citations have a closer relationship to patents' actual economic value than references, claims, or family size. Moreover, variation in forward citations is used to account for other margins of patent heterogeneity; see the survey by Jaffe and De Rassenfosse (2017), including technical value (Trajtenberg 1990) and technological influence (Corredoira and Banerjee 2015). Recent studies also use citations in network settings, going beyond measuring knowledge flow between two patents. For example, citations are used to examine the diffusion of knowledge (Rosell and Agrawal 2009) or to determine centrality of specific patents (Funk and Owen-Smith 2017; Park et al. 2023). Nevertheless, working with citation data is 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 economic phenomena. To address these challenges, Kuhn et al. (2020) recommend selecting appropriate patent and citation types and employing a fixed effects approach to control for remaining differences (e.g., across technology areas and time) in the patenting process.

A well-known challenge to using forward citations is their application to cross-country comparisons. This is because heterogeneity across the legal frameworks of national patent examination leads to significant variation in forward citations generated across patent offices. For a set of triadic patent families following national standards, Michel and Bettels (2001) show that the US Patent and Trademark Office (USPTO) applies three-times more patent references than the European Patent Office (EPO) and patent examiners are more likely to cite domestic patents, which is also known as "home bias" (Bacchiocchi and Montobbio 2010). Thus, naïve comparisons of international citation measures across (and within) countries may be biased. When examining international knowledge flows, some studies have avoided citations and instead relied on counting patent applications by foreign applicants (Eaton and Kortum 1999) or international co-applicants (De Rassenfosse and Seliger 2020).

Although foreign filings tend to be a positive and more homogeneous selection compared with domestic filings because it is more costly to file in more than one patent office, considerable heterogeneity remains within selected samples. To address this issue, several studies have used forward citations while attempting to control for potential differences in the data-generating process. A typical approach restricts the data-generating process of citations to a single patent office. For example, the studies by Lee and Yoon (2010) and Wu and Mathews (2012) compare forward citations received by USPTO applications filed by applicants from the US, Japan, Korea, and Taiwan. While focusing on a single patent office can increase the comparability of the citations generated, allocation of these citations may still be subject to the aforementioned home bias, favoring US patents, while those of other countries represent a positive selection. A second limitation of this approach is its narrow focus on patenting in one country, which limits its global relevance (De Rassenfosse et al. 2014).

Another set of studies investigating international knowledge flows increases the number of analyzed countries but faces the limitation of differing data-generating processes for patents and citations across countries.[2] Examining 40 major countries between 1976 and 2020, Liu and Ma (2023) investigate whether patents filed in a given country cite other patents filed in that country or abroad. Patents are either assigned by the country of inventors, applicants, or patent office (in that order). As an invention can generate patent applications in more than one country, all related patents are grouped by patent family and the information is attributed to the priority application. Eugster et al. (2022) introduce further refinements by only selecting patent families with a minimum of two national applications, for which the country is identified according to the address of the first inventor, and excluding self-citations between patents with the same inventors.[3] The citation window, referring to the time period in which a cited patent can receive citations from a citing patent, is set to four years after the publication of the cited patent.[4] While excluding most recent years from the analysis due to truncation issues, this practice ensures comparability between patents filed at different points in time.

The rise of China has significantly contributed to global patenting activities; however, numerous pro-patent policies have also led to an increase in marginal patents and related citations. While China is globally leading in terms of patent output in both national applications by residents and PCT applications since 2011 and 2019 (WIPO 2023), respectively, in 2020 Chinese examiners were handling 47% more patents than examiners in the US and 136% more than those in Europe

[2]A well-documented historical example is Japan's single-claim patent before 1989 (Goto and Motohashi 2007). Although the introduction of multiclaim patents and more stringent selection criteria in patent applications reduced the number of patents (Motohashi 2004), ceteris paribus, such patterns may have some persistence over time. Additional differences between patent offices include divergent rules for applicant citations. Whereas in the US the applicant needs to provide references to all relevant prior art that they are aware of, the EPO requires only the examiner and not the applicant to provide references to prior art (Michel and Bettels 2001).

[3]Self-citations account for about 10% of citations received (Higham et al. 2021). The exclusion of self-citations is a common practice because larger firms typically have more patents from which to potentially cite their own prior art. To address this concern, it is instrumental to define self-citations at the applicant level rather than the inventor level.

[4]Previous research shows that patents reach the highest probability of citation around three years after publication (Hall et al. 2005).

(Branstetter et al. 2023; Yin and Sun 2023). Excessive workload, reduced examination time, and low salaries for examiners[5] can potentially degrade the quality of examinations, subsequently introducing measurement error regarding the citations made by such patents (Branstetter et al. 2023).

Citation data from China's patent office have only recently become available; however, national patenting targets (Sun et al. 2021), subsidies (Branstetter et al. 2023), and tax cuts (Wei et al. 2023) have all contributed to distorted patenting activities, which makes the interpretation of citations emanating from the Chinese patent office more difficult. Several studies substantiate this concern by relating citations to economic measures. For example, Yin and Sun (2023) show that forward citations 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 patent citations and firms' total factor productivity after restricting their sample to patents that incurred higher filing costs because they exceeded the threshold of 10 claims. Boeing and Mueller (2019) restrict their analysis to citations generated by ISRs of PCT applications. Investigating the correlation between R&D expenditure and citation-weighted patents, the authors find that only foreign citations, but not domestic and self-citations (which may be partially policy-driven), have a significant and positive relationship with R&D stocks in China. Referencing Germany as a country without domestic policy support for patenting, they show that all three citation measures have the expected positive correlation with R&D inputs. Taking a broader international perspective, Schmoch and Gehrke (2022) compare non-Chinese and Chinese PCT applications and demonstrate that subsequent to the international phase, 79% of non-Chinese applications are transferred to the national phase (in patent families with three or more national applications), whereas the corresponding rate for China is only 66%. This indicates lower average patent value, which is associated with China's subsidies and targets related to PCT applications.

Despite heterogeneity in the data-generating process of forward citations across national patent offices, some studies use forward citations in international comparison. Han et al. (2023) observe patents filed in the US that cite patents filed in China and vice versa, to measure decoupling and dependence. Bergeaud and Verluise (2022) divide global patenting activity into five geographic areas to investigate the rise of China in terms of six frontier technologies. In the most conservative analytical setting, they observe forward citations originating in PCT applications and received by the top 10% most cited (overall) patents in each technology, year, and country. While citations from PCT applications are a more homogeneous set, the mixture of citations generated in the international and subsequent national phase of the PCT process still introduces heterogeneity. Furthermore, the selection of

[5] Anecdotal evidence implies a monthly salary of around 10,000 RMB, which is equivalent to USD 1,600 (Branstetter et al. 2023).

cited patents is endogenous to the citation intensity of national processes.

To provide a rigorous assessment regarding the quality and global influence of inventions, analyses must consider differences in examination rules and types of patents filed. We follow Boeing and Mueller (2016) by including these aspects as, to the best of our knowledge, their approach provides the most rigorous setting for cross-country comparison of patent quality. The authors only examine PCT applications, which can make references or receive forward citation, and restrict such references (generated by ISRs) to foreign origin (i.e., the citing patent is abroad, while the cited patent is domestic), which also avoids potential upward bias in citations due to domestic policies.

2.3 Measures of influence

The global influence of countries can be measured in several ways. In this section, we first review literature that compares countries' innovative performance based on patent indicators. We then examine the bilateral influence between countries, as observed through patents and scientific publications, and finally consider the influence of policy on such relationships. At the most basic level, researchers have been interested in raw patent counts to measure influence. Traditionally, the US and Europe were the most significant patent applicants; however, they lost their leading position to East Asian countries in more recent years. In 2020, China filed 16.1% of global PCT applications (WIPO 2023), making it the world leader in patenting, followed by the US, Japan, Korea, and Germany. However, a simple comparison of patent counts, even if adjusted by conventional measures of patent quality, will most likely be misleading due to substantial heterogeneity across patents.

Addressing the concern of international comparability, Boeing and Mueller (2016) use foreign ISR citations, which are independent from domestic policy, to investigate the technological capacity of the top-five innovative countries. Technological capacity is measured as annual patent counts weighted by average quality. The authors' analysis covering 2001 to 2009 shows that the US is leading in overall technological capacity, followed by Japan, Germany, and Korea, while China takes the last position.

Analyzing more recent patent data up to 2019, Breitinger et al. (2020) identify the top 10% patents in force for 58 forward-looking technology areas, which is measured by family size and forward citations. After attributing patents to countries according to inventor addresses, the findings demonstrate the dominant position of the US while also highlighting growing patenting activities in East Asia, notably China, in recent years. The US leads in 50 of the 58 technologies evaluated in the study. In contrast, European countries appear to be lagging behind, leading in only two technology areas of wind energy and functional foods. However, the results also highlight the inventiveness and dynamism of East Asia, which has surpassed the US in some areas and is closing the gap in others. China has gained considerable momentum in recent years and is advancing more rapidly than the US and Europe in almost all sectors. Additionally, countries outside of the three leading innovation regions find it challenging to obtain a significant role.

Using an alternative approach, Bergeaud and Verluise (2022) measure countries' global influence based on the number of patent applications, forward citations, and the radicalness inferred from patents' semantic content. Focusing on six frontier technologies from 1974 to 2019, the authors observe that the US maintains a relatively high position in all technologies when considering the quantity of applications, while Europe's significance is limited to fewer technologies. The steady growth of China's influence is also confirmed, while the proportion of Japanese patents drops to a lower level by 2019, indicating Japan's declining significance as an innovation hub (Criscuolo and Timmis 2018; Ito et al. 2019). Notably, Bergeaud and Verluise (2022) confirm that Chinese patents are of inferior quality compared with European, US, and Japanese counterparts. Nonetheless, this gap is narrowing over time. In general, the patenting activities in frontier technologies are increasingly polarized between the US and China as the main players.

Other studies investigate the bilateral influence between countries. Cerdeiro et al. (2021) analyze the impact of global knowledge flows on countries' economic performance from 2000 to 2013. For China and other countries, the primary sources of knowledge spillovers are the US and Japan, to a lesser extent. China's contribution to other countries is substantial and exceeds that of the traditional technological leaders in Europe. All countries, including the US, appear to have increasingly benefited from China's innovation drive. Han et al. (2023) examine the bilateral relationship between the US and China, developing measures for technology decoupling and dependence. The authors reveal a consistent rise in technological integration (as opposed to decoupling), with China's reliance on the US increasing in the first decade and subsequently reducing in the second decade of the millennium.

A related literature examines global influence through scientific publications. According to the Nature Index 2023, China has overtaken the US for the first time in the natural sciences, which include the physical sciences, chemistry, earth and environmental sciences, and biological sciences (Nature 2023). The metric considers each author's share of articles published in 82 scientific journals between 2015 and 2022. However, recent studies provide a more nuanced picture of China's scientific prowess. Qiu et al. (2022) demonstrate that the high impact of US-based research on Chinese scientific publications persists. Nonetheless, Chinese scientists working in China and abroad are now significant contributors to the global knowledge frontier; however, cross-border frictions to knowledge spillovers persist in both directions. For example, Qiu et al. (2022) show that even after controlling for the quality of Chinese research, articles by Chinese principle investigators receive 28% fewer citations from US researchers. Xie and Freeman (2021) find that Chinese researchers abroad can alleviate such frictions, determining that an article from a diaspora author is more likely to cite China-addressed papers than non-China-addressed articles without a diaspora author. Similarly, China-addressed articles are more likely to cite non-China-addressed papers with a diaspora author than non-China articles without a diaspora author.

Policymakers who are conscious of the need to strengthen technology sovereignty also implement measures to impede the free flow of ideas by restricting scientific collaborations. For example, the 2018 China Initiative in the US is a recent illustration of restrictions implemented on scientific cooperation between US and Chinese inventors. Aghion et al. (2023) find a negative effect of the initiative on average publication quality and US coauthors of Chinese researchers with prior US collaborations. Furthermore, this negative effect is stronger for Chinese researchers with higher research productivity and those who worked in US-dominated fields and/or topics prior to the policy shock. Interestingly, the policy impact goes beyond direct effects on the US and China, as European researchers have become more attractive as coauthors for Chinese researchers, whereas researchers in the US have suffered from policy intervention. Jia et al. (2023) find that the research conducted since the China Initiative coincides with a decline in the productivity of US scientists with previous collaborations with scientists in China relative to those with international collaborators outside of China, particularly when considering the impact of publications (proxied by citations).

In summary, the literature underscores the enduring role of the US as a global knowledge source as well as China's ascent as a substantial knowledge contributor and user. However, the intensifying competition between these two major powers also has implications for research in other regions, in terms of innovation activities and the degree to which countries bilaterally influence one another. In addition, more research is needed to investigate how these factors impact countries' technology sovereignty. In the next section, we describe how this study measures the global influence of countries and their respective technology sovereignty.

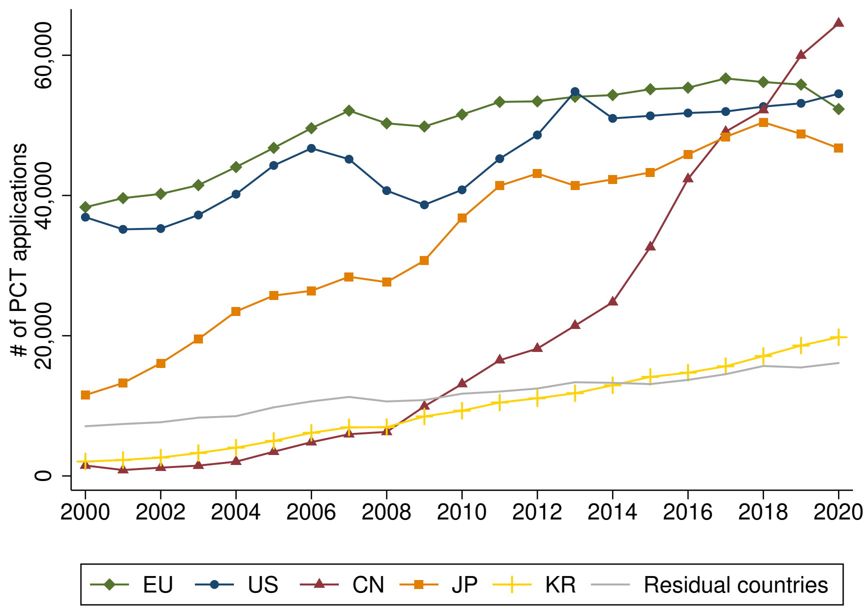
3 Data and Measurement

3.1 The PCT system

The PCT system, which is administered by United Nations' (UN) WIPO, allows applicants to simultaneously protect intellectual property in up to 157 countries. Figure 1 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

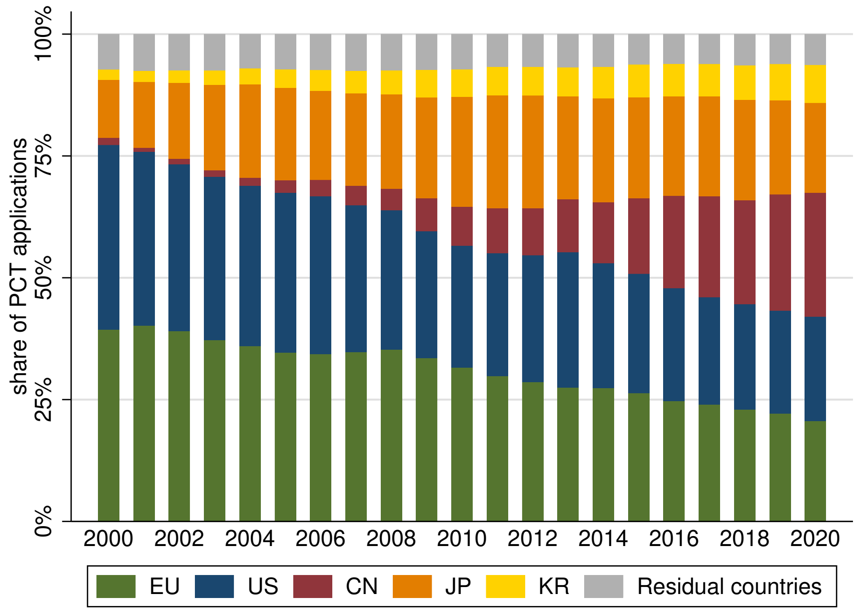
2020. Specifically, this growth is largely influenced by East Asian countries, particularly China, Japan, and Korea, in comparison to Western countries such as the US and European nations. China has been the number one ranked PCT applicant country since 2019, surpassing the US, Japan, Korea, and Germany. The shift in innovation activity from the West to the East is also reflected in Figure 2. In 2000, more than three-quarters of PCT applications originated from the US and Europe; however, Western dominance 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 1: Number of PCT applications by countries



Under the PCT system, prior art searches are conducted within 30 months of filing the application during the international search phase. 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 influence 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.

Figure 2: Share of PCT applications by countries



The selected references measure the technical and legal relationships among patents and are the appropriate measures of an invention's influence 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 China National Intellectual Property Administration (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 deciding to grant a patent. 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 they are not originally published in English, PCT applications are easily identifiable as potentially relevant prior art. 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.

3.2 Measurement

Following Boeing and Mueller (2016), we ensure comparability in the data-generating process of 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 global influence 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 ensures independence from potential bias through domestic policy. The priority year indicates the year in which the first patent application for a given invention was filed, regardless of the chosen patent office. 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. 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 and a high degree of timeliness.

We contribute to the literature by constructing empirical measures of technology sovereignty that are calculated based on PCT filings with priority years between 2000 and 2017 (the inclusion of more recent years would introduce truncation to our citation measure). 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).[6] We also identify the main technology areas of each application based on its main International Patent Classification (there are 35 classes). We then quantify the number of citations a country receives from another country and vice versa. Our empirical analysis focuses on three aspects.

First, we analyze the strength of influence at the patent level, where i is the index for an individual invention as represented by a patent family and K is the universe of PCT applications that can potentially cite (i.e., the PCT applications that have a priority date within the 3-year time period following the priority date of the individual invention of interest). The indicator function ISR cites$_{ik}$ equals one if application i is cited by application k within the defined time window and zero otherwise. This indicator function only considers nonself-citations received from applications from outside the own national borders. Stated differently, all domestic citations are excluded.

$$\text{ISR citations}_{\,i} = \sum_{k=1}^{K} \text{ISR cites}_{\,ik} \tag{1}$$

Second, we explore the geographic direction of influence and how it changes over time. This allows us to assess how important the influence of a focal country is for other countries' inventions that contribute to the universe of PCT applications K. Hence, we observe the country that the citing application k is originating from and attribute the citation accordingly to the inventions of the focal country. For example, a US patent is receiving a citation from China.

Third, to quantify bilateral influence, we sum all inventions in a country in a given time period (2012–2017), excluding the time period subscript to simplify the notation. *Bilateral influence*$_{LJ}$ denotes the bilateral influence that country L has with respect to country J. $L(J)$ represents the set of applications in country $L(J)$ in the given time period. In this way, we can determine whether bilateral influence is reciprocal or skewed toward independence or dependence in the focal country.

$$\text{Bilateral influence}_{\,LJ} = \sum_{l=1}^{L} \text{ISR citations}_{\,l} - \sum_{j=1}^{J} \text{ISR citations}_{\,j} \tag{2}$$

3.3 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

[6] Taiwan is excluded 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.

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%.

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 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 total patent applications from 2000 to 2005 with those from 2012 to 2017 reveals that China's contribution has increased by a remarkable 1,693.5%, while Korea and Japan experienced an increase of 316.6% and 141.2%, respectively. In comparison, the US and Europe increased by only 35.1% and 31.4%. 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 have reduced 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 strength of each county's influence at the patent level and provide a rigorous validation of our measure. Second, we examine the geographic direction of each country's influence. Third, we calculate the bilateral influence between a specific set of two countries. Finally, we obtain each country's global influence as the average weighted bilateral influence for that country relative to the aggregate of all other countries.

4.1 Influence of countries

We proceed to present our regression specification, depicted in Eq. (3). 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). Variations in the outcome are assumed to depend on the country (k) which the cited patent is originating from (e.g. the US, China, Japan, Korea, and residual countries), with Europe as the reference category. Additional variables that capture patent-specific heterogeneity are summarized in X_{it}. Unobserved time and technology-specific factors are controlled for through year (φ_t), technology area (φ_a), and year-technology area (φ_{ta}) fixed effects. ε_{it} is an i.i.d. error term with a mean of 0 and variance of σ_ϵ^2.

$$y_{it} = \alpha_0 + \gamma \sum_{k=1}^{K} \text{country}_k + X_{it}\beta + \varphi_t + \varphi_a + \varphi_{ta} + \varepsilon_{it} \tag{3}$$

The main parameter of interest in Eq. (3) is γ, which measures the average effect of a patent's geographic origin on outcome y_{it} (i.e. the number of ISR citations received from other countries over a three-year period). In this setting, a significant γ would reject the null hypothesis of no correlation of patents' geographic origin on the extent of influence of the focal patent to other countries. To broaden our analysis of influence, we also investigate two additional margins for each patent. First, we consider the number of citing countries to capture the spatial dimensions of influence. Second, we consider the number of citing technology areas to measure patents' general relevance across the full range of 35 technology areas.

Table 3 presents our main regression results. We start by estimating Eq. (3) 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. 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.[7] The coefficient of 0.095 for the US in column (3) indicates a level of influence 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 influence 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 strength of influence 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 control variable. This finding demonstrates that over and above receiving more citations,

[7] Because residual countries collectively account for only 6.9% of global PCT applications, we omit them from the discussion.

US patents also have a stronger influence 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 influence through multiple channels. Conversely, the influence of China and Japan is shown to be weaker.

Table 3: Influence of countries

	(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***	0.087***	0.095***	0.068***	0.023***	0.062***	0.024***
	(0.002)	(0.002)	(0.002)	(0.001)	(0.001)	(0.001)	(0.001)
China (0/1)	−0.067***	−0.105***	−0.097***	−0.070***	−0.023***	−0.061***	−0.022***
	(0.005)	(0.003)	(0.002)	(0.001)	(0.001)	(0.001)	(0.001)
Japan (0/1)	−0.003	−0.020***	−0.040***	−0.030***	−0.010***	−0.028***	−0.012***
	(0.002)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Korea (0/1)	0.105***	0.072***	0.074***	0.044***	0.008***	0.030***	0.001
	(0.005)	(0.003)	(0.003)	(0.002)	(0.001)	(0.002)	(0.001)
Residual countries (0/1)	0.131***	0.114***	0.085***	0.063***	0.022***	0.059***	0.025***
	(0.003)	(0.003)	(0.003)	(0.002)	(0.001)	(0.002)	(0.001)
ISR citations					0.483***		0.402***
					(0.010)		(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 γ (the relationship between a patent's geographic origin and its influence), 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 influence. 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. (3) 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 γ 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 γ 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***	0.072***	0.096***	0.070***	0.078***	0.045***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
China (0/1)	−0.097***	−0.072***	−0.096***	−0.044***	−0.065***	−0.014***
	(0.002)	(0.002)	(0.002)	(0.001)	(0.002)	(0.002)
Japan (0/1)	−0.040***	−0.013***	−0.040***	−0.033***	−0.024***	−0.004***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
Korea (0/1)	0.074***	0.093***	0.075***	0.031***	0.099***	0.058***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Residual countries (0/1)	0.085***	0.099***	0.086***	0.083***	0.078***	0.086***
	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)	(0.003)
Number of claims (log)		0.106***				0.087***
		(0.002)				(0.002)
University applicant (0/1)			−0.032***			−0.010***
			(0.002)			(0.002)
Chinese receiving office (0/1)				1.872***		1.855***
				(0.014)		(0.014)
English full text (0/1)					0.105***	0.057***
					(0.001)	(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 PCT in 2009.[8] Cost reductions from subsidies disproportionately incentivize the excess production of patents of marginal value and the additional citations generated by such patents may inflate the outcome (see the discussion in

[8] 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).

Section 2.2).[9] By construction, our measure 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 once the full text is available in English, which could occur at the time of application or later. Unsurprisingly, the availability of 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.

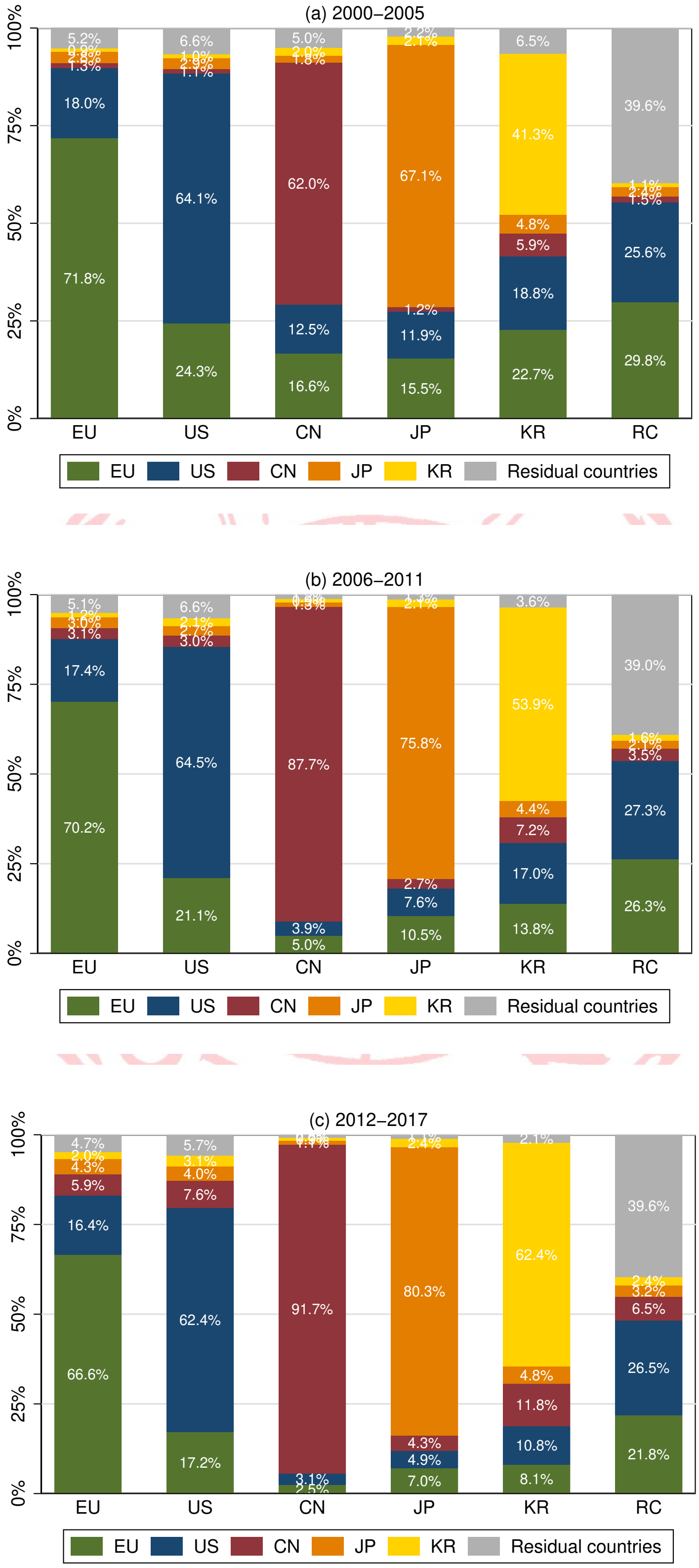
4.2 Geographic direction of influence

We proceed with our analysis by considering the geographic direction of influence, which allows us to assess one country's specific influence on other countries. To analyze both the international and domestic dimensions of influence, in this section we relax our strict selection criteria and also include domestic ISR citations. Although such citations may be inflated by domestic policies, which amounts to an upward bias in China's case, this comparison is yet indicative of the level of technological self-reliance in a given country. To analyze changes over time, in Figure 3 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 influence on inventions in the US, the influence on other countries in the earlier years is more marginal.

Several insights stand out. 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 24% of citations coming from the respective partner, highlighting the potential of international cooperation. In addition, the share of citations from other countries to 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

[9]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, foreign citations, which are independent of domestic policy, show the expected inflation of Chinese patents.

Figure 3: Geographic direction of influence



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

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 influence.

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 technological self-sufficiency combined with a declining international influence of Chinese innovation 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 influence on innovation developed elsewhere. As a noteworthy exception, Korea received 38% of its citations from abroad, confirming a stronger international influence than Japan and China.

4.3 Bilateral influence

Technology sovereignty positions countries heterogeneously in terms of technological influence and dependence. The desired balance between global integration (complementarity) and national self-sufficiency (substitution) also determines domestic R&D needs. Considering bilateral influence, a country's dependence on another country's technology and the influence of its own technology on that country crucially depends on the nature of domestic R&D (Griffith et al. 2004). Therefore, given the technological relationships between any two countries, domestic R&D plays an important role in avoiding one-sided dependence that can erode the technology sovereignty of a more dependent country. To that end, pursuing complementarity is an efficient strategy, but only if there is sufficient reciprocal bilateral dependence. In this section, we present measures for bilateral influence and dependence.

Considering the time period 2012–2017, Table 5 presents the bilateral influence of the focal country indicated in the top row in relation to the countries noted in the column below. This measure considers both the influence and quantity 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.[10] For instance, a value of -22 suggests that Europe depends more on the US than the US does

[10] The measurement of bilateral influence is described in more detail in the Appendix, where the full details of our measure calculation are presented in Table A1.

on Europe, whereas a value of 27 indicates that Europe depends less on China than China does on Europe. Europe's global influence, which is calculated as the average bilateral influence weighted by the time-variant shares in the number of patents of the respective country, has a value of -8 and indicates modest reliance on foreign innovation overall, placing the continent at a disadvantage in its global technology sovereignty, except in comparison to China.[11]

Table 5: Bilateral influence (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 influence*	-8	26	-37	8	3	-1

Note: Columns show the bilateral influence 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. *Global influence is calculated as the average bilateral influence weighted by the time-variant shares in the number of patents of the respective country.

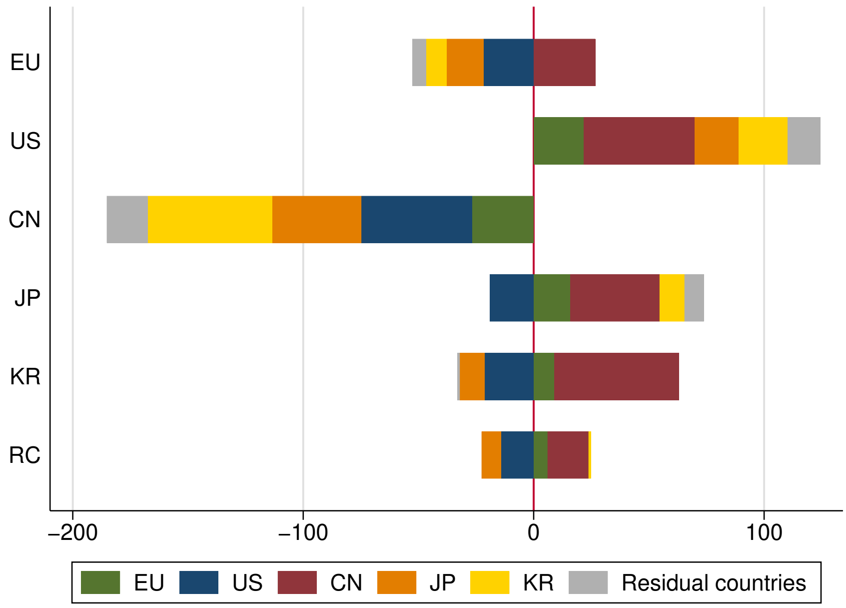
Notably, the US consistently shows higher levels of independence in relation to all other countries, as demonstrated by its global influence value of 26, and exhibits its strongest position in relation to China. Conversely, China has the weakest overall position, with an global influence of -37. At the 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 greater independence in relation to almost all other countries, as evidenced by a value of global influence of 8 and 3, respectively. While both countries are dependent on the US, Korea also depends on Japan.

For a more comprehensive international perspective, in Figure 4 we illustrate the stacked bilateral influence for each country. Because we are quantifying the bilateral influence over all five partner countries, upper and lower bounds expand from 100 and -100 to 500 and -500, respectively. While values for bilateral influence are presented in Table 5, Figure 4 allows for a more detailed and comprehensive representation of international properties, 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 (63 and -33) have mixed

[11]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.

accounts of stacked bilateral influence, with more moderate respective upper and lower values.

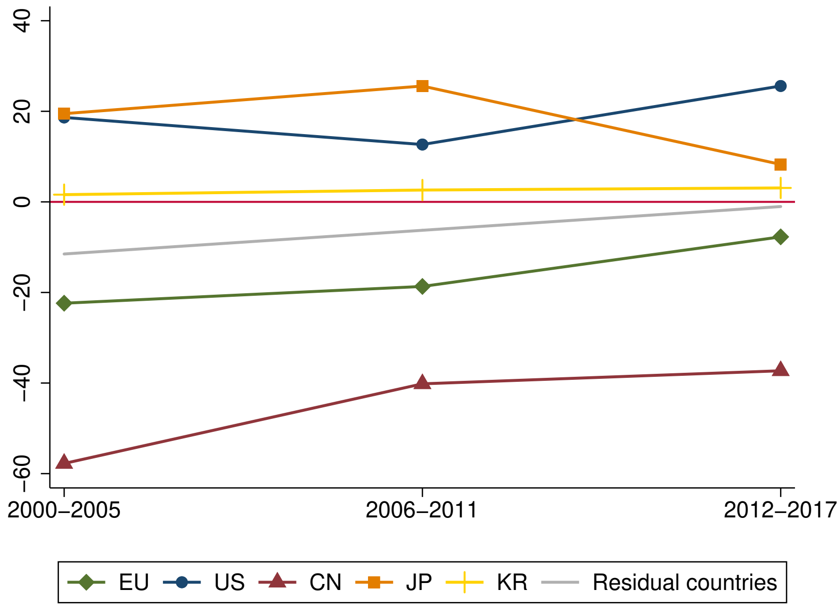
Figure 4: Stacked bilateral influence (2012-2017)



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

Figure 5 displays each country's global influence. This is calculated as the average weighted bilateral influence for each country relative to the aggregate of all other countries, where the weights are the time-variant shares in the number of patents of the respective country. 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 influence and quantity of inventions; however, the rise of China and the recent decline of Japan are also evident. The decrease in the average influence of China's PCT applications is outweighed by increased quantity. In contrast, Japan is experiencing a decline in average influence without a sufficiently robust rise in patent quantity, leading to a decrease in its global influence. Korea accounts for the lowest number of PCT applications, however, its persistent and high rate of citations amounts to a modest but stable global influence.

Figure 5: Global influence over time (2000-2017)



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

4.4 Key enabling technologies

Key enabling technologies (KETs) are crucial for the development and continuation of technology sovereignty. Such 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. Therefore, we conduct an additional analysis focusing on KETs from 2012 to 2017. Empirically, KETs are classified referencing the criteria outlined in Van de Velde et al. (2013), encompassing nanotechnology, photonics, industrial biotechnology, advanced materials, micro and nanoelectronics, and advanced manufacturing technologies.[12] Besides the economic importance, the focus on KETs also offers a methodological advantage. While countries' actual technology sovereignty is partly determined by their endogenous selection of technologies, KETs are a rather exogenous selection of technologies that could be considered as similarly relevant for all countries.

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 international influence based on average ISR citations received per pate (compare with Table 2), the US leads with a mean value of 0.257

[12] As the widespread use of artificial intelligence is still a very recent phenomenon, these patents are not considered separately.

for KETs, compared to a mean value of 0.242 for all PCT applications. The corresponding 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 (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 results 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 with 0.074 for all technologies. For China, we obtain a coefficient for KETs of -0.071 compared to -0.097 for all technologies, while in 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.

The geographic direction of influence reveals only minimal differences for KETs compared to all technologies (compare Figure 3). 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 influence on other countries. Finally, replicating the results for bilateral and global influence restricted to KETs (compare Table 5), reveals the following notable results. Europe improves its global influence from -8 to -3, while Japan drops from 8 to -7 and Korea from 3 to -10. Japan and Korea show a lower bilateral influence 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 sovereignty 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 that perspective and include Germany as the single most important European country in terms of PCT patent applications. However, for measurement reasons we also keep Europe (without Germany) included, allowing for a comparison of Germany with the rest of Europe.[13] 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

[13] This setting also ensures direct comparability with our prior results. Alternative settings could, for example, (i) put all remaining European countries individually into the residual country group or (ii) exclude all non top-five countries from the analysis altogether. However, results from different settings are not directly comparable.

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 less citations from outside of Europe.

Following from this, Germany's global influence is more than 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 gap compared to all technologies.

5 Discussion and Policy Implications

In this section, we first discuss our main results and then outline policy implications. Across all results, it is evident that the US has maintained its influential position as the world's technological superpower. The US has the strongest global influence and surpasses all other countries in respective bilateral relationships, establishing superior technology sovereignty. However, this conclusion is far from obvious. Since 2019, China has overtaken the US, Japan, Korea, and Germany as the number one country in terms of PCT patent applications. Additionally, there is anecdotal evidence that China has been making substantial progress in certain future-oriented technology areas such as batteries (Breitinger et al. 2020). Nonetheless, our analysis suggests that China's focus on quantitative patent targets combined with industrial and innovation policies and occasional moonshot projects has not yet amounted to inventions with an overwhelming global influence. In contrast, our findings reveal China's continuous dependence on all other innovation-leading countries, which is evident across all technologies and future-oriented KETs. Despite improving its global influence throughout the first decade of the millennium, China's recent growth trend is similar to Korea, albeit its level being significantly lower. Hence, our results do not suggest that China is about to overtake the US as the world's technological superpower.

Another important insight is the strong mutual relationship between the US and Europe with respect to the direction of global influence. In comparison to this high degree of integration in the West, for East Asia, we generally find a growing internal focus over time. Notably, this is true for China, which is explicitly seeking to reduce foreign dependence as well as Japan. A remarkable finding is that Japan's global influence is weakening over time, representing the only country with a downward trend. In contrast, the US, Europe, China, and Korea have improved their positions. The cases of China (for all PCT applications) and Japan (for KETs PCT applications) also demonstrate that leadership in quantity does not necessarily equate to a higher technological influence. For example, while Europe files a relatively lower quantity of KET applications in recent years, the respective influence is actually stronger than in total technologies.

Several implications emerge from our findings for policymakers to consider. Despite ongoing integration between the US and Europe in the midst of a changing geoeconomic landscape, the US and Europe differ markedly in their respective global positions. The US has achieved outstanding technology sovereignty, whereas Europe is dependent on all countries except China. Therefore, it is crucial for European policymakers to address this dependency. An essential aspect of a related policy approach should focus on promoting KETs, as Europe has already obtained relative advantages. European policymakers view the US, Japan, and Korea as dependable partners, limiting the need for immediate bilateral interventions; thus, Europe should strive for more balanced, long-term bilateral partnerships with these countries, while also avoiding future dependence on Chinese innovations.

Policymakers in Japan face distinct challenges. This country still has a very high global influence and bilaterally solely relies on the US, which it considers a reliable partner. Despite this, Japanese inventions are recently experiencing a declining influence, albeit from a high level. This is also related to the discussion about relocating innovation and production abroad, possibly adding to Japan's recent decline to fourth place among the world largest economies. Although Japan is highly involved in future-oriented innovation related to KETs, this inventive activity has not yet been adequately translated into international influence. Innovation from Japan is cited less frequently abroad over time, not just from fewer countries and technology areas, resulting in a reduction in its overall influence. Addressing the cause of this trend is imperative for policymakers. For Korea, in contrast, its sustained global influence could possibly be attributed to continued high domestic R&D investment. Likewise, Korea receives a larger share of citations from abroad than neighboring Japan and China.

Finally, Chinese policymakers face a difficult circumstance. Its geoeconomic environment is characterized by systemic rivalry and other countries' push for technology sovereignty can be seen as a response to this. Additionally, the US, Europe, and other countries are recently promoting de-risking in commodity trade and foreign direct investment. China is possibly perceived as an unreliable partner by these governments due to concerns that Chinese policymakers may exploit economic and technological dependence during periods of conflict. The timing of these events poses a challenge for China, as it has made significant strides in terms of the quantity and influence of inventions, but remains more dependent on other countries than the reverse.

Although maximal global integration seems not to be the order of the day, collaboration among like-minded and geoeconomically reliable partners still allows countries to benefit from their inclusion in the global innovation network. However, cooperation with less reliable countries should be embedded in a setting of at least reciprocal bilateral dependence, while actively reducing unilateral dependence but building up inventive capacity domestically or among reliable partners. Nonetheless, it is obvious that political requirements for reciprocity and redundancy will also reduce economic efficiency.

6 Conclusion

We analyze the technological influence and interdependence of the world's leading innovation countries to investigate their technology sovereignty, a concept at the crossroads of geoeconomics and innovation studies. This paper introduces a novel empirical approach that measures bidirectional knowledge flows using patent citations observed through the universe of PCT applications, and offers a first empirical assessment of technology sovereignty.

Our main findings are as follows. The US maintains its status as the leading technological superpower, exerting strong global influence and also outpacing all other countries in bilateral relations, thus maintaining superior technology sovereignty. Despite persistent integration between the US and Europe in the midst of a changing geoeconomic landscape, the US and Europe differ substantially in their respective global positions. Europe is dependent on all countries except China. Although China has shown a strong rise in patent counts, our research reveals that it is dependent on all other countries and shows the largest global dependence. This is the case for the total of all technologies as well as for future-oriented technologies separately. Notably, Japan has witnessed a decline in its global influence over time, despite previously holding a top position. As a result, it is the only country to show a recent downward trend. Korea, on the other hand, accounts for the lowest number of PCT applications among the leading innovation countries, but its patents receive the second-highest number of average citations. Overall, this amounts to a modest but stable global influence, in line with bilateral independence from China and Europe.

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 could motivate a selection of technologies and examine them in more detail. Second, our approach to measuring the influence of patents can also be extended to using ISR citations to scientific publications. This will not only be helpful for examining the underlying dependence of countries' more basic research, but also to provide context for the trends in PCT patent applications that we have documented here. Third, we have developed a measure for technology sovereignty, performed a validation, and reported descriptive results. Understanding the drivers of technology sovereignty, e.g. domestic R&D and other factors, will be important next steps for identifying how countries can adjust their respective position.

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Appendix

Calculation of bilateral influence

Table A1 contains the figures that underlie the calculation of the measure of bilateral influence 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 influence is calculated as the total number of citations received by country L from country J minus the total number of citations received by country J from country L 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 influence of -22 that Europe (country L) 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 influence of Europe on the US.

Second, when it comes to the bilateral influence 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 influence. E.g., the US obtained 16,603 citations from China whereas China obtained 5,823 citations from the US.