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EMPIRICAL MEASUREMENT OF TECHNOLOGY SOVEREIGNTY

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Empirical Measurement of Technology Sovereignty

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Contents

Abstract

Amid the global supply-chain crisis, there is a growing interest in whether countries can sustain their needed industries. In addition, as the US-China technology competition intensifies, it has become important whether a country has the technologies to support its core industries. Technology sovereignty is a concept that summarizes these concerns. As governments' interest in technology sovereignty has increased, various policies have been announced to enhance technology sovereignty. However, the rationale behind these policies remains qualitative or a collection of fragmentary evidence. In this study, we define the core components of technology sovereignty as innovation capabilities, production capabilities, and supply-chain independence and propose operational definitions to measure their individual and aggregated levels. We measure each of these elements of technology sovereignty using publicly available data on international patents, exports, and imports and present the results of international comparisons. The framework for measuring technology sovereignty presented in this study can be applied not only to cross-country comparisons but also to compare the level of technology sovereignty across different industries within a country. In addition, cross-country comparisons can be made by focusing on specific industries, and this study presents the results of an international comparison of technology sovereignty in the semiconductor industry as an example. The results of the empirical analysis show that each country has different strengths and weaknesses in various components of technology sovereignty. This suggests that technology sovereignty policies cannot be composed of one standardized package but should be differentiated according to the context of each country.

1. Introduction

1.1. Emergence of the technology sovereignty debate and related policies

The rise of the technology sovereignty debate has recently accelerated because of the COVID-19 pandemic and the Russian invasion of Ukraine. These events disrupted global supply-chains, preventing countries from obtaining essential goods (Ivanov and Dolgui, 2020; Ivanov and Dolgui, 2021; Jagtap et al., 2022; Butollo et al., 2024). Consequently, countries are questioning their ability to sustain core industries amid such disruptions. Furthermore, strategic competition between the US and China has heightened geopolitical tensions, emphasizing the importance of high-tech industries and core technologies (Liu and Woo, 2018; Schneider-Petsinger et al., 2019; Jisi & Ran, 2019; Danilin, 2020). Consequently, there is growing interest in whether a country can independently produce the necessary technologies and maintain essential industries, a concept known as technology sovereignty (Bauer and Erixon, 2020; Crespi et al., 2021).

Although academic discussions on technology sovereignty have existed for decades (Grant, 1983; Wriston, 1988), they have only gained significant momentum since 2020 (Crespi et al., 2021; Edler et al., 2023; March and Schieferdecker, 2023). Despite the maturing academic debate, major countries have proactively announced policies related to technology sovereignty. For example, in the semiconductor sector, which is central to this debate, the US has implemented measures such as subsidies and export controls under the CHIPS and Science Act of 2022 to boost domestic production and reduce supply-chain dependency (Luo and Van Assche, 2023; Peters, 2023). Similarly, the EU introduced policies under the European Chips Act of 2023 to fund R&D, invest in production capacity, and monitor supply shortages to strengthen its position as a technology frontier

(Dachs, 2023). China established the National Integrated Circuit Industry Investment Fund in 2014 to strengthen the government's support across all segments of the semiconductor supply-chain, including foundries, packaging and testing, materials, and equipment (Marukawa, 2023); in 2024, China announced a third investment phase worth 344 billion yuan ($47.5 billion). Additionally, in 2020, China issued a document titled "Several Policies to Promote the High-Quality Development of the Integrated Circuit Industry and Software Industry in the New Era," offering various incentives for foreign semiconductor companies to transfer technology, intellectual protocol (IP), and research and development (R&D) facilities to China, aiming to enhance self-reliance in semiconductor technology (Sutter, 2021). South Korea also announced a Semiconductor Mega Cluster Creation Plan in 2024, including policies for developing research infrastructure, providing tax credits, fostering fabless companies, and strengthening supply-chains through global alliances.

These policies share several similarities. They include not only instruments of traditional science, technology, and innovation (STI) policy, such as R&D support and the establishment of research infrastructure, but also elements of industrial policy to enhance the production capacity of specific industries, as well as measures of trade policies such as import tariffs and export controls (Edler et al., 2023; Criscuolo et al., 2022; March & Schieferdecker, 2023; Butollo et al., 2024; Criscuolo & Lalanne, 2024). This trend suggests that the technology sovereignty policy is evolving into an overarching concept that integrates previously independent policy areas. The EU has recognized this in its review of technology sovereignty policy, advocating a coherent mix of research, industrial, and trade policies (European Commission, 2021).

Additionally, as countries announce their technology sovereignty policies, they identify critical and emerging technologies as the main focus areas, and the targeted technologies and industries appear to be similar across nations. A comparison of key areas across various countries/regions such as the US (Goodman & Roberts, 2022; The White House, 2024), China (Zenglein & Holzmann, 2019), the European Union (Ramahandry et al., 2021; Dortmans et al., 2022; European Commission, 2023), and Canada (Araya & Mavinkurve, 2022), reveals that they consistently prioritize fields such as artificial intelligence (AI), biotechnology, advanced manufacturing, and quantum technology, providing significant support for these areas.

Despite their different historical strengths and contexts, countries are adopting similar policy combinations, raising questions about whether these policies are based on a rigorous and objective rationale tailored to each country's specific needs or are uncritically modeled after those of competing nations.

1.2. Quantitative analysis of the current state of technology sovereignty

The concept of technology sovereignty has been discussed in policy communities since the late 2010s, particularly as tensions between the US and China began to escalate (Edler et al., 2020; Huotari et al., 2020). Despite the lack of an accepted definition in the academic literature (Edler et al., 2023), numerous policies have been enacted, and substantial state funding has been allocated (VerWey, 2019; Sutter, 2021; Luo & Van Assche, 2023; Dachs, 2023; Marukawa, 2023; Butollo et al., 2024).

This represents a classic case of policy outpacing theory. This phenomenon, in which policy advances without a rigorous conceptual definition and analysis, can lead to several issues. First, if technology sovereignty policies are driven by political objectives, without a clear understanding of the severity of the problem, hasty or excessive interventions may be implemented. This could hinder the balanced evolution of the innovation ecosystem in the long term. Second, even if technology sovereignty is acknowledged as an important policy agenda, without accurate analysis, the selection of policy targets, objectives, and instruments may be prone to errors and biases, leading to a waste of national resources. Therefore, there is an urgent need to build a consensus on the concept of technology sovereignty and to collect quantitative evidence on the subject.

Since 2010, there has been a growing interest in the “science of science policy,” which seeks to find a quantitative basis for science policy (Fealing et al., 2011). This field is driven by the increasing importance of the societal and economic impacts of scientific and technological advances, growing complexity of policy environments, and heightened uncertainty in technological innovation systems (Marburger, 2011). In this context, the

National Science Foundation (NSF) has initiated the National Network for Critical Technology Assessment project (NNCTA, 2023) to quantitatively analyze the current state of competitiveness of critical technologies in the US. This study aims to contribute to the establishment of evidence-based innovation policies by presenting a quantitative analysis framework related to technology sovereignty and the objective analysis results using these tools, in line with recent trends in the science of science policy.

Notable efforts have been made to analyze technology sovereignty quantitatively. For instance, Rand Australia was commissioned by the Australian government to develop a framework for identifying strategic technologies crucial to Australia's technology sovereignty (Dortmans et al., 2022). This framework involves collecting and quantitatively analyzing sector-specific data such as patents. Caravella et al. (2021) quantitatively analyzed technology sovereignty for climate mitigation technologies, whereas da Ponte et al. (2023) presented a technology sovereignty index for the 5G telecommunications industry using a multidimensional composite index. Additionally, Caravella et al. (2024) evaluated technology sovereignty in the European context, focusing on the photovoltaic industry, and comprehensively analyzed the technological competitiveness and import dependence of the industry across the upstream, midstream, and downstream stages.

Despite these efforts in the literature, the following limitations were noted. Many analyses are confined to specific industries, such as climate mitigation technology (Caravella et al., 2021), telecommunications (da Ponte et al., 2023), and photovoltaics (Caravella et al., 2024). Others present data selectively, using metrics such as papers and patents that are thought to support technology sovereignty (Puglierin & Zerka, 2022; da Ponte et al., 2023). This study aims to achieve three primary objectives: First, to propose a comprehensive framework to examine the concept of technology sovereignty by analyzing the relationships between its components; second, to conduct a quantitative analysis using this framework to compare the current status of technology sovereignty across various countries; and third, to demonstrate the applicability of this analytical framework to specific industries and to compare relative levels of technology sovereignty across different industries within a single country. The analytical framework presented in this study is expected to enhance future discussions on technology sovereignty and aid in the formulation of context-specific and differentiated technology sovereignty policies.

The remainder of this paper is organized as follows. Section 2 presents the definition and components of technology sovereignty and synthesizes them into an analytical framework. Section 3 operationalizes the definition for empirical analysis and introduces the data used. Section 4 presents the results of the analysis of technology sovereignty at the country level. Section 5 provides examples of how the framework can be used to compare the status of technology sovereignty across industries within a country, or to make international comparisons for specific industries. Finally, Section 6 summarizes the results of the analysis and offers policy implications and directions for future research.

2. The framework of technology sovereignty and its components

2.1. Definition of technology sovereignty

Technology sovereignty can be defined as a country's ability to possess and acquire the technology required to produce essential goods without one-sided structural dependency on other countries (Grant, 1983; Edler et al., 2023). This concept involves several critical considerations.

First, within the context of technology sovereignty, technology includes various elements of technology capability. Researchers such as Dosi (1982, 1988), Lall (2000), and Lee et al. (2019, 2021) have argued that technology manifests in multiple forms. There is a conceptual distinction between the capability to generate innovative ideas, often represented through scientific papers or patents, and the practical skills required for production. Notably, production-related technology capability predominantly consists of tacit know-how, which is not explicitly documented in patents and tends to be enhanced with accumulated production experience. From the standpoint of distinguishing technology capability from innovation and production capabilities, Dosi (1982, 1988) categorized them into 'knowing" and "doing" for empirical analysis. Similarly, Lee et al. (2019, 2021) divided these capabilities into implementation and design capabilities for assessment at the national level. Considering the objectives of this study, it is important to consider both innovation and production capabilities required for manufacturing when evaluating whether a country possesses the necessary technologies.

Second, in discussing technology sovereignty, it is essential to focus not on all existing technologies but rather on those necessary for a nation's survival and prosperity. This involves the technologies required to produce goods and services essential for the country or those in industries where the country relies heavily on imports. For instance, while the technology needed for cooking is vital for self-sufficiency, advanced technologies such as space launch vehicles may be irrelevant from a technology sovereignty perspective. Therefore, it is imperative to identify and analyze technologies pertinent to specific industries (Helfat & Raubitschek, 2000; Castellacci & Natera, 2013; Eum & Lee, 2022; Pugliese et al., 2019). This necessitates the consideration of industry-technology linkages in empirical analyses.

Third, structural dependencies in international supply-chains must be considered when analyzing technology sovereignty. Excessive dependence on a country for essential imports renders the economy vulnerable to exogenous crises, thus undermining its sovereign autonomy. Hence, even if a nation possesses high overall technology capability, its technology sovereignty should be deemed low if structural dependence is significant.

These three considerations are integral to the development of an analytical framework for technology sovereignty.

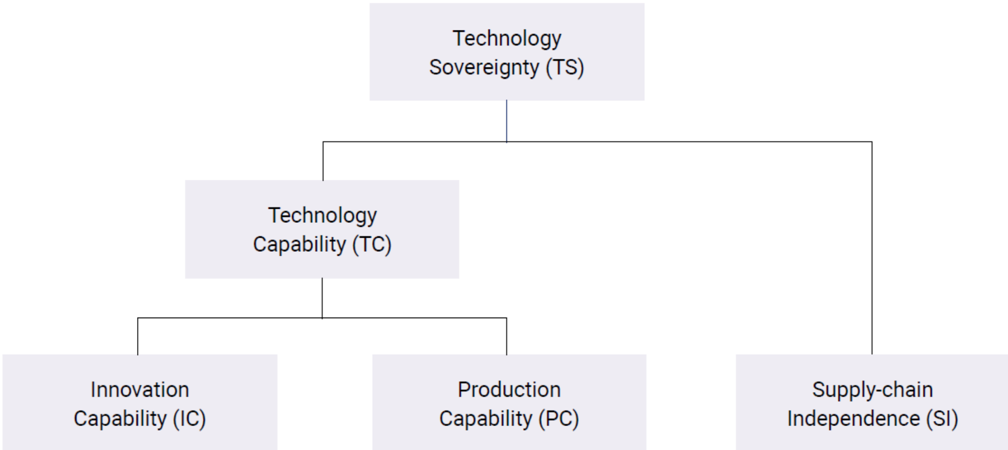
2.2. Interpreting the components of technology sovereignty

Building on the previous discussion, we propose understanding technology sovereignty through three primary components: innovation capability, production capability, and supply-chain independence.

Innovation capability denotes the capacity to generate innovative ideas, primarily from scientific and technological perspectives, and is measured by the number of international patents filed by a country. Production capability reflects the technological proficiency required for production, as represented by the volume of exports. Production is measured in terms of exports rather than domestic production, because it is meaningful for technology sovereignty analysis only when the goods produced are competitive on an international scale. Supply-chain independence assesses the degree of reliance on a single country for imports.

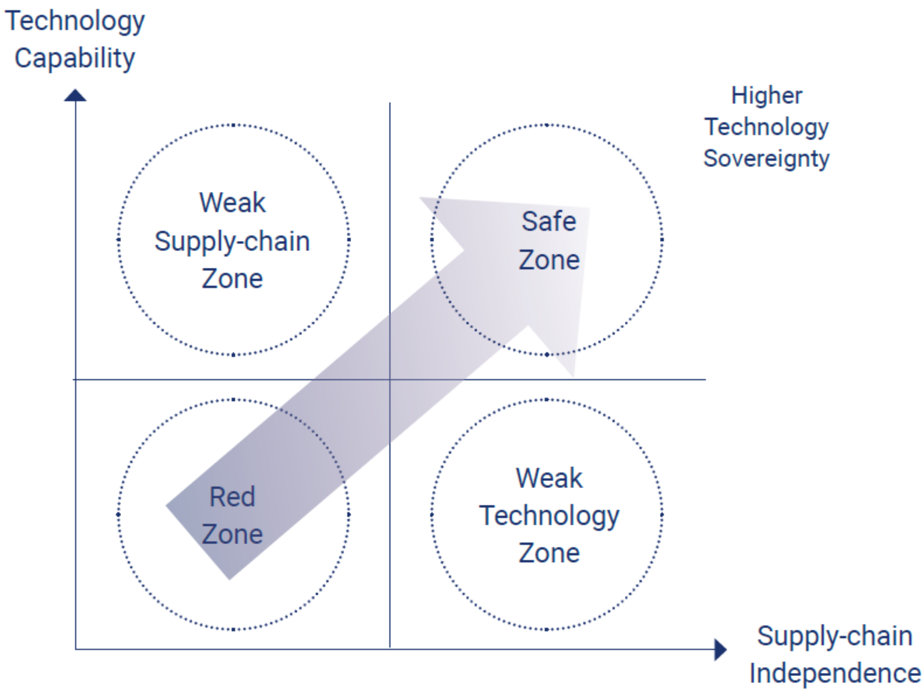
Among these components, innovation and production capabilities are quantitative measures based on patents and exports, respectively. In contrast, supply-chain independence is a qualitative measure that is expressed as the ratio of imports from a particular country to the total amount of imports. Considering both innovation and production capabilities together can reveal the overall technology level that can transform innovative ideas into internationally competitive export products, which is defined as composite technology capabilities. In this study, technology capability is expressed as the product of innovation and production capabilities.

Figure 1 Relationship between technology sovereignty and its components



Using the framework presented in Figure 1, a country's technology sovereignty status can be intuitively visualized on a two-dimensional plane, based on the degree of composite technology capability and supply-chain independence (see Figure 2). In Figure 2, the first quadrant represents the safe zone, characterized by high technology sovereignty owing to both high supply-chain independence and strong composite technology capability. The second quadrant indicates a weak supply-chain zone, where composite technology capability is high, but supply-chain independence is low. This situation arises when a country has the capability to produce its own products but heavily depends on imports from a specific nation. The fourth quadrant, which combines high supply-chain independence with low composite technology capability, represents a weak technology zone, which is problematic from the technology sovereignty perspective. The third quadrant is the red zone, indicating extremely low technology sovereignty owing to deficiencies in both composite technology capability and supply-chain independence.

Figure 2 Framework for evaluating technology sovereignty



2.3. Technology sovereignty and national policies

The three components of technology sovereignty align with the key policies related to achieving sovereignty. First, innovation capabilities encompass traditional STI policies, such as subsidies and tax incentives to support R&D, initiatives to foster the next generation of talent and attract foreign expertise, and investments in science and technology infrastructure. Policies related to production capabilities include traditional industrial policies aimed at strengthening domestic production in specific industries. These policies may involve manufacturing incubation, reshoring efforts, labor force security, cluster creation, certification and standards, tax credits, and loans for facility investments, along with other policies that bolster the production base. Third, supply-chain independence encompasses trade-related policies, such as bilateral or multilateral trade agreements, export controls, supply-chain diversification measures, and foreign direct investment (FDI) restrictions on foreign competitors.

Innovation, industrial, and trade policies have different time horizons. Typically, innovation policies have the longest time horizon; industrial policies, a medium-term horizon; and trade policies, a relatively short-term horizon. Table 1 summarizes this alignment with key policies.

Table 1 Alignment of technology sovereignty components with policies

<table>
<tr><th rowspan="3">Components</th><th colspan="3">Technology Sovereignty (TS)</th></tr>
<tr><th colspan="2">Technology Capability (TC)</th><th></th></tr>
<tr><th>Innovation Capability (IC)</th><th>Production Capability (PC)</th><th>Supply-chain Independence (SI)</th></tr>
<tr><td>Policy Type</td><td>Science, Technology, and Innovation Policy</td><td>Industrial Policy</td><td>Trade Policy</td></tr>
<tr><td>Time horizon</td><td>Long-term</td><td>Medium-term</td><td>Short-term</td></tr>
</table>

Policies related to technology sovereignty in the US, the EU, China, and Japan integrate STI, industrial, and trade policies, as illustrated in the framework above. Table 2 provides a breakdown of policies related to the semiconductor industry in the US, EU, China, and South Korea.

Table 2 Detailed policy components for technology sovereignty in the semiconductor industry

<table>
<tr><th rowspan="2">Country</th><th colspan="3">Policy Components of Technology Sovereignty</th></tr>
<tr><th>Science, Technology and Innovation Policy</th><th>Industrial Policy</th><th>Trade Policy</th></tr>
<tr><td>US
CHIPS and Science Act</td><td>· R&D programs for National Semiconductor Technology Center, National Advanced Packaging Manufacturing Program, Manufacturing USA Semiconductor Institute ($11 billion)
· University-based prototyping and lab-to-fab transition of semiconductor technologies ($2 billion)</td><td>· Manufacturing incentives for the construction of domestic facilities and equipment for semiconductors ($39 billion)
· Development of highly skilled domestic workforce ($0.2 billion)
· 25% investment tax credit for semiconductor manufacturing investments</td><td>· Supporting international information and communication technological security and semiconductor supply-chain activities ($0.5 billion)
· Preventing the funding recipients from expanding certain semiconductor manufacturing capacity in countries of concern</td></tr>
</table>

EU European Chips Act	· Setting up a virtual design platform to reinforce Europe's chip design capacity · Enhancing existing and developing new advanced pilot lines for prototyping, testing and experimentation of cutting-edge chips · Building capacities for accelerating the development of quantum chips and associated semiconductor technologies	· Defining integrated production facilities and open EU foundries, and supporting the fast-tracking of permit-granting procedures if recognized as first-of-a-kind facilities within each Member State · Establishment of competence centers across Europe to support a skilled workforce · Support for innovative start-ups, scale-ups and small and medium-sized enterprises in accessing equity finance through the operation of the Chips Fund	· Establishment of a toolbox for monitoring semiconductor supply-chains, collecting information, and evaluating response measures through cooperation among EU Member States.
China Policies to Promote the High-Quality Development of the Integrated Circuit Industry and Software Industry in the New Era	· R&D investments focusing on high-end chips, integrated circuit equipment and process technology, integrated circuit key materials, integrated circuit design tools · Expanding integrated circuit and software majors in colleges and universities, along with developing teaching laboratories and internship training bases	· Corporate income tax exemptions for integrated circuit manufacturers based on line widths from 28 nm to 130 nm, ranging from 2 to 10 years	· Import duties exemption for key integrated circuit design and production companies, as well as advanced packaging and testing companies, within a certain period of time

South Korea Semiconductor Mega Cluster Creation Plan	· Technology research hubs to be established in Pangyo (AI semi-conductor), Suwon(Compound Semiconductor) and Pyeongtaek (next-gen-eration devices/advanced packaging) · Expansion of specialized semiconductor graduate schools, development and operation of speci-alized centers to support system semiconductor convergence education programs	· Tax credits for semi-conductor R&D and fa-cility investments (15% for large and me-dium-sized firms and 25% for small firms) · Financial support for fa-bless companies with preferential loans and guarantees (24 trillion won) and Investment in Semiconductor Ecosystem Fund (300 bil-lion won)	· Establishment of an early warning system for sup-ply-chains among Korea, the US, and Japan, and a supply-chain dialogue with the Netherlands to address supply-chain cri-ses · Development of bilateral and multilateral export control regimes with ma-jor semiconductor equip-ment countries

Sources: The White House (2022), European Union (2023), General Office of the State Council of the People's Republic of China (2020), and Ministry of Trade, Industry, and Energy (2024).

Industrial policies related to production capabilities and trade policies related to supply-chain independence are integral to economic security policies. In other words, technology sovereignty can be viewed as the sum of innovation and economic security capabilities. Consequently, policies aimed at enhancing technology sovereignty should combine innovation and economic security policies.

As illustrated in Table 2, the framework of technology sovereignty presented in this study offers a systematic and logical approach to understanding the current state of policies related to technology sovereignty in the real world. Notably, it highlights that technology sovereignty policy is not confined to narrowly defined STI policies but is a broad concept encompassing industrial and trade policies.

3. An operational definition of technology sovereignty and the required data

3.1. Defining the components of technology sovereignty

The first component of technology sovereignty, innovation capability (IC), can be expressed as the number of international patents a country holds relative to other countries. Let I_{ci} be the number of patents in the *i*-th sector of country c, and $I_i (= \Sigma_c I_{ci})$ be the sum of all patents filed by all countries in sector *i*. The IC indicator for sector *i* in country *c* is defined in Equation (1) as follows:

$$IC_{ci} = I_{ci} / I_i \tag{1}$$

As countries have multiple sectors, weighting is essential for aggregation. To represent the relative importance of each sector, this study employs the Product Complexity Index (PCI), scaled between 0 and 1, and then rescaled as a probability distribution to sum to 1. The rescaled PCI for sector i, denoted as $\widehat{PCI_i}$, serves as a weight, as shown in Equation (2). The PCI is designed to capture the diversity, uniqueness, complexity, and sophistication of the knowledge and skills required to produce the outputs of an sector. It has been widely used in previous studies on cross-country industrial competitiveness (Hidalgo & Hausmann, 2009; Felipe et al., 2012; Hausmann et al., 2014; Córcoles et al., 2014; Stojkoski et al., 2016; Le et al., 2022; Mealy & Teytelboym, 2022).

$$IC_c = \Sigma_i (\widehat{PCI_i} \cdot IC_{ci}) \tag{2}$$

Expressing the IC indicator in this manner aligns with our intuition: the more patents a country c holds in sector i, the higher its IC_{ci} and consequently its overall IC_c, reflecting the country's innovation capability. Additionally, when a country files patents in a new field for the first time, IC_c increases accordingly.

Similarly, production capacity (PC) represents the level of production technology, and can be evaluated based on the volume of exports. While domestic production is important, a country must also possess the technology to produce goods that meet the quality standards of the export market. Analogous to IC, if X_{ci} is the export volume of country c in sector i and $X_i(=\Sigma_c X_{ci})$ represents the total export volume in sector i, the PC index for sector i in country c is defined in Equation (3) as follows:

$$PC_{ci} = X_{ci}/X_i \quad (3)$$

The importance of different sectors may vary when aggregating across all sectors in a country. Therefore, the PCI of each sector is scaled to a value between 0 and 1. The rescaled PCI, $\widehat{PCI}_i$, is then adjusted to form a probability distribution that sums to 1, and this adjusted PCI is used as a weight, as shown in Equation (4).

$$PC_c = \Sigma_i (\widehat{PCI}_i \cdot PC_{ci}) \quad (4)$$

By defining production capabilities in this manner, we obtain the intuitively desirable property that as country c exports more in sector i, its PC_c increases. Additionally, as it begins to export in new sectors, its PC_c also increases. This is associated with the sum of the existing Revealed Comparative Advantage (RCA) indices, which is discussed in Appendix A. The discussion in Appendix A applies equally to IC as it does to PC due to their similar structure.

Technology capability (TC) can be defined as the product of a country's capacity to generate innovative ideas (IC) and produce them as goods (PC). This aligns with the existing notion that a country's TC comprises both innovation and production capabilities. It also implies that a country's TC is higher if it possesses both capabilities, and should be assessed in a discounted manner if it lacks either, rather than simply averaging the two. The calculation formula for the TC indicator presented in Equation (5) integrates the two sub-indicators of innovation and production capabilities, with the results normalized to values between 0 and 1:

$$TC_{ci} = \sqrt{(IC_{ci} + a)(PC_{ci} + a)} - a \tag{5}$$

Given the above definition, the value of TC lies between the geometric and arithmetic means of IC and PC. In this study, we set the value of a to 10^{-4}; a more detailed discussion can be found in Appendix B.

To aggregate the TC values for each sector within a country, the PCI values of the sectors were scaled to values between 0 and 1. The sum is calculated using the re-normalized $\widehat{PCI_i}$ as weights, ensuring that the total equals 1, as shown in Equation (6).

$$TC_c = \Sigma_i (\widehat{PCI_i} \cdot TC_{ci}) \tag{6}$$

The third factor, supply-chain independence (SI), measures the extent to which a country is not reliant on a specific country for imports due to a lack of production capacity. This can be defined using the import volume as the basis. Let M_{ci} represent the import volume of sector i in country c, and M_{ci}^1 represent the import volume from the largest import source for sector i in country c. The SI index for sector i in country c is defined in Equation (7) as follows:

$$SI_{ci} = 1 - \frac{M_{ci}^1}{M_{ci}} \tag{7}$$

When the SI values for each sector were aggregated within a country, they were summed by scaling the PCI values of the sectors to values between 0 and 1. The re-normalized $\widehat{PCI_i}$, adjusted to form a probability distribution summing to 1, was used as weights, as shown in Equation (8).

$$SI_c = \Sigma_i (\widehat{PCI_i} \cdot SI_{ci}) \tag{8}$$

Equation (8) satisfies the intuitively desirable property that SI_c increases as country c becomes less dependent on its largest import source within sector i and decreases as it begins to import from new sectors.

3.2. Required data

The quantitative measurement of technology sovereignty requires data across various industries and technologies, particularly the systematic utilization of data from numerous countries and of data that can be easily updated. Therefore, this study relied exclusively on publicly available and regularly updated data on international patent performance, exports, and imports by country to measure the components of technology sovereignty. This approach is crucial for the replicability of the analysis and ensures that the results can be updated periodically with ease. As official organizations regularly update international patent and trade data, the systematic implementation of the technology sovereignty framework benefits from the automatic updating of results.

Innovation capability is measured using patent data from the European Patent Office's Patent Statistical Database (PATSTAT) and USPTO registrations published by the Organisation for Economic Co-operation and Development (OECD). The technology classification is based on the four-digit International Patent Classification (IPC), which includes 658 categories. For imports and exports, this study uses the BACI dataset, collected and published by the Centre d'Etudes Prospectives et d'Informations Internationales (CEPII), based on data from the United Nations Commodity Trade Statistics (UN Comtrade) database. The sector classification consists of 5198 six-digit categories aggregated according to the 2012 version of the Harmonized System (HS 12). To categorize and aggregate patent data by sector, we used the HS-IPC concordance table published by the Korean Intellectual Property Office (2023). Depending on the purpose of the analysis, sector classification details can vary from more aggregated to more detailed.

The empirical analysis in this study includes all countries available in the original datasets (over 100 countries for patents and over 250 countries for imports and exports). However, this paper visualizes the results for the top 50 countries by gross domestic product (GDP) based on 2022 data from the International Monetary Fund, taking into account the level of economic development and international relevance in terms of technology sovereignty. The focus was on country rankings to provide intuitive information. The analysis covered the period from 2012 to 2022 to highlight the recent changes in the global industrial and technological landscape.

4. Results of the cross-country comparison of technology sovereignty

4.1. Innovation capability, production capability, and supply-chain independence

Figure 3 depicts the rankings of countries based on their innovation capability over five-year intervals. As of 2022, the rankings for innovation capability are as follows: the US, Japan, China, Germany, South Korea, and France. Notably, China witnessed rapid growth in innovation capability, moving from 9th place in 2012 to 3rd place by 2022. This observation aligns with previous findings indicating a sharp increase in China's national investment in science and technology, which in turn has accelerated its innovation output as evidenced by patent registrations (Hu & Mathews, 2008; OECD, 2017; WIPO, 2023; Clay & Atkinson, 2023; CICC Research & CICC Global Institute, 2024).

Figure 4 presents the results of the production capability analysis. As expected, China, known as the "world's factory," emerged as the country with the highest production capability in 2012, followed by Germany and the US, which have traditionally been strong in high-tech manufacturing. European countries, Japan, Taiwan, and South Korea have consistently maintained high rankings. Notably, Vietnam emerged as a new production base, climbing significantly from 32nd to 19th place in production capability over the past decade. These observations are consistent with the findings from previous studies on production capabilities across countries (Li, 2018; IMF, 2022; Dhar et al., 2023).

Figure 5 shows the rankings for supply-chain independence (SI). While the US and China exhibited high rankings in innovation capability (IC) and production capability (PC), they ranked low in supply-chain independence. By contrast, Germany showed a stable level of supply-chain independence. Japan (28th), South Korea (33rd), and Taiwan (31st) exhibited low supply-chain independence rankings in 2022. These countries have high innovation and production capability, especially in high-tech industries, but they share the common characteristic of being highly dependent on certain countries, such as China, for intermediate goods. Consequently, they are particularly vulnerable to disruptions in supply-chains due to events such as the COVID-19 pandemic or trade disputes; this finding is consistent with previous studies (Hertel et al., 2014; Martin et al., 2023).

Figure 3 Country rankings for innovation capability (IC) (2012, 2017, 2022)

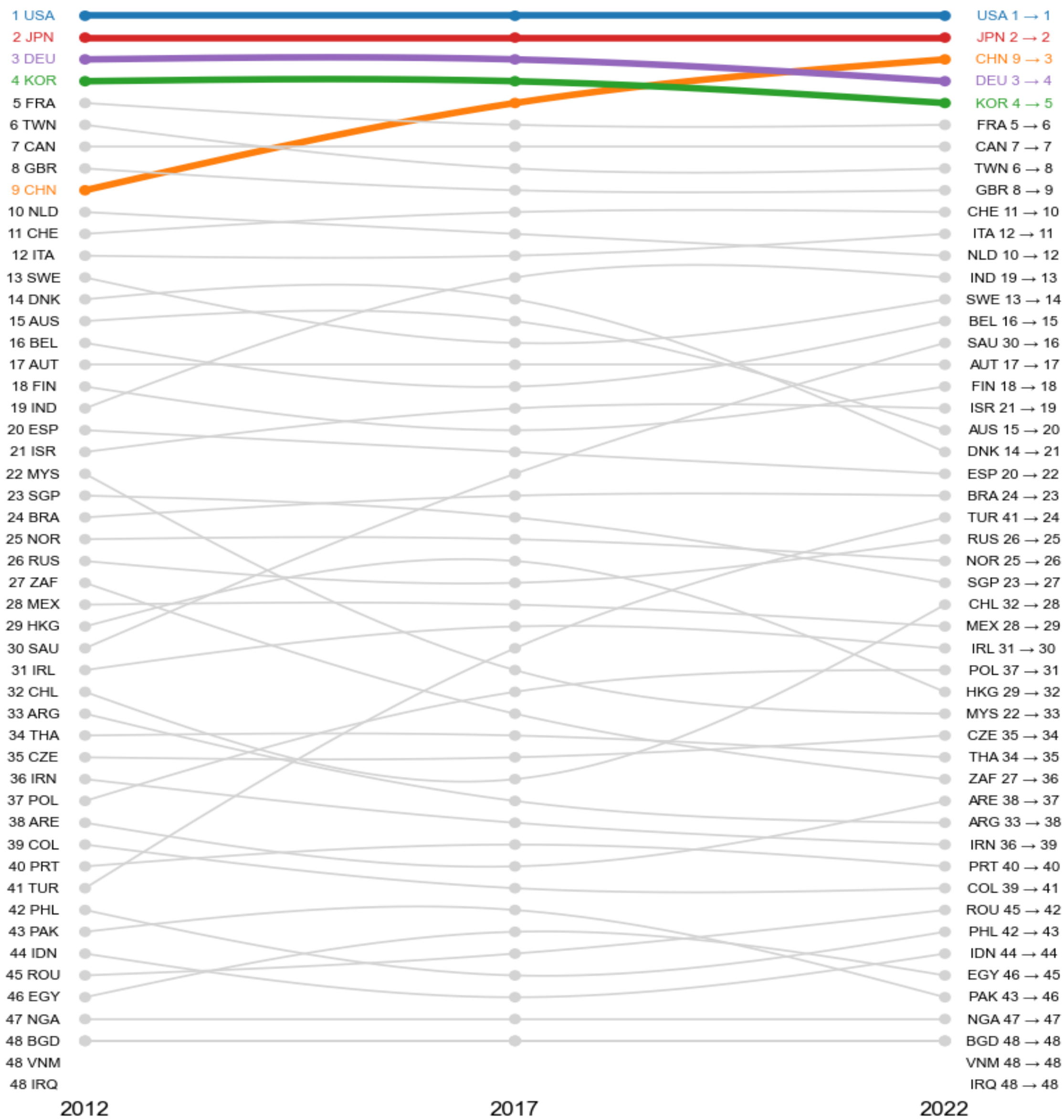


Figure 4 Country rankings for production capability (PC) (2012, 2017, 2022)

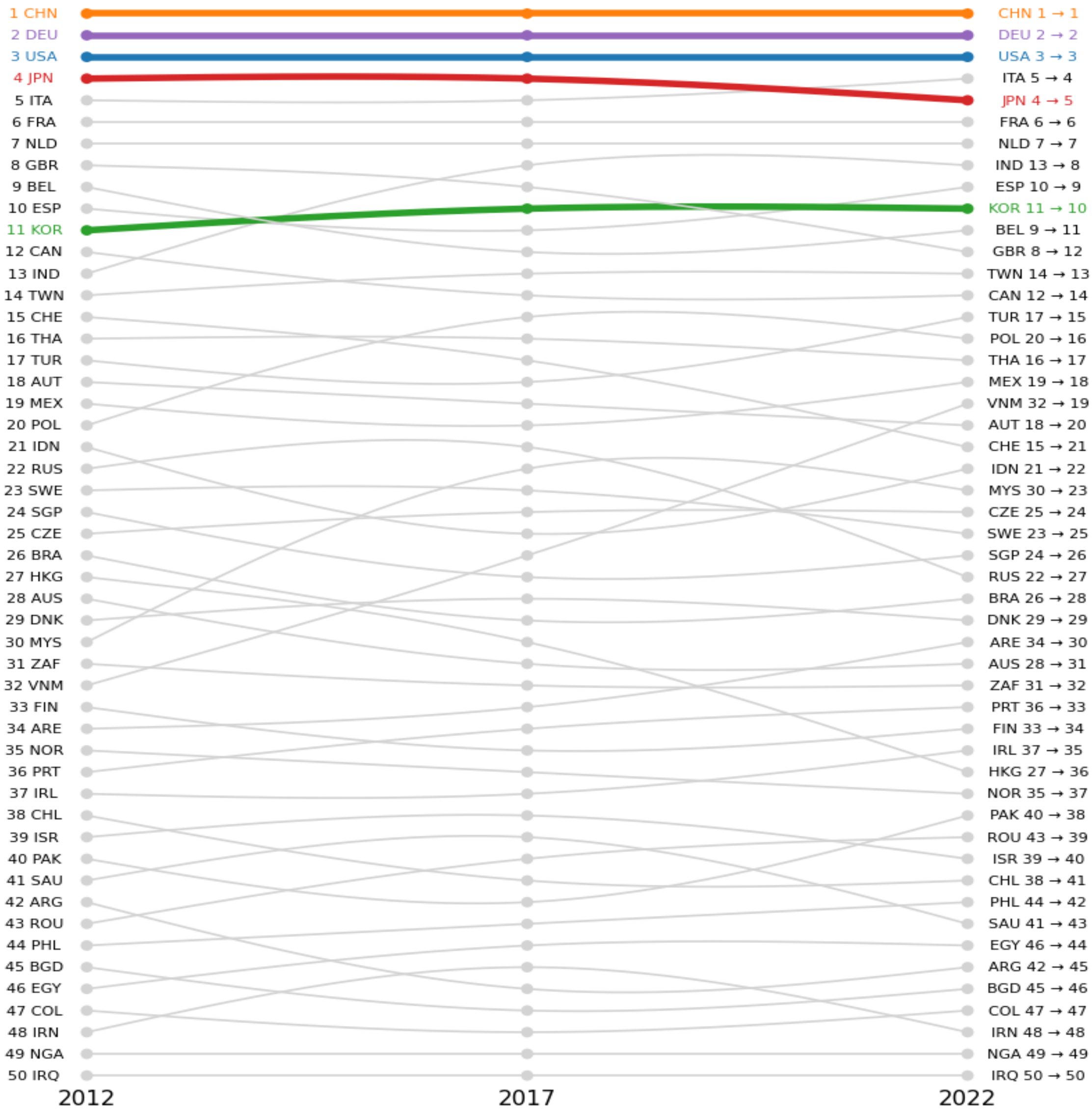


Figure 5 Country rankings for supply-chain independence (SI) (2012, 2017, 2022)

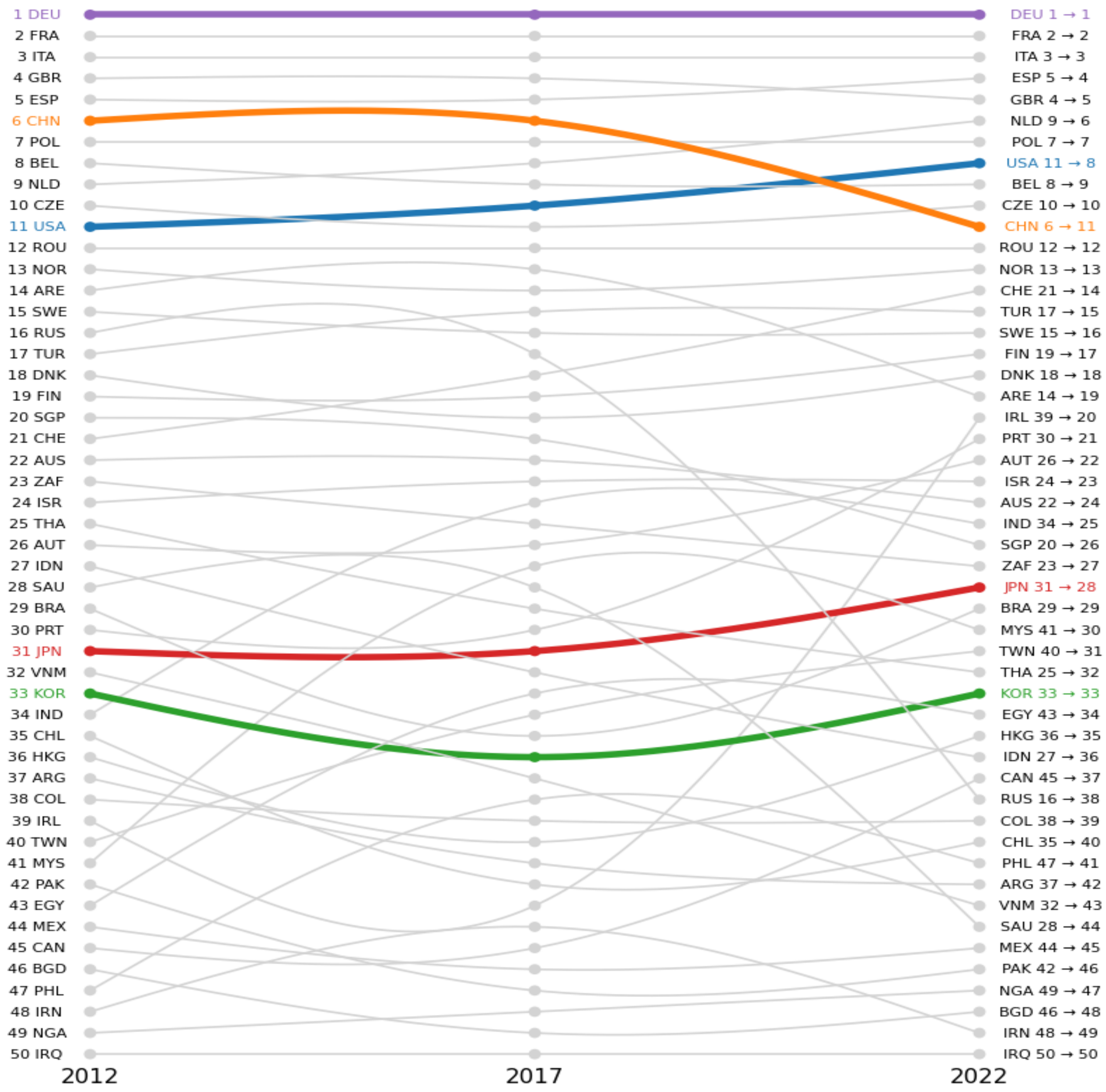
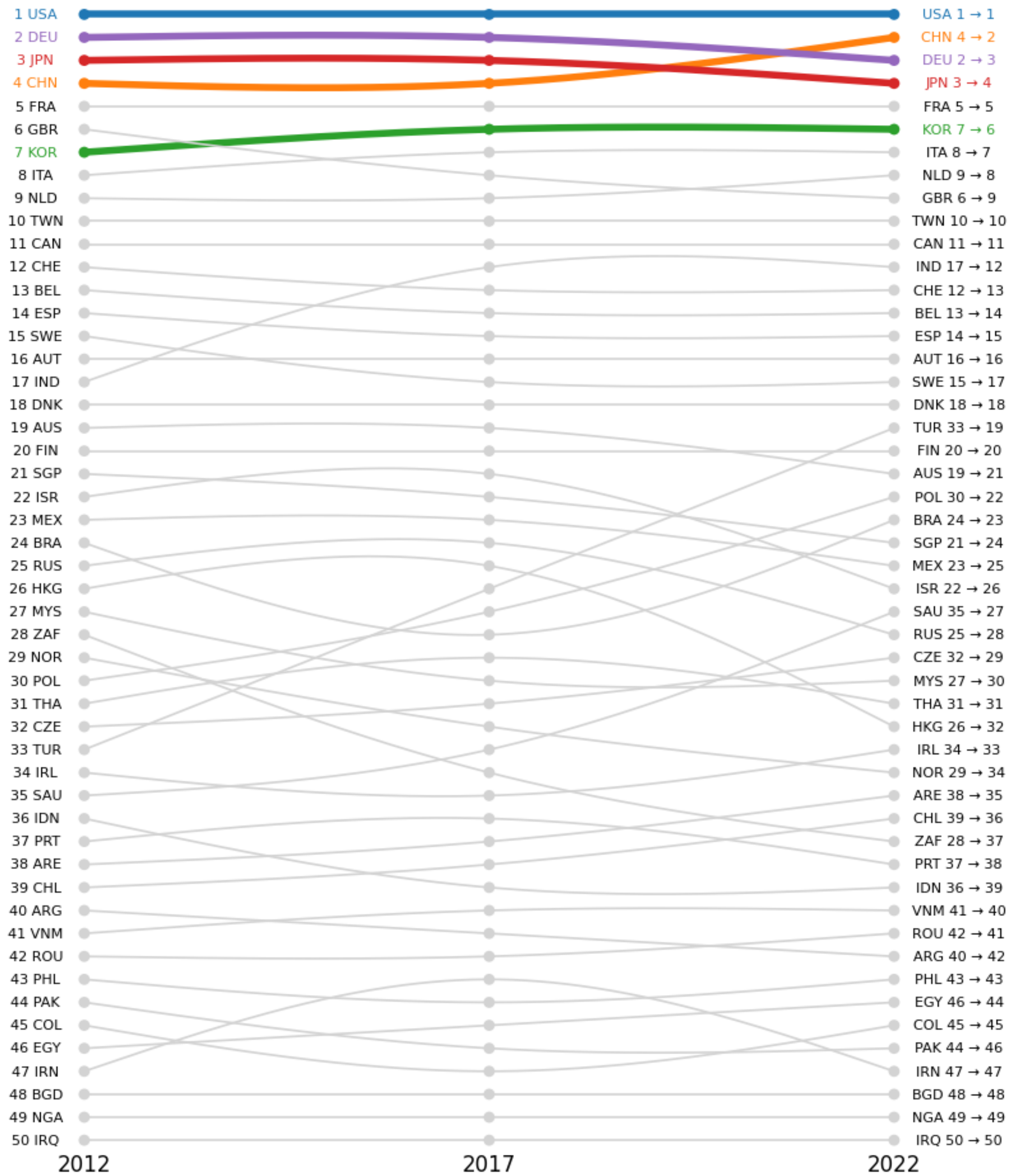


Figure 6 Country rankings for technology capability (TC) (2012, 2017, 2022)

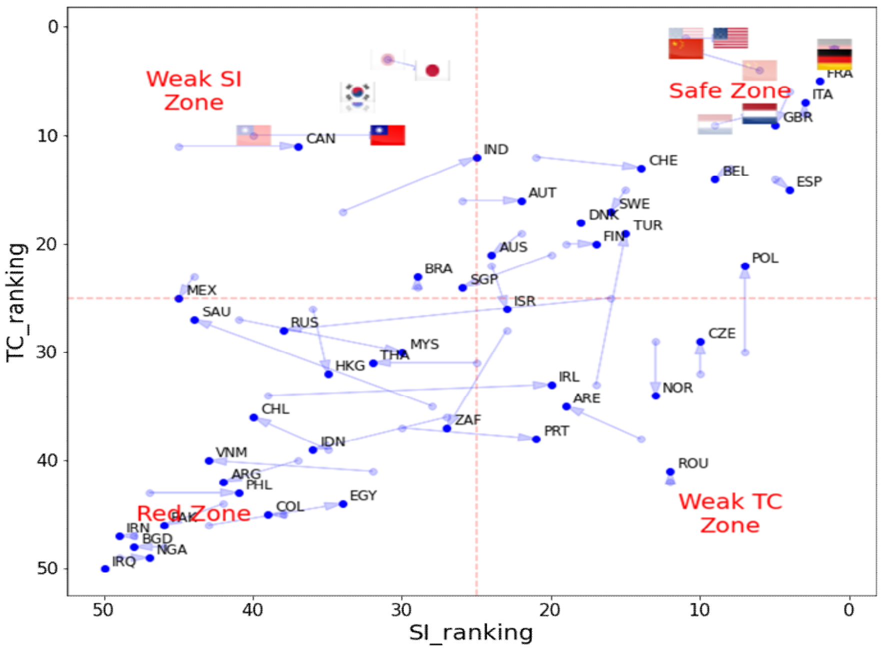


An analysis of technology capability, which is a composite of innovation and production capability, is shown in Figure 6. The countries at the top of this list are those that can convert innovative ideas into goods, such as the US, China, Germany, Japan, France, and South Korea.

4.2. Relative rankings of countries for technology sovereignty

Technology sovereignty is categorized into four quadrants based on technology capability and supply-chain independence, as illustrated in Figure 7. Countries such as the US, Germany, and China, which have established technology sovereignty through high technology capability and robust supply-chain independence, are positioned in the “safe zone” in the top-right corner. By contrast, countries such as South Korea, Japan, and Taiwan, which exhibit high technology capability but comparatively lower supply-chain independence, are situated in the “weak SI zone” in the top left corner. The “weak technology zone” includes countries with low technology capability but strong supply-chain independence, including natural resource exporters (e.g., the United Arab Emirates and Norway) and nations proficient in assembly production (e.g., the Czech Republic and Romania). To track temporal shifts in country rankings, we compared the data from 2012 and 2022. Most countries with high technology capability exhibited moderate improvements in supply-chain independence. Specifically, China experienced a slight decline in its ranking, while South Korea continued to face challenges in maintaining low supply-chain independence, despite its strong composite technology capability.

Figure 7 Changes in country rankings of technology sovereignty based on technology capability (TC) and supply-chain independence (SI) (2012, 2022)

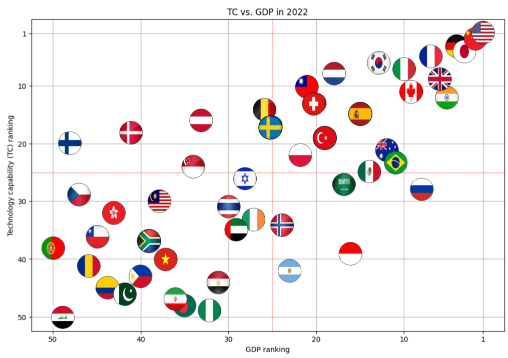


4.3. Comparison of GDP rankings with technology capability and supply-chain capability rankings

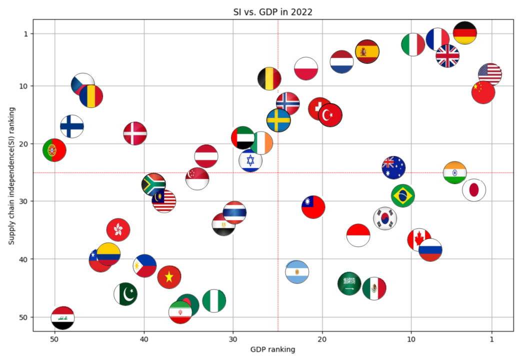
Figure 8 presents the comparison of countries' GDP rankings with their rankings for technology capability and supply-chain independence, which are key components of technology sovereignty. There is a positive correlation between technology capability and GDP rankings. However, countries such as Saudi Arabia, Argentina, Indonesia, and Brazil, despite having low technology capability, exhibit high GDP rankings. These countries rely on exports based on FDI or natural resource exports.

The relationship between supply-chain independence and GDP rankings appears to be weaker. For instance, countries such as South Korea and Japan exhibit high GDP rankings despite their relatively low supply-chain independence. These countries may face greater economic vulnerability compared to others in the event of supply-chain disruptions.

Figure 8 Relationship between technology capability and supply-chain independence rankings and GDP rankings (2022)



(a) Relationship between technology capability and GDP rankings



(b) Relationship between supply-chain independence and GDP rankings

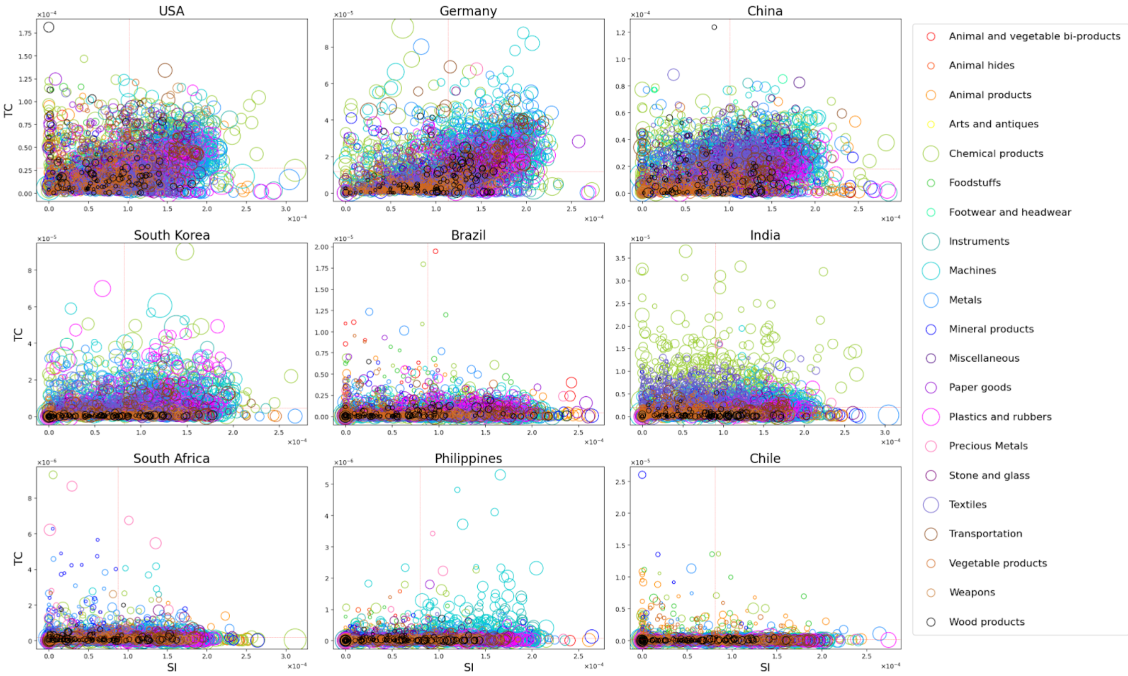
5. Application of the technology sovereignty framework

5.1. Comparison of technology sovereignty across industries within a nation

The technology sovereignty framework developed in this study can be used to compare and analyze the vulnerability of industries within a nation by assessing technology capability and supply-chain independence. Figure 9 presents the comparison of technology capability with supply-chain independence across industries within a nation. To facilitate a comparative analysis of technology sovereignty across industries within a nation, the HS codes were converted from six to four digits. This approach provides a more intuitive and streamlined visual comparison of results for key countries, facilitating a clearer interpretation than that gained through the use of six-digit HS codes.

As shown in Figure 9, the status of technology sovereignty varies among nations, depending on their position within the international trade network and the characteristics of their industrial ecosystems. For example, major economies such as the US, Germany, and China, positioned in the top row, demonstrate high composite technology capability across diverse industries. They exhibit both high technology capability and supply-chain independence, particularly emphasizing products with high PCI. In the second row, countries such as South Korea exhibit traits similar to the aforementioned nations, while Brazil and India show high technology capability and significant supply-chain independence limited to specific industries. Conversely, lower-income countries generally exhibit lower levels of technology capability and supply-chain independence across most industries, with their technology capability being concentrated in products with a lower PCI. These analytical insights underscore that while all nations prioritize technology sovereignty, policies should differentiate and prioritize industries accordingly. Utilizing the framework of this analysis at the policy level enables the identification of industries that require focused attention from a technology sovereignty perspective.

Figure 9 Comparison of technology sovereignty across industries within a nation (2022; HS code four-digit)



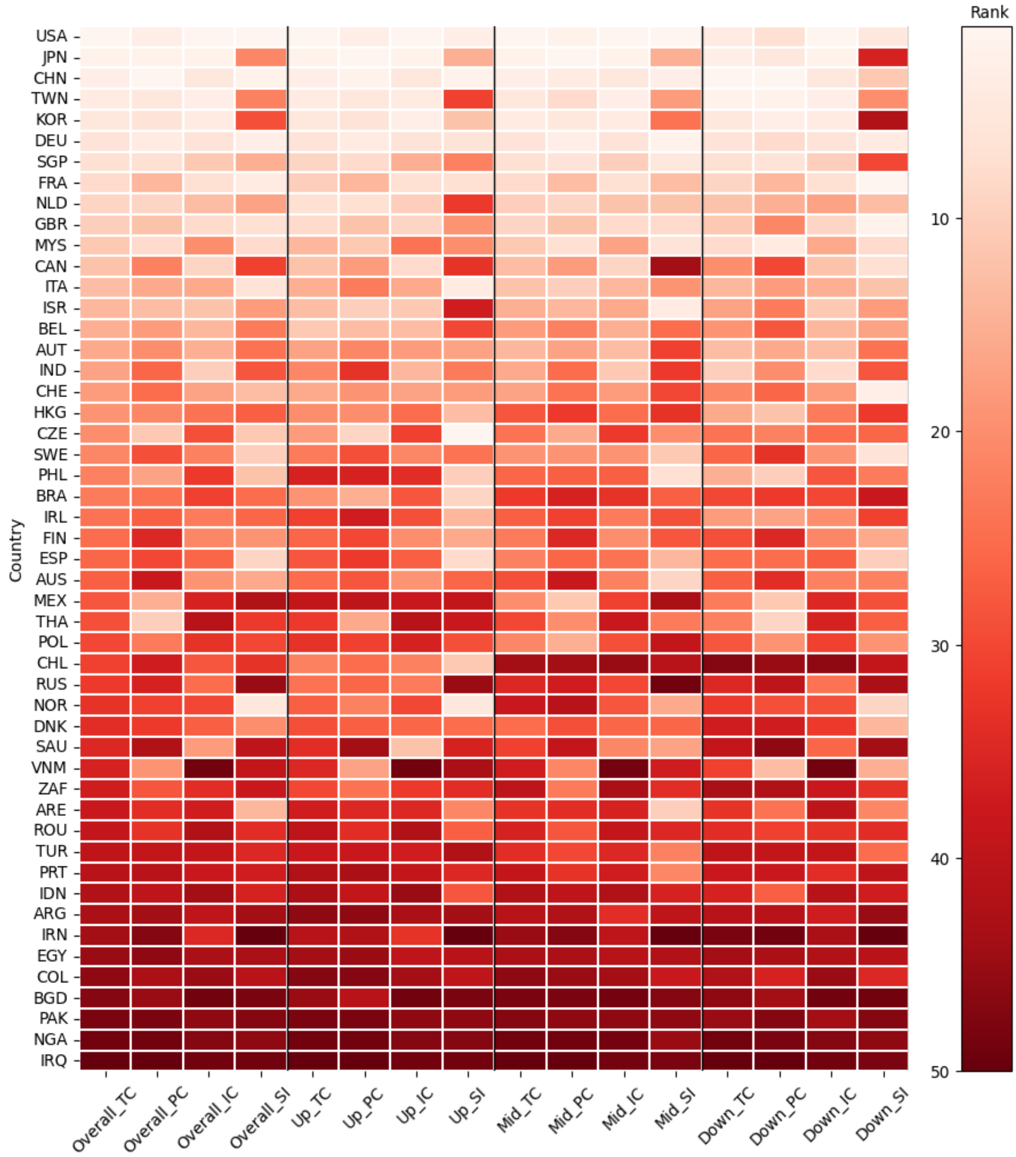
Note: ○ The size is proportional to Product Complexity Index (PCI)

5.2. Comparison of technology sovereignty status across countries for a specific industry

The technology sovereignty framework proposed in this study extends its applicability beyond broad industrial sectors to specific industries. For instance, in the case of the semiconductor industry, as detailed in Appendix C, the taxonomy of global supply-chain stages can be employed. This classification delineates the stages into upstream (including raw materials, inputs for wafers, silicon wafers, and foundry inputs), midstream (involving equipment), and downstream (comprising the final products) stages (Bonnet and Ciani, 2023).

Based on this framework, applying the concept of technology sovereignty to the production stages of the supply-chain enables a comparative assessment of technology sovereignty levels in the semiconductor industry across nations. For example, in South Korea's semiconductor industry, although innovation capacity, production capability, and technological expertise are high across all stages, vulnerabilities in supply-chain independence are evident.

Figure 10 Comparative analysis of technology sovereignty status across nations in the semiconductor industry's supply-chain stage (2022)



Note: The analysis presents the rankings of technology sovereignty factors (IC, PC, TC, SI) across supply-chain phases (overall, upstream, midstream, downstream) in the semiconductor industry for the top 50 GDP countries.

6. Conclusions and policy implications

As the intensification of technology competition between the US and China coincides with the worsening global supply-chain disruptions, technology sovereignty has emerged as the primary focus of policy interest across numerous countries. Accordingly, nations leverage their national resources through strategies in innovation, industrial development, and trade to strengthen their technology sovereignty. Despite the active political and policy discourse surrounding technology policies, conceptual ambiguity remains regarding the definition of technology sovereignty. Moreover, the systematic development of a framework and quantitative analyses to effectively gauge the levels of technology sovereignty remain inadequate.

Considering these circumstances, this study proposes a conceptual framework to assess technology sovereignty. At the core of this framework, technology sovereignty is determined by three primary factors: innovation capability, production capability, and supply-chain independence. Innovation and production capability are integrated into technology capability, consistent with existing research that highlights how a nation's technology capability comprises both the knowledge to innovate and the practical skills essential for production. According to this framework, technology sovereignty can be effectively conceptualized on a two-dimensional plane consisting of technology capability and supply-chain independence.

For the empirical measurement, this study introduces operational definitions to evaluate the individual components of technology sovereignty using international patent data and trade statistics. These definitions, as outlined in this study, are not only intuitively understandable but also advantageous because of their ease of third-party verification and straightforward periodic updates, leveraging publicly accessible data.

The technology sovereignty framework in this study was used to compare the components of technology sovereignty between nations and to provide an overall assessment. Furthermore, this study demonstrated the applicability of the framework to specific industries. Although this study focused on the semiconductor industry, the framework is adaptable to all industries. Comparative analyses of industries in several countries were also conducted to identify which industries within a nation should be targeted for technology sovereignty policies.

The primary finding of this analysis was the heterogeneous nature of technology sovereignty across countries. However, the observation that the determinants of technology sovereignty exhibit substantial variation is significant. Therefore, in devising strategies to enhance technology sovereignty, it is imperative to prioritize specific policies—long-term innovation policies, medium-term industrial policies, or short-term trade policies—based on their distinct impacts and contextual relevance. Furthermore, in terms of policy targets, it is essential to acknowledge that different industries may necessitate different levels of policy focus contingent on a country's unique circumstances. Additionally, discrepancies exist within different segments of the production chain—upstream, middle, and downstream—among countries within the same industry. In conclusion, the crucial insight gleaned from this study is that technology sovereignty manifests diversely across nations, industries, and supply-chain stages. This underscores the need to employ a systematic framework for quantitative assessment before drawing definitive conclusions regarding technology sovereignty.

At a cursory glance, this observation underscores crucial implications for the ongoing global discourse on technology sovereignty. Presently, many countries' policies pertaining to technology sovereignty tend to replicate similar policy frameworks that focus predominantly on comparable industrial sectors, particularly those deemed promising. A straightforward comparison of the technology sovereignty policies announced by countries such as the US, Europe, China, Japan, South Korea, and Taiwan, especially concerning the semiconductor industry, distinctly illustrates this trend. This phenomenon arises because of the lack of a systematic framework that comprehensively integrates technology sovereignty across industries, thereby relying on fragmented evidence. Furthermore, policy formulation often entails aggregating inputs from sector-specific expert committees in a top-down manner, inevitably exposing policies to expert biases and hindering the equitable assessment of sectoral significance.

In this context, our framework enables a national perspective to evaluate sector-specific levels of technology sovereignty and to discern the underlying causes. This approach facilitates the development of technology sovereignty policies by identifying the appropriate targets and selecting suitable policy instruments based on objective evidence. Consequently, our study's framework can be used as an evidence-based tool for policy formulation, underscoring its potential significance for policy making.

The framework introduced in this study exhibits potential for advancement from multiple perspectives. When assessing intercountry dependencies, political alignment can be incorporated as a control variable to adjust for structural dependencies by deducting revenue from non-friendly nations. Moreover, by leveraging patents and scholarly publication achievements, the concept of technology sovereignty can be extended to encompass the three-dimensional linkages among science, technology, and production.

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Appendix

A. Relationship between Production Capability (PC), Revealed Comparative Advantage (RCA), Economic Complexity Index (ECI) and Fitness Index (F)

Production capability, as defined in this study, is conceptually similar to the weighted average of Revealed Comparative Advantage (RCA). This can be mathematically expressed as follows:

$$PC_c = \Sigma_i (\widehat{PCI_i} \cdot \frac{X_{ci}}{\Sigma_c X_{ci}}) = \Sigma_i (\widehat{PCI_i} \cdot \frac{X_{ci}}{\Sigma_c X_{ci}} / \frac{\Sigma_i X_{ci}}{\Sigma_i \Sigma_c X_{ci}} \cdot \frac{\Sigma_i X_{ci}}{\Sigma_i \Sigma_c X_{ci}}) \quad \text{(A-1)}$$
$$= \frac{X_c}{X} \Sigma_i (\widehat{PCI_i} \cdot RCA_{ci})$$

On the other hand, the Economic Complexity Index (ECI) provides another aggregation method for RCAs; it is represented as follows:

$$ECI_c = \frac{1}{\Sigma_i M_{ci}} \Sigma_i (PCI_i \cdot M_{ci}) \quad \text{(A-2)}$$

Where,

$$M_{ci} = \begin{cases} 1, \text{ if } RCA_{ci} \geq 1 \\ 0, \text{ if } RCA_{ci} < 1 \end{cases} \quad \text{(A-3)}$$

Production capability, as defined in this study, can be interpreted as the sum of RCAs weighted by the Product Complexity Index (PCI), multiplied by a country's share of the global production ecosystem. Essentially, it is a composite measure that reflects a country's comparative advantage in a diverse range of sophisticated goods and the extent of its participation in the global production ecosystem.

Compared to the ECI, PC is more sensitive to absolute changes in capabilities for a given product. This sensitivity stems from the PC's use of actual RCA values, as opposed to the binary matrix M_{ci} (represented as either 0 or 1) used in the ECI. Furthermore, unlike the ECI, which averages the sum of the PCIs with comparative advantage divided by the diversity of a country, i.e., $M_c = \Sigma_i M_{ci}$, PC is multiplied by the share of the country in the global production ecosystem (X_c/X), which can provide extensive information about the absolute size of the country's share of world production. In the context of technology sovereignty, considering the capital-intensive nature and economies of scale in technological development, as well as a country's influence or share in the global technology ecosystem, the extensive form captured by PC offers a more appropriate measure of a country's competitiveness.

Furthermore, in this study, PC renormalizes the PCI of Hausmann and Hidalgo (2009), whose mean was standardized to zero, into a positive value using a probability distribution. This renormalization ensures that PC satisfies an intuitive property: even for products with low complexity, an increase in exports leading to a higher RCA will result in at least a marginal increase in PC.

On the other hand, PC is also related to the definition of the Country's Fitness Index (Tacchella et al., 2012), which introduces a non-linear method to obtain more consistent results in the economic complexity framework of Hidalgo and Hausmann (2009). The Fitness Index, F, is defined as follows:

$$F_c^N = \Sigma_i Q_c^N \cdot M_{ci} = \Sigma_i \frac{1}{\Sigma_c M_{ci} \cdot (1/F_c^{N-1})} \cdot M_{ci} \quad \text{(A-4)}$$

$$F_c^N(weighted) = \Sigma_i Q_c^N \cdot X_{ci}/X_i = \Sigma_i \frac{1}{\Sigma_c X_{ci} \cdot (1/F_c^{N-1})} \cdot PC_{ci} \quad \text{(A-5)}$$

The PC_{ci} proposed in this study is consistent with W($= X_{ci}/X_i$), which is used instead of the M matrix to render the Fitness index an extensive metric. Thus, PC_c has a similar mathematical form to that of a weighted Fitness index. In other words, introducing Product Complexity defined by the Fitness index method instead of the normalized PCI in our definition of PC results in the extensive metric of Cristelli et al. (2013).

As briefly discussed above, the definition of PC presented in this study includes most of the information of the Complexity and Fitness indices from previous studies. Additionally, this study has the advantage of fully reflecting the differences in absolute size between countries. This discussion also applies to IC, which is a proxy for innovation capability.

B. Meaning and selection criteria for *a* in TC calculations

Technology capability, TC, as defined in this study, can be represented by both linear and geometric methods, which are two representative methods for constructing composite indicators (OECD et al., 2008), depending on the parameter a. In the aggregation of IC and PC, the closer a is to 0, the closer it is to the geometric method, and as a increases to positive infinity, it becomes a linear method. This is shown in Equations (A-6) and (A-7).

$$i)\, a = 0: \tag{A-6}$$

$$TC_{ci} = \sqrt{(IC_{ci} + a)(PC_{ci} + a)} - a = \sqrt{IC_{ci} \cdot PC_{ci}}$$

$$ii)\, a = \infty: \tag{A-7}$$

$$TC_{ci} = \sqrt{(IC_{ci} + a)(PC_{ci} + a)} - a \approx \sqrt{a^2 + (IC_{ci} + PC_{ci}) \cdot a} - a$$

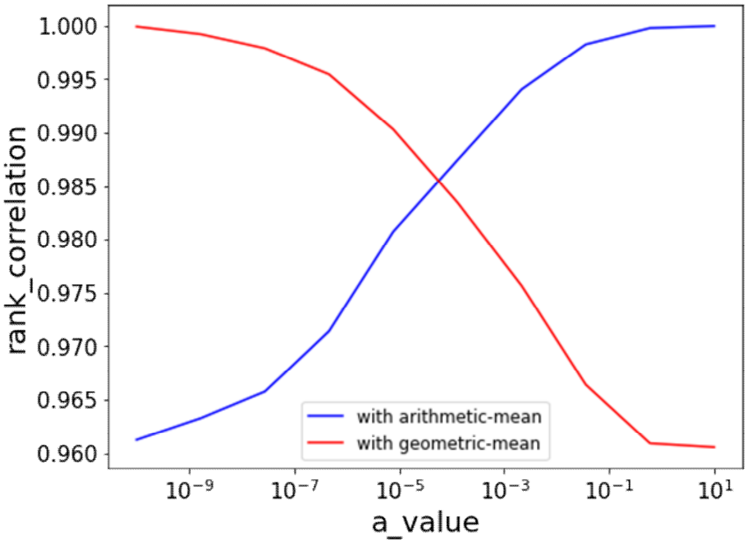
$$= a \cdot \sqrt{1 + \frac{IC_{ci} + PC_{ci}}{a}} - a \approx a(1 + \frac{IC_{ci} + PC_{ci}}{2a}) - a = \frac{IC_{ci} + PC_{ci}}{2}$$

The linear method of aggregation assumes that IC and PC are perfectly substitutable in a country's technology capability, which is not the case because innovation and production capability are not perfect substitutes in reality. In addition, choosing the geometric method of aggregation is not realistic because the value of TC, the composite index, becomes zero when one of the two capabilities, IC or PC, is completely absent, rendering the other capability useless. Therefore, this study empirically chooses the middle ground between the two mutually exclusive methods, as expressed by the following inequality:

$$\sqrt{IC_{ci} \cdot PC_{ci}} \leq TC_{ci} = \sqrt{(IC_{ci} + a)(PC_{ci} + a)} - a \leq \frac{1}{2}(IC_{ci} + PC_{ci}) \tag{A-8}$$

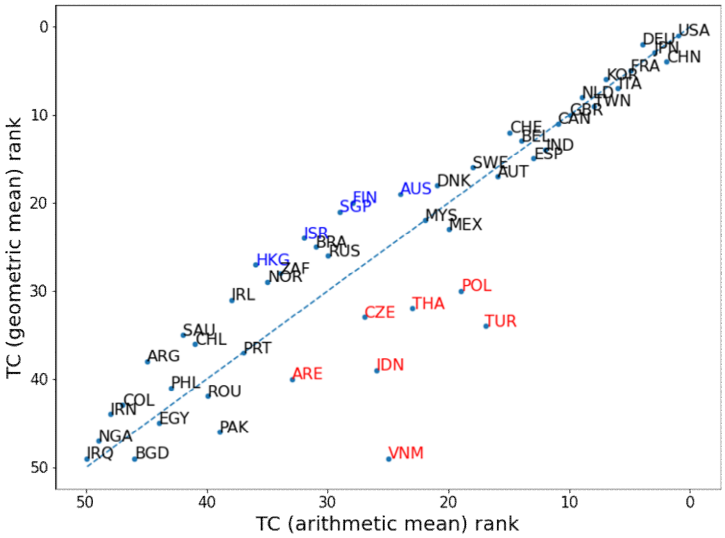
Figure A1 shows how the correlation of the TC values across 98 countries (excluding those without patent data) changes with the a value using the arithmetic mean (blue) and geometric mean (red) methods. In this study, we present the results in terms of rank for each country for intuitive information; thus, the correlation between these ranks is based on $a = 10^{-4}$, which is the midpoint between the two methods. Even if the values change, the correlation of the rankings is between 0.96 and 1.00, indicating that the ranking results in this study are robust to changes in the a value.

Figure A1 Changes in correlation of TC rankings as value changes



Note that the countries with large differences in TC rankings depending on the value a are those that are skewed toward either IC or PC, as shown in Figure A2. For example, countries such as Poland (POL), Turkey (TUR), Thailand (THA), and Indonesia (IDN) in red have relatively high values of PC, but not very high or almost zero values of IC, which leads to a relatively large drop in ranking when calculating TC using the geometric mean method. Conversely, countries such as Australia (AUS), Finland (FIN), Singapore (SGP), and Israel (ISR), which are colored blue, do not have zero IC or PC values and have relatively even IC and PC values. Therefore, their ranking increases when calculating TC using the geometric mean method.

Figure A2 Differences in TC rankings for the two aggregation methods (arithmetic and geometric means)



C. Taxonomy for categorizing supply-chain in the semiconductor industry

Categories	HS Code	Description
Upstream (Raw materials, inputs for wafers, silicon wafers, foundry inputs)	280461	Silicon with 99,99% purity
	282560	Germanium oxides, zirconium dioxide
	284920	Silicon Carbides Only
	285000	Hydrides, nitrides, and silicides
	370130	Photographic plates/film, sensitized, >255mm
	370199	Monochrome photography plates/film only
	370790	Preparation of chemicals for photographic uses
	381800	Chemical elements and compounds doped for use in electronics, in the form of discs, wafers, cylinders, rods, or similar forms, or cut into discs, wafers, or similar forms, whether or not polished or with a uniform epitaxial coating
	811299	Articles of niobium "columbium," gallium, indium, vanadium, and germanium, n.e.s.
	900120	Polarising material sheets and plates
	900190	Unmounted optical elements, excluding
	900219	Optical elements, excluding cameras
Midstream (Equipment)	903084	Electrical quantity measuring devices
	903082	Measuring semiconductor wafers/devices
	848690	Parts for semiconductor machinery
	848640	Machines for semiconductor manufacture
	848630	Machines for flat panel displays
	848620	Semiconductor device manufacturing machines
	848610	Machines for wafer manufacturing
	842199	Parts of machinery and apparatus for filtering or purifying liquids or gases, n.e.s.
	842139	Machinery and apparatus for filtering or purifying gases
	842129	Machinery and apparatus for filtering or purifying liquids
	841950	Heat-exchange units (excl. those used with boilers)
	841459	Fans
Downstream (Final products)	852351	Solid-state, non-volatile data storage devices for recording data from an external source
	852352	Cards incorporating an electronic integrated circuit and parts thereof
	852359	Semiconductor media
	853290	Electrical capacitors, fixed, variable, or adjustable(pre-set) parts

	854110	Diodes other than photosensitive or light-emitting diodes (LED)
	854129	Transistors, Other Than Photosensitive, Others
	854140	Electrical apparatus: photosensitive, including photovoltaic cells, whether or not assembled in modules or made up into panels, light-emitting diodes (LED)
	854160	Mounted piezo-electric crystals
	854231	Electronic integrated circuits as processors and controllers, whether or not combined with memories, converters, logic circuits, amplifiers, clock and timing circuits, or other circuits
	854232	Electronic integrated circuits as memories
	854233	Electronic integrated circuits as amplifiers
	854239	Electronic integrated circuits (excl. such as processors, controllers, memories and amplifiers)
	854290	Parts of electronic integrated circuits, n.e.s.

Note: Bonnet and Ciani (2023) presented HS codes related to the semiconductor industry, categorized into raw materials, silicon wafers, inputs for wafers, foundry inputs, equipment, and final products. Based on this, this study further categorizes the supply-chain of the semiconductor industry into upstream, midstream, and downstream.

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