Journal of Infrastructure, Policy and Development 2024, 8(6), 2436.
https://doi.org/10.24294/jipd.v8i6.2436

Article

Interdependence and specialization in the global semiconductor industry

Alena Dorakh

Faculty IV: Business Administration, Economics, Social Sciences, Mathematics, Computer Sciences, Trier University, 54296 Trier, Germany; s4aldora@uni-trier.de

CITATION

Dorakh A. (2024). Interdependence and specialization in the global semiconductor industry. Journal of Infrastructure, Policy and Development. 8(6): 2436. https://doi.org/10.24294/jipd.v8i6.2436

ARTICLE INFO

Received: 19 July 2023
Accepted: 6 November 2023
Available online: 3 June 2024

Abstract: Interdependence between the United States (U.S.), European Union (EU) and Asia in the semiconductor industry, driven by specialization, can serve as a preventive measure against disruptions in the global semiconductor supply chain. Moreover, with rising geopolitical tensions, the cost-intensive nature of the semiconductor industry and a slowdown in demand, interdependence and partnership provide countries with opportunities and benefits. Specifically, by analyzing global trade patterns, developing the Interdependence Index within the semiconductor market, and applying the Grubel-Lloyd Index to the U.S., the EU, and Asian countries from 2011 to 2022, our findings reveal that interdependence enhances regional semiconductor supply chains, such as the establishment of semiconductor foundries in the U.S., Japan, and the EU; reduces dependence on a single supplier, such as the U.S. distancing from China; and increases market share in different semiconductor segments, as demonstrated by Taiwan in automobile chips. The evidence indicates that China heavily depends on foreign sources to meet its semiconductor demand, while Taiwan and South Korea specialize as foundry service providers with lower Interdependence Index values. The U.S. maintains a moderate level of dependence on semiconductor imports due to its strong presence in manufacturing and research, while the EU exhibits a relatively higher level of interdependence, emphasizing its reliance on semiconductor imports. The stage-specific analyses indicate that the U.S. and the EU rely on Asia for semiconductor devices, while China and Taiwan have a higher dependence on American intermediate inputs and European lithography machines.

Keywords: Grubel-Lloyd Index; supply chain; lithography machines; FDI; automotive chip

1. Introduction

Semiconductors are critical components used in modern electronics, including not only smartphones but also biomedical technologies, industrial equipment, self-driving cars, and various electronic defense systems. The rapid development of artificial intelligence, the Internet of Things, 5G, as well as advanced driver assistance systems and electric vehicles, is a key driver for the semiconductor market. Semiconductors are the third most traded product globally in 2022, after petroleum and cars. According to the Boston Consulting Group, demand for semiconductor manufacturing is expected to grow by 56% by 2030 (BCG, 2021).

The semiconductor industry is highly complex and interdependent, with different stages of production and supply chain partners spread across numerous countries: a semiconductor could be designed in the U.S. or EU, manufactured in Taiwan using chemicals from Japan or Germany, equipment from the Netherlands, and packaged in China or Malaysia. This complexity has become increasingly vulnerable to recent disruptions from the COVID-19 pandemic, rising geopolitical tensions, export restrictions, and a decline in semiconductor trading activity.

The semiconductor shortage has already had a negative impact on economies, especially in the automobile industry in 2021: In Europe, vehicle production dropped by 3.3 million units, accounting for 24% of the globally lost vehicles, and in North America, it contributed to 25% of the losses (ACEA, 2022). This has made the EU and the U.S. among the most affected regions. As a response, countries aim to create partnerships and alliances with a broader range of suppliers and manufacturers to ensure a consistent and diverse supply of semiconductors.

Government initiatives, such as the CHIPS and Science Act of 2022 in the United States, the European Chips Act of 2023 focus on increasing domestic or regional semiconductor manufacturing capabilities with foreign direct investment (FDI). The U.S., in particular, stands out as a leader in this field, being the first to establish domestic semiconductor production in Arizona. Export controls on the sale of advanced chips and chip-making equipment to Chinese firms, originating from the U.S. and the EU, also aim to reduce dependence on a single country at the market, as disruptions can have far-reaching effects via industrial interdependence worldwide. However, while the analysis may already indicate a shift in the U.S. supply chain away from China to nearby countries (Mexico and Canada), China remains the primary source of semiconductors for the EU. Moreover, the EU's share in the global semiconductor market has significantly declined over the years. In the 1970s, the EU's share accounted for more than 40% of the global market, while the current share has diminished to only 8%. To address this, the EU aims to double its global share to 20% by 2030 (European Chips Act of 2023) (European Commission, 2021).

The global structure of the semiconductor supply chain is developed based on unique business models and production specialization. The semiconductor supply chain involves various production stages, ranging from research to design, front-end manufacturing (wafer fabrication), and back-end manufacturing (assembling, packaging, and testing). In the middle segment of semiconductor production, wafer fabrication in "fabs" involves processing silicon wafers with photoresists and chemicals to build integrated circuits, while lithography and etching processes define the specific circuit patterns. Packaging is the final step that encapsulates the chips and provides the necessary connections for integration into electronic devices (Mönch et al., 2018).

No single country today dominates all stages of the semiconductor supply chain. Semiconductor companies may specialize in one stage of the supply chain or integrate vertically across several stages, functioning as Integrated Device Manufacturers (IDMs). In this paper, based on trade data, Interdependence Index and the results of applying the Grubel-Lloyd Index to the U.S., the EU, and Asian countries from 2011 to 2022, we demonstrate that major European and American companies operate as IDMs, while Asian countries specialize more in manufacturing semiconductors.

As a result, Asian countries, including China, Taiwan, and South Korea, have significantly increased their market presence by adopting the new business model of fabs with locally specialized technical capabilities. Asian semiconductor giants Taiwan Semiconductor Manufacturing Company (TSMC) and Samsung produce 92% of the global market's advanced chips, while China is as a crucial source for semiconductor devices.

Rapid advancements in technology and weak demand for electronic devices have led to an oversupply of memory chips, resulting in a new trend: partnerships in automotive chip manufacturing. Namely, TSMC, which doesn't have a market share in the terminal automotive chip market, is deepening its collaboration with key automakers in Europe and the U.S.

The United States continues to hold a prominent position in the sector, since a dominant part of the global semiconductor exports ultimately ends up in electronic products for the U.S. Moreover, the U.S. and the EU account for more than 70% of semiconductor design work, which is not covered by trade data. The EU's role in the semiconductor industry is also noteworthy, as it produces raw materials, semiconductor equipment and advanced lithography machines that are crucially relied upon by semiconductor fabrication (fabs) in Taiwan and China.

At all stages of the semiconductor value chain, a significant trend of industry consolidation is evident due to increasing interdependence. In the following chapters, our primary focus will be on the perspectives of the EU and the U.S., with consideration of Taiwan's role as a key partner. Nevertheless, we will also draw comparisons with other major chip economies.

This paper contributes to the debate about whether geopolitical tendencies and interconnections with Asian countries, particularly with China, may disrupt the semiconductor supply chain and pose risks to national security. Contrary to concerns, it argues that economic interdependence, combined with the high concentration and specialization in the semiconductor industry, emphasizes the need for cooperation. We advocate for a more strategic approach towards China that does not compromise interdependence.

This research contributes to the existing literature by examining the interdependence and specialization between key partners in the semiconductor industry over 2011–2022 years. Our approach not only examines the countries trade dependence at the different stages of the semiconductor supply chain but also provides a description of the semiconductor production from the perspective of intermediate inputs and equipment. We quantify the interdependence within the semiconductor supply chain by creating the Interdependence Index and assessing intra-industry trade with the Grubel-Lloyd Index. Our analysis reveals that countries involved in multiple stages of semiconductor production, particularly in the U.S. and EU, exhibit a higher degree of vertical integration.

The remainder of the paper is structured as follows. In Section 2, we review key theoretical concepts and methodologies for measuring interdependence and specialization, including an analysis of business models in the semiconductor industry. Section 3 presents the descriptive analysis of trade interdependence in the semiconductor industry. Analyzing stage-specific and product group interdependence, as well as the interpretation of the results for each stage of the semiconductor supply chain for the sample countries, including the application of the Grubel-Lloyd Index, is presented in the fourth section. Some concluding remarks are made in Section 5.

2. Methodology and theoretical perspectives on cooperation

Although many scholars (Kleinhans and Lee, 2021; Martin et al., 2023; Thadani and Allen, 2023) and institutions (OECD, 2019) have explored the potential of value chain resilience through multilateral partnerships between the U.S., EU and Asian countries, far fewer have examined their interdependence and specialization, resulting from the specific business models in the semiconductor supply chains. Specialization enables countries to gain a competitive advantage, and it is crucial for the U.S. and the EU to enhance its collective capacity to improve its position in the global semiconductor value chain.

Semiconductor companies can be categorized into four types based on their level of integration and business model: Integrated Device Manufacturers (IDMs), fabless design firms, foundries, and outsourced assembly and test companies (OSATs). In the earlier years, IDMs dominated the industry, but the growing need for both investment and specialization gave rise to the fabless-foundry model (BCG, 2021; Mönch et al., 2018).

Since in the 2000s, horizontal segmentation started to separate semiconductor design firms from contract foundries, especially for advanced semiconductors such as integrated circuits (ICs), major European and American companies primarily operated as integrated device manufacturers, including Intel, NXP Semiconductors N.V. (NXP), and Infineon. As a result, despite certain manufacturing in the U.S., both the U.S. and the EU lack advanced chip foundries, mainly located in Asian countries, including TSMC in Taiwan and Samsung in South Korea. Moreover, in the EU, there are no large IC designers similar to those in the U.S., such as Broadcom, NVidia, and Qualcomm. The cost-intensive nature of the semiconductor industry necessitates cooperation between the EU, the U.S., and Southeast Asia, particularly Taiwan, to reshape the semiconductor supply chain.

Starting from 2023, partnerships in automotive and industrial chip manufacturing are becoming a new trend with the establishment of the European Semiconductor Manufacturing Company (ESMC) in Dresden. ESMC is projected to be 70% owned by TSMC, with Infineon, NXP, and Bosch as key collaborators.

Despite trade data and experts (Alfaro and Chor, 2023) suggesting a decrease in the direct U.S. sourcing from China, China continues to be the primary trade partner in the global semiconductor market. While the most researchers (Ciani and Nardo, 2022; Farrell and Newman, 2019) argue that interdependence increases the vulnerability of supply chains, this paper analytically contributes to an approach that economic interdependence via cooperation provide ways to reduce one-sided dependence for both the EU and the U.S.

The global structure of the semiconductor industry today reflects the theory of comparative advantage, which was originally proposed by Ricardo (1817). According to this theory, countries benefit from specializing in producing goods and services for which they have a lower opportunity cost compared to other countries. In the context of the semiconductor industry, the U.S., EU and Asia may have a different comparative advantage, which leads to trade and interdependence between them.

Comparative advantage, achieved through specialization, enables countries to fragmentize semiconductor production across borders and participate in the global semiconductor supply chain. No single country or firm holds dominance across all stages of the semiconductor value chain. Instead, specialization is observed, with different entities focusing on specific areas, necessitating trade at each stage of the semiconductor supply in this paper, we propose a comprehensive set of trade metrics and indices, including the Interdependence Index and the adopted Grubel-Lloyd Index, to identify specific stages in the semiconductor supply chain where interdependence and specialization exist.

To analyze the complexity of interdependence in the semiconductor industry, we embrace the Organization for Economic Cooperation and Development (OECD) practice (2019) and focus on the production of semiconductors in the middle segment of the chain, including processes such as wafer fabrication ("fabs"), lithography, etching, and packaging. However, we further enhance this approach by examining not only the different stages of the semiconductor supply chain but also by providing a description of the semiconductor value chain from the perspective of intermediate inputs and equipment. This is achieved through the development of an Interdependence Index and adopting the Grubel-Lloyd Index for each stage of the supply chain. Additionally, we assess the share of countries and their contributions at each stage of the supply chain of semiconductors.

In our study, the principal source of data is product-level trade statistics from the United Nations Commodity Trade Statistics Database (UN Comtrade), one of the most widely recognized and trusted datasets for trade statistics, maintained and published by the United Nations. It provides valuable insights into direct import and export patterns over time. These trade statistics are complemented by data from the Ministry of Finance, Taiwan, and the Ministry of Economic Affairs, Republic of China (R.O.C.) To enrich our analysis, we incorporate additional data from various sources, including information on multinational activity and FDI, as well as assessments of the state of the manufacturing sectors in the U.S. and the EU.

We collected trade for all major trade partners and semiconductor producers worldwide, including the EU, U.S., China, Taiwan, South Korea, and Japan, covering the years 2011 to 2022. Our focus was on each stage of semiconductor production and the relevant group of product categories (Appendix). Semiconductors (ICs) and semiconductor-related goods are grouped based on product categories into specific sets:

- Raw materials.
- Semiconductor equipment and lithography machines.
- Integrated circuits and semiconductor devices.

The product categories reflect the classification of the Harmonized Commodity Description and Coding System (HS codes) by the World Customs Organization on a six-digit level. This approach enables us to obtain valuable insights into the interdependence among the main trade partners and producers in the semiconductor industry, namely the U.S., EU, China, Taiwan, South Korea, and Japan. Furthermore, we conducted an analysis of trade patterns and dynamics at different stages of the semiconductor manufacturing, providing a comprehensive understanding of the interactions between these key partners. Additionally, we show how the exports and imports per stage are divided among various regions or countries.

To begin, we calculate an aggregate country Index of Interdependence Equation (1) in the semiconductor industry between the selected countries and the rest of the world (RoW). This Index aims to capture the level of integration of each trade partner in the global semiconductor value chain. Additionally, examining the Interdependence Index in the context of a country's business model within the semiconductor industry can provide valuable insights into its trade relationships and dependencies.

$$Country\ Interdependence\ Index = \left(\frac{Imports\ of\ semiconductor\ goods\ from\ RoW\ to\ Country}{Total\ Country\ imports}\right) / \left(\frac{Exports\ of\ semiconductor\ goods\ from\ Country\ to\ RoW}{Total\ Country\ exports}\right) \quad (1)$$

The EU Interdependence Index in the semiconductor industry focuses on overall trade flows between the EU and Asian countries. It calculates the ratio of imports from Asian countries to the EU to the total EU imports, and the ratio of exports from the EU to Asian countries to the total EU exports Equation (2). This index provides a measure of the extent to which the EU's, China's, or Taiwan's trade is interdependent. By analyzing the EU Interdependence Index, we can also assess the level of the significance of the semiconductor industry in facilitating interdependence.

$$EU\ Interdependence\ Index = \left(\frac{Imports\ of\ semiconductor\ goods\ from\ China\ (Taiwan)\ to\ the\ EU}{Total\ EU\ imports}\right) / \left(\frac{Exports\ of\ semiconductor\ goods\ from\ the\ EU\ to\ China\ (Taiwan)}{Total\ EU\ exports}\right) \quad (2)$$

The index value ranges from 0 to 1, where 0 represents no interdependence and 1 represents complete interdependence. A higher index value indicates a higher level of interdependence between the EU and Asian countries in semiconductor trade.

It's important to note that the level of interdependence may vary across the different stages of the semiconductor supply chain. While previous papers (Funke and Wende, 2022; Ji et al., 2023; OECD, 2019) have suggested dividing the semiconductor supply chain into stages, there is a lack of studies that calculate the Interdependence Index for each stage of the supply chain. In this study, we aim to fill this gap by developing the Interdependence Index for each semiconductor-related group of goods. Namely, we calculate the Interdependence Index for the groups of raw materials, semiconductor equipment and lithography machines, and semiconductor devices, which characterize different stages of the semiconductor supply chain. This Index allows us to quantitatively assess the degree of interdependence for each stage of the semiconductor supply chain between the EU and Asian countries.

The Grubel-Lloyd Index is a well-established and widely recognized measure that, when applied to the semiconductor sector reveals the extent of intra-industry trade and indicates the degree of horizontal specialization and a country's integration into the global supply chain for IDM semiconductor companies. Utilizing the methodology developed by Silber and Broll (1990), we employ the Grubel-Lloyd Index Equation (3) to assess specialization and product similarity within the semiconductor industry when comparing the EU or the U.S. and Asian countries. This index quantifies intra-industry trade, which involves the simultaneous export and import of similar products within the same industry.

$$Grubel - Lloyd\ Index = \left(1 - \frac{\Sigma|Xi - Mi|}{\Sigma(Xi + Mi)}\right) \quad (3)$$

where:

Xi represents the value of semiconductor exports from country *i* (EU) to country *j* (Asia);

Mi represents the value of semiconductor imports from country *j* (Asia) to country *i* (EU);

Σ indicates the summation over all relevant product categories in the semiconductor industry.

The higher Grubel-Lloyd Index would indicate a greater level of intra-industry trade and product similarity between the EU, the U.S. and Asian countries. Additionally, when a country has a high level of intra-industry trade in the semiconductor sector, it indicates that the country is both importing and exporting intermediate goods that suggests a higher degree of specialization and integration into the global value chain, particularly if the country is involved in various stages of semiconductor production, such as design, fabrication, packaging, and testing.

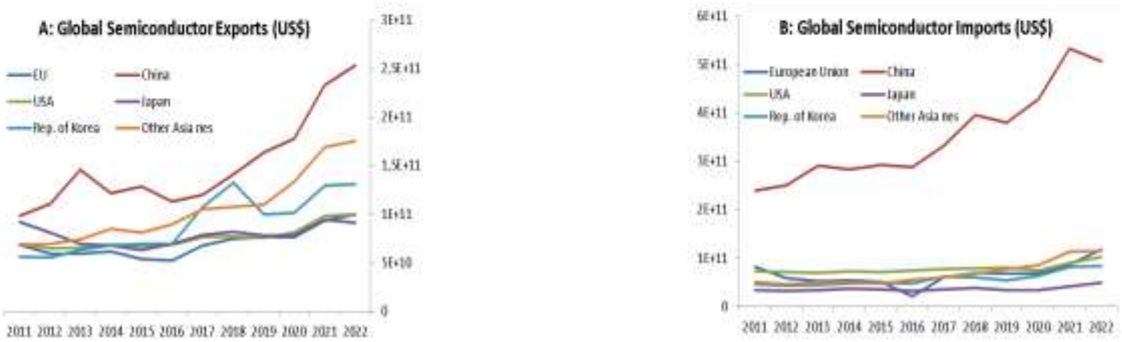
Conversely, a lower level of intra-industry trade may suggest a more vertical integration, particularly in the context of IDMs, where a country relies less on intermediate imports for final products. This suggests a higher degree of specialization for the EU and the U.S., where regions are engaged in the production and exchange of components for similar products with Asian countries, indicating a complementary relationship between partners. Understanding the patterns of trade interdependence and intra-industry dynamics can inform policymakers, industry stakeholders, and researchers about the opportunities for cooperation, associated with trade interdependence between the EU, U.S. and Asia in the semiconductor sector.

3. The global patterns of trade interdependence in the semiconductor industry

To identify the main trends in the semiconductor industry and emerging trade relationships, we first look for patterns and changes in trade volumes of semiconductors over the selected time period. For this, we visualize the trends in total exports (**Figure 1a**) and total imports (**Figure 1b**) of semiconductor-related goods and equipment of the main partners and the rest of the world. Additionally, the **Figure 1** helps us identify any notable shifts in trade volumes and potential growth markets that may be shaping the industry's landscape.

Figure 1 shows that the exports and imports of semiconductors of Asian countries increased substantially over the observed period, particularly in China, Taiwan, and South Korea. Looking at the imports (**Figure 1b**), the value of Chinese imports of semiconductors is growing at a faster rate compared to that of the EU and the U.S. Since the introduction of China's semiconductor policy in 2014, the import of semiconductor-related goods and equipment in China has increased threefold. Additionally, the import of semiconductors of China far exceeds exports (**Figure 1a**). In fact, China accounts for 60% of global demand for semiconductors due to the concentration of global consumer electronics production there. Although China has experienced a significant increase in its semiconductor trade values, and has expanded its presence in the semiconductor value chain in recent years, it still lags behind South Korea and Taiwan as a semiconductor producer (Platzer et al., 2020).

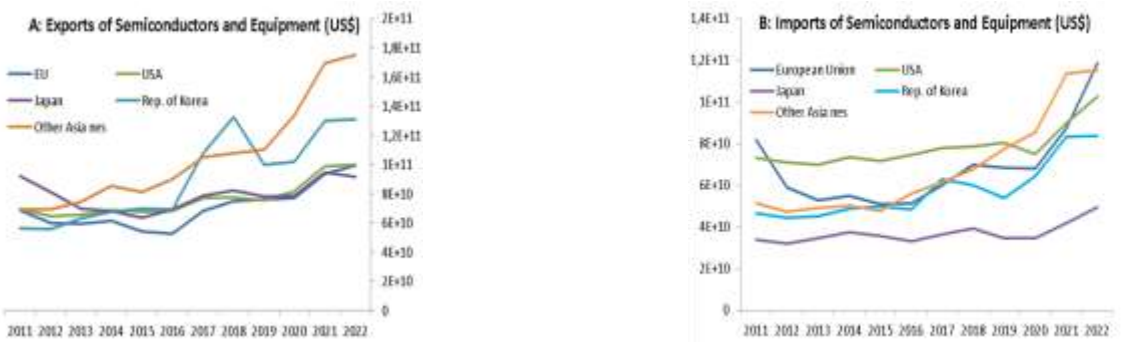
Zooming in on the trends among other main partners, disregarding the volume of China's trade in the sector, Taiwan and South Korea have demonstrated a more pronounced growth in semiconductor exports and imports. Indeed, most of the world's fabs are located in the Indo-Pacific region. Taiwan and South Korea are also the largest purchasers of wafer fabrication, assembly, and test equipment (**Figure 2**).



(a) **(b)**

Figure 1. **(a)** global semiconductor exports from 2011 to 2022 (US$); **(b)** global semiconductor imports from 2011 to 2022 (US$).

Sources: International trade statistics of the United Nations (UN Comtrade) and own calculations.
Notes: Semiconductor-related goods and equipment are classified according to the HS codes and grouped as per Chapter 2, which includes raw materials, semiconductor manufacturing equipment, semiconductor devices, and lithography machines. The trade data for Taiwan, Province of China, is categorized under "Other Asia, nes".



(a) **(b)**

Figure 2. **(a)** exports of semiconductors and equipment (US$); **(b)** imports of semiconductors and equipment (US$).

Sources: International trade statistics of the United Nations (UN Comtrade) and own calculations.
Notes: Semiconductor-related goods and equipment are classified according to the HS codes and grouped as per Chapter 2, which includes raw materials, semiconductor manufacturing equipment, semiconductor devices, and lithography machines. The trade data for Taiwan, Province of China, is categorized under "Other Asia, nes".

As seen from **Figure 2**, starting from 2016, exports and imports in Taiwan and South Korea increased sharply, at a time when EU companies began shifting to fabless models. At all stages of the semiconductor value chain, a broad movement of industry consolidation was apparent in the increasing number of new fabs in Asian countries. Additionally, Taiwan made significant investments in leading-edge manufacturing technology, which led to TSMC becoming the world leader in advanced chip production (Ciani and Nardo, 2022). From this time, European countries increased their reliance on foreign suppliers from Asian countries, and the EU's imports of semiconductor goods has grown by approximately 131.62% from 2016 to 2022 (**Figure 2b**).

When imports of semiconductors to the EU, U.S., and Japan have started to actively grow over the past years (**Figure 2b**), the exports have been relatively stagnant for most of the period, with a recent increase (**Figure 2a**). Consequently, this trend has resulted in an expansion of the semiconductor trade deficit for the EU and the U.S.

Based on the findings presented in **Figure 1** and **Figure 2**, it is evident that each of the main semiconductor exporters and producers is also a semiconductor importer. Not all semiconductor goods are equal, and no producer specializes in every semiconductor product category, which means that exporters and importers are interdependent.

To represent how each country is integrated into the semiconductor global value chains, we introduce and calculate an aggregate Index of Interdependence in the semiconductor industry between the selected countries and rest of the world (**Table 1**).

Table 1. Interdependence Index in the semiconductor industry in 2022.

Trade partners	Interdependence index in the semiconductor industry	Grubel-Lloyd Index in the semiconductor industry
China	2.641	0.67
EU	1.022	0.91
Taiwan	0.784	0.80
South Korea	0.664	0.78
U.S.	0.627	0.99
Japan	0.450	0.70

Source: Own calculations based on the international trade statistics of the United Nations (UN Comtrade). Note: Interdependence index in the semiconductor industry calculated between the selected countries and the rest of the world (RoW).

By comparing values of the Interdependence Index for main trade partners in the semiconductor supply chain (**Table 1**), China has the highest degree of internationalization and external orientation of a country's semiconductor industry. It suggests that the country has a high dependency on foreign sources for meeting its semiconductor demand and has a high level of integration in the global semiconductor value chains. Indeed, China is not only a significant consumer of semiconductor products but also a major manufacturer of various components and automotive electronics and electronic devices that use semiconductors. Its position as both a producer and a consumer contributes to a high Interdependence Index.

Conversely, the lower Interdependence Index for Taiwan and South Korea compared to China highlights their specialized role as foundry service providers. Their export-oriented semiconductor manufacturing, coupled with balanced trade relationships, underlines their significance in the global semiconductor industry as key contributors to manufacturing and production capabilities. The relative low Interdependence Index suggests that their role is primarily export-oriented.

The United States holds a substantial position in the global semiconductor industry. The Interdependence Index of 0.627 (**Table 1**), indicating a moderate level of dependence on semiconductor imports, aligns with the U.S.'s role as a significant player in the semiconductor manufacturing, research, and development sectors. This index value suggests that while the U.S. participates in the global semiconductor supply chain and imports certain semiconductor-related components, it also has a degree of self-sufficiency in semiconductor production, particularly in the context of Integrated Device Manufacturers. By contrast, when comparing the EU's Interdependence Index of 1.022 to other regions or countries, it becomes evident that the EU exhibits a relatively higher level of interdependence in the semiconductor industry. This suggests a stronger reliance on semiconductor imports and a close linkage to global semiconductor supply chains, confirming that the EU relies predominantly on IDMs in the technology and electronics sectors. It also may imply that for specific stages of the semiconductor supply chain its trading partners rely on the EU for other components for production, raw materials and chemicals. This mutual strategic dependence reflects the complex and interconnected nature of global semiconductor trade.

Japan, with an Interdependence Index value of 0.450 (**Table 1**), showcases a minimal reliance on foreign sources within the semiconductor industry. This suggests that Japan likely possesses a self-sufficient or robust domestic semiconductor manufacturing sector, enabling it to minimize its dependence on imports and maintain a heightened level of independence in fulfilling its semiconductor needs.

The Grubel-Lloyd Index in the semiconductor industry (**Table 1**) reflects a higher degree of specialization in the U.S. and the EU within the industry, driven by their specific business models in semiconductors, such as IDMs and foundries, where both regions are actively involved in the intra-industry exchange. This implies a complementary relationship with partner countries. In contrast, China exhibits the lowest value of the Grubel-Lloyd Index, indicating that the country's business model, which includes mostly fabless design firms and foundries, leans towards reliance on imports of semiconductor-related goods rather than exporting them.

To compute a detailed EU Interdependence Index within the semiconductor supply chain, we initiate the process by identifying the pivotal countries from which the EU procures semiconductor-related products. Simultaneously, we spotlight the primary destinations for EU semiconductor exports, with a specific emphasis on China and Taiwan. In this context, we calculate the market share of semiconductor exports and imports for each country within the sample for the most recently available year. Subsequently, these market shares are ranked, and we pinpoint the top 10 partners with the most substantial market shares in terms of trade values (**Figure 3**).

(a) **(b)**

Figure 3. Export and import partners of the EU semiconductor industry in 2022 (%).

Sources: Own calculations based on the international trade statistics of the United Nations (UN Comtrade). Notes: Semiconductor exports and imports encompass semiconductor-related goods and equipment as per Chapter 2 classification. The trade data for Taiwan, Province of China, is categorized under "Other Asia, nes".

As seen from **Figure 3**, Asian countries, such as Taiwan, China, South Korea, have emerged as the key trading partner for the EU in both the import and export of semiconductor-related goods. While the United States has traditionally been the primary exporter to the EU market, China now is the largest importer for the EU in the semiconductor supply chain. However, China's rapid development in semiconductors has resulted in expanding economic ties with the EU and the U.S., where the strategic import dependence in some parts of supply chains is mutual. Indeed, the obtained results of the Interdependence Index and the Grubel-Lloyd Index imply that China imports more semiconductor-related goods than it exports, suggesting a high dependence from other countries, namely the U.S. and the EU.

This analysis of European semiconductor trade patterns directly confirms the data from the Semiconductor Industry Association (SIA) (2021) that the sample countries together with Malaysia and Singapore, involving in various stages of semiconductor supply chain, collectively accounted for close to 80% of global trade in semiconductor-related goods. While trade data may not provide an exact representation of semiconductor production, it does suggest that more than 75% of chips were traded from East Asia, indicating that manufacturing took place primarily in the region, with China and Taiwan emerging as prominent players in the industry. This greatly encourages trade by lowering the supply costs, making trade an essential operational aspect of semiconductor production.

A more detailed snapshot of the role of the main trade partners in the global supply chain of semiconductors and the interdependence at the different stages of supply chain between the EU, U.S., and Asian countries can be obtained by stage-specific and the product group analyzing.

4. EU stage-specific and the product group interdependence in the semiconductor sector

The production of semiconductors begins from the detailed product specifications with intermediate inputs, namely silicon, gallium, arsenic, germanium and other chemicals. Europe, partially Germany, occupies a critical space in the materials supply chain, especially in the chemical sector.

The interdependence and specialization between the EU and China in the raw materials (**Figure 4**) supply chain confirm the EU patterns of the semiconductor trade. With more than 30% of the global market share, the EU is a major supplier of chemicals to various industries worldwide (Eurostat, 2022). Asian countries, particularly China, heavily rely on European imports for chemicals. China, on the other hand, holds a strong position in the supply of certain raw materials, such as low-grade gallium and germanium, which are used in electronics and semiconductors in Europe. Indeed, the EU has a higher Interdependence Index in raw materials with China compared to Taiwan that indicates that the EU is more reliant on imports of raw materials for the semiconductor industry from China than from Taiwan in 2022.

Taiwan's semiconductor industry relies on imported chemicals from the EU less than China does. A decreasing Grubel-Lloyd Index (**Figure 4**) suggests a decline in the proportion of raw materials being traded between the EU and Taiwan in the semiconductor industry. Possible reasons for this could include an increase intra-industry trade with Japan and the U.S. However, when it comes to high-purity silicon wafers, Taiwan is a major importer (**Figure 5**).

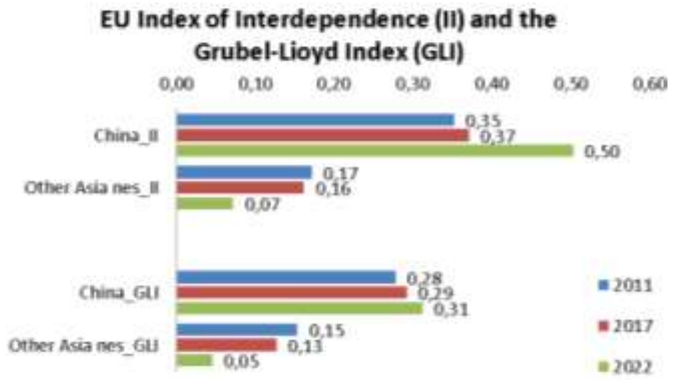


Figure 4. EU Index of Interdependence (II) and the Grubel-Lloyd Index (GLI) in raw materials.

Sources: Own calculations based on the international trade statistics of the United Nations (UN Comtrade). Notes: China_II and China_GLI represent the Interdependence Index and the Grubel-Lloyd Index, respectively, for raw materials in the semiconductor sector between the EU and China. Similarly, Other Asia nes_II and Other Asia nes_GLI refer to the Interdependence Index and the Grubel-Lloyd Index, respectively, for raw materials between the EU and Taiwan.

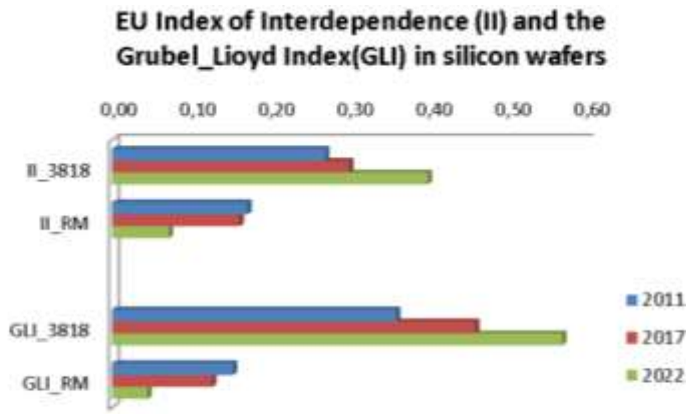


Figure 5. Index of Interdependence (II) and the Grubel-Lloyd Index (GLI) in silicon wafers between the EU and Taiwan.

Sources: Own calculations based on the international trade statistics of the United Nations (UN Comtrade). Notes: II_3818 and II_RM represent the Interdependence Index for raw materials and silicon wafers, respectively, in the semiconductor sector between the EU and Taiwan. Similarly, GLI_3818 and GLI_RM refer to the Grubel-Lloyd Index for raw materials and silicon wafers, respectively, between the EU and Taiwan.

As seen from **Figure 4**, the EU Index of Interdependence (II) and the Grubel-Lloyd Index (GLI) in raw materials between China and Taiwan exhibited contrasting trends from 2011 to 2022. The EU Index of Interdependence (II) with China increased by 15 percentage points (p.p.) over the period. In contrast, the Index for Taiwan decreased by 10 p.p. during the same period. The Grubel-Lloyd Index (GLI) also displayed a similar pattern, with an increase for China and a decrease for Taiwan in raw materials. Nevertheless, in the case of high-purity silicon wafers, Taiwan stands out as a prominent importer.

High-purity silicon wafers are a crucial material in semiconductor manufacturing. Silicon wafers make up the largest portion of the materials market and a third of total semiconductor materials sales in recent years (Thadani and Allen, 2023). Taiwan's semiconductor industry heavily depends on imported silicon wafers, also from the EU, since Taiwan is one of the world's largest producers of semiconductors (**Figure 5**). This indicates a strengthening level of interdependence in silicon wafers between Taiwan and the EU, confirming that Taiwan imports intermediate inputs for production, which aligns with its strong foundry business model. At the same time, the high level of interdependence and intra-industry trade between the EU and Taiwan in silicon wafers, coupled with a high level of imported finished semiconductors, suggests, by analogy with the U.S., the presence of IDMs and fabless design firms within the semiconductor industry in the EU.

The calculated results of interdependence in raw materials for semiconductor production between the EU and Asian countries are robustly supported by the trends observed in global export flows and the dynamics of raw material sourcing (**Figure 6**).

As seen from **Figure 6**, China is the largest net importer of raw materials from the EU, particularly from Germany. China holds a significant market share in global exports, with approximately 35% of global germanium exports and 38% of global silicon carbide exports originating from China (Ji et al., 2023). These observations highlight the significant role of China, serving as a substantial consumer of EU raw materials while also emerging as a major exporter of essential raw materials for the semiconductor industry.

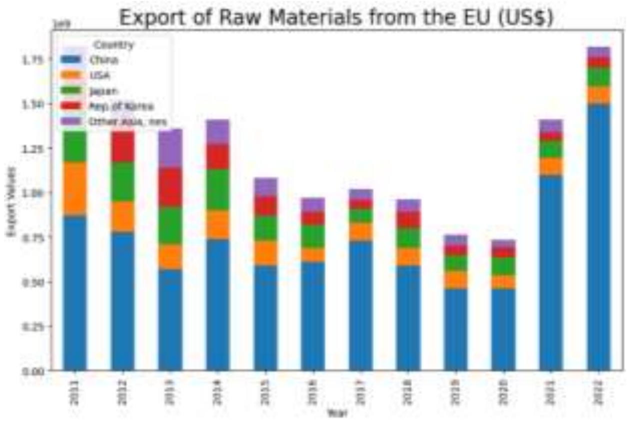


Figure 6. EU Export of raw materials in the semiconductor industry (US$).

Sources: International trade statistics of the United Nations (UN Comtrade) and own calculations.
Notes: Raw materials are classified according to HS codes and grouped based on Chapter 2. The trade data for Taiwan, Province of China, is categorized under "Other Asia, nes".

At the same time, the EU, U.S., and Japan have been the three major suppliers dominating the global gallium arsenide semiconductor component substrate market for over 30 years (Chan, 2023). Consequently, the Chinese government's decision to impose export controls on gallium from August 2023 will not have a significant negative impact on the industry supply chain.

At the next stage of the semiconductor manufacturing, silicon and other semiconductor raw materials are melted and cast in the form of a large shape known as an ingot and then sliced into wafers using lithography machines. The slicing process is a critical step in creating the necessary substrates for semiconductor production and requires cutting-edge equipment.

Semiconductor manufacturing equipment that facilitates the production is expensive and extremely difficult to make. As such, its supply is highly concentrated in key companies and regions. Most of the world's equipment producers are located in the countries of the EU, U.S., and Japan, collectively capturing over 70 percent of the global semiconductor manufacturing equipment market share by exports (UN Comtrade, 2023).

Semiconductor manufacturing equipment includes wafer fabrication on the front end as well as semiconductor assembly, test, and packaging equipment for back-end fabrication. The EU has a large trade surplus in manufacturing equipment for the both production of wafers and advanced assembly, test and packaging equipment (**Figure 7**).

Almost half of all EU equipment exports originate from the Netherlands and are mostly produced by Advanced Semiconductor Materials Lithography (ASML). Asian foundries purchase semiconductor equipment mostly from ASML, which is renowned for their advanced technology and expertise in the lithography machines. As seen from **Figure 7**, the export of semiconductor equipment from the EU has exhibited steady growth over the selected period. However, there was a slight drop in 2022, which could potentially be attributed to export control measures implemented from October 2022 onwards.

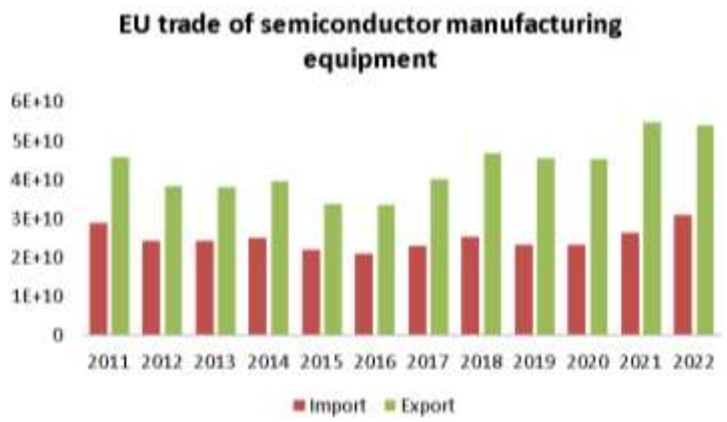


Figure 7. EU exports and imports of semiconductor manufacturing equipment (US$).

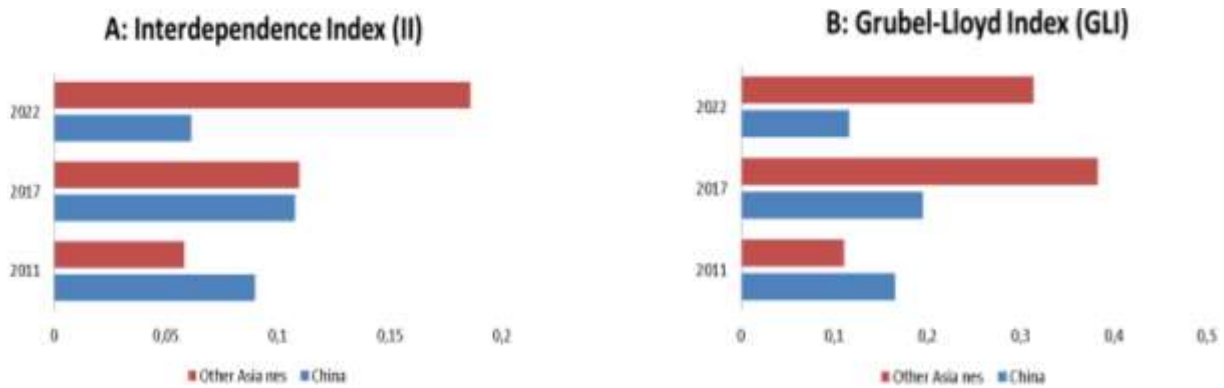
Sources: International trade statistics of the United Nations (UN Comtrade) and own calculations.
Notes: Semiconductor manufacturing equipment is classified to HS codes and grouped based on Chapter 2 and Appendix.

Taiwan and South Korea, and more recently China, are the countries accounting for the majority of EU exports of manufacturing machines. The import of such equipment and machines is essential for supporting the operations of the foundries in Asia and ensuring their competitiveness in the global semiconductor market. This demonstrates the clear interdependence between regions, as the foundries heavily rely on imported technology and equipment to effectively sustain their operations. This interdependence is supported by our calculated results of the Interdependence Index (II) and the Grubel-Lloyd Index (GLI) between the EU and Asian partners (**Figure 8**).

As seen, the level of interdependence and intra-industry trade in semiconductor manufacturing equipment between the EU and Taiwan is higher than with China. This indicates that Taiwan holds a prominent position as a world-leading foundry in ICs that rely on lithography machines from ASML.

The Interdependence Index between the EU and Asian countries in the semiconductor equipment sector has undergone a shift. In 2011, the Interdependence Index indicated a higher level of interdependence with China, while in 2022, it indicates a higher level of interdependence with Taiwan (**Figure 8a**). This suggests a change in the dynamics of trade and collaboration in the semiconductor equipment industry between the EU and Asian countries.

The higher Grubel-Lloyd Index (**Figure 8b**) in the semiconductor industry in Taiwan compared to China means a higher degree of specialization and a greater concentration on certain good (ICs) in semiconductor sector in Taiwan.



(a) **(b)**

Figure 8. Index of semiconductor manufacturing equipment. **(a)** EU Index of Interdependence; **(b)** Grubel-Lloyd Index.

Sources: Own calculations based on the international trade statistics of the United Nations (UN Comtrade). Notes: Semiconductor manufacturing equipment is classified to HS codes and grouped based on Chapter 2 and Appendix. The trade data for Taiwan, Province of China, is categorized under “Other Asia, nes”.

Additionally, the higher GLI than the Interdependence Index (**Figure 8**) implies that the trade concentration between the EU and Taiwan in the semiconductor equipment sector, namely lithography machines, is relatively high compared to the overall interdependence. Indeed, Taiwan is the main destination market for EU machines for the production of semiconductors and integrated circuits, while China is the main importer of EU machines for the production of boules and wafers, and for the production of flat panel displays (Ciani and Nardo, 2022).

At the same time, China’s manufacturing strength is not only in low-tech but is also expanding into high-tech sectors (**Table 2**) that requires advanced semiconductor equipment to support its manufacturing operations.

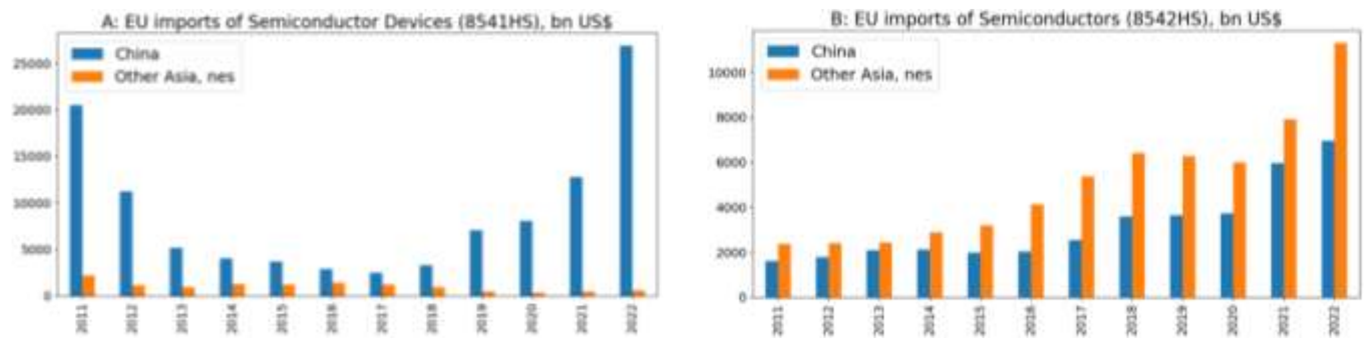
As seen from **Table 2**, most of the European advanced machinery is exported to Taiwan, but China and South Korea also receive a large share of the equipment. In particular, access to the ASLM’s ultraviolet lithography is vital for China’s ambitions to build up a competitive semiconductor industry. The Dutch government’s announcement on June 30, 2023 of export controls on advanced lithography machines, including those manufactured by ASML, signifies a change in the semiconductor trade interdependence between China and the EU. While this move may help to secure and diversify the semiconductor supply chain, it also can have economic consequences for Dutch companies involved in the production and export of these lithography machines. Export controls could restrict their ability to sell these machines to Chinese customers, impacting their profits and market share.

Table 2. Share of EU exports of advanced semiconductor equipment to Asian countries (%).

Trade partners	Share of export to Taiwan	Share of export to China	Share of export to South Korea
2019	0.48	0.18	0.10
2021	0.41	0.17	0.30
2022	0.44	0.15	0.25

Source: Own calculations based on the international trade statistics of the United Nations (UN Comtrade). Note: The share of EU exports of advanced semiconductor equipment is calculated between the selected countries as a percentage of total EU exports for the specific HS group of goods (HS codes 848620 and 848640).

At the last stage of the semiconductor manufacturing, the wafers and equipment serve as the foundation for fabricating individual semiconductor devices, such as microchips and integrated circuits. Specialization in semiconductor equipment, such as advanced lithography machines and fabrication tools (**Table 2**), may contribute to the level of advancement in chip production. Indeed, the disparity in specialization in semiconductor equipment between Taiwan and China has indeed contributed to the difference in their levels of advancement in semiconductor chip production, Taiwan, specifically known for its semiconductor industry hub, has developed advanced capabilities in chip manufacturing. TSMC is a leader in advanced high-performance chips for various applications, including consumer electronics, automotive, and artificial intelligence. On the other hand, while China has been investing heavily in its semiconductor industry, it is generally considered to be a step behind Taiwan in terms of advanced chip manufacturing. However, China has a strong presence in the production and export of less advanced semiconductor devices in this category (**Figure 9**).



(a) **(b)**

Figure 9. (a) EU imports of semiconductor devices (8541HS); **(b)** EU imports of semiconductor (8542HS).

Sources: International trade statistics of the United Nations (COMTRADE) and own calculations. Notes: Semiconductor parts under Harmonized System (HS) code 8541 and HS code 8542 (latest observations are from 1 January 2023). In practice, only trade of Taiwan, Province of China is included under "Other Asia, nes" (code 490).

As seen from **Figure 9a**, in the sector of diodes, transistors, and similar semiconductor devices (HS code 8541) China has a dominant position, while Taiwan an advantage in exporting to the EU goods in the most advanced chips and memories **(Figure 9b**). Indeed, according to UN Comtrade and Eurostat data, in 2016–2017, China accounted for an average of about 20–28% of the EU's semiconductor imports in the category 8541 HS, while in 2020 that number had raised to around 60%. Notably, China's share of EU imports in this category has continued to rise, surpassing 80% in 2022. This trend highlights the significant role that China plays in the EU's semiconductor market. Taiwan is the leading exporter of integrated circuits to the EU, accounting on average, for around 20% of EU imports in this category for the period 2017–2022.

Figure 10 illustrates the application of the EU Index of Interdependence (II) and the Grubel-Lloyd Index (GLI) in analyzing the interdependence and intra-industry trade between the EU and Asian countries in ICs and semiconductor devices. By examining the values of these indices, it is possible to assess the extent to which the EU and Asian countries rely on each other for imports and exports of semiconductor devices and integrated circuits.

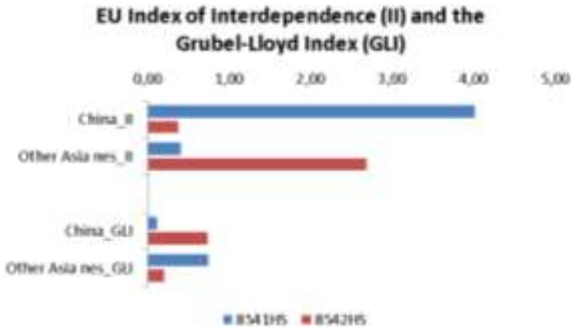


Figure 10. EU Index of Interdependence (II) and the Grubel-Lloyd Index (GLI) in semiconductor devices and integrated circuits in 2022.

Sources: Own calculations based on the international trade statistics of the United Nations (UN Comtrade). Notes: Semiconductor devices and integrated circuits are classified to HS codes and grouped based on Chapter 2 and Appendix. The trade data for Taiwan, Province of China, is categorized under "Other Asia, nes".

As seen from **Figure 10**, the EU Interdependence Index value in diodes and transistors as a part of electrical machinery and electronics (8541HS), greater than 1. This indicates that the EU has a higher level of dependency on semiconductor imports from China compared to its own semiconductor exports. This suggests that the EU relies more on foreign sources for semiconductor goods to meet its domestic demand. By analogy, a similar pattern is observed in the EU's dependency on electronic integrated circuits (8542HS) imports from Taiwan compared to its own semiconductor exports. Additionally, a Grubel-Lloyd Index value below 0.8 suggests a lower level of intra-industry trade in that particular category.

However, if we compare the EU Index of Interdependence (II) and the Grubel-Lloyd Index (GLI) in semiconductor devices (**Figure 10**) with the indices in semiconductor manufacturing equipment (**Figure 8**) or the indices in silicon wafers (**Figure 5**) or in raw materials (**Figure 4**), we can draw conclusions about the interdependence in both directions between the EU, China, and Taiwan.

Indeed, if the EU Index of Interdependence in semiconductor manufacturing equipment and materials is between 0.06 and 0.49, it implies that the EU is a net exporter of semiconductor equipment and raw materials, has a lower dependence on China and Taiwan in these specific categories. This suggests that the EU has a relatively higher level of self-sufficiency and export competitiveness in the intermediate inputs and lithography machines. On the other hand, as the index of semiconductor devices is greater than 1, it indicates that the EU has a higher level of dependency on semiconductor device and integrated circuits imports from China and Taiwan compared to its own semiconductor device exports.

By considering both indices, we gain insights into the interdependence and trade dynamics between the EU, China, and Taiwan in the semiconductor industry, with the EU playing a significant role as a net exporter of semiconductor equipment while relying more on imports of semiconductor devices.

In general, electronic integrated circuits (HS code 8542) and diodes, transistors, and similar semiconductor devices (HS code 8541) have a positive dynamic in import from Asia that turned over in negative trade balance resent years. This dependence on China and Taiwan in semiconductors is because electronic integrated circuits and semiconductor products are highly demanded, supply chains spread across multiple countries, and domestic production capacity in the EU are limited. This means that the EU's semiconductor trade deficit is likely to persist in the near future, with the EU importing more semiconductors than it exports. To address this issue and strengthen the EU's semiconductor production capabilities, it may be necessary to attract FDI from Asia in the sector and enhance partnerships with the U.S.

5. Results and discussion

In an era where geopolitical tensions and conflicts between major powers can disrupt global semiconductor supply chains, the interdependence and specialization in the sector serve as a pathway to stability. This paper allows Europe, the U.S., and Asia to recognize the benefits of interdependence and specialization in the semiconductor industry through cooperation.

The semiconductor supply chain is not dominated by any single country today. Rather, semiconductor exporters and producers depend on imports, fostering interdependence and facilitating trade. This emphasizes the limitations of direct and unilateral country changes to the global semiconductor supply chain.

The trade analysis reveals that cooperation and interdependence between semiconductor partners facilitates the growth of regional semiconductor supply chains, encourages the establishment of semiconductor foundries in the U.S., Japan, and the EU, reduces reliance on single suppliers (e.g., the U.S. distancing from China), and contributes to increased market share in various semiconductor segments, exemplified by Taiwan's success in automobile chips.

This paper investigated also how interdependence shapes the dynamics of the semiconductor industry, specifically focusing on the semiconductor trade interdependence between the U.S., the EU and Asian countries over 2011–2022. To assess the degree of their interdependence and specialization in the semiconductor industry, we developed the Interdependence Index and applied the Grubel-Lloyd Index.

The analysis of global patterns of trade interdependence in the semiconductor industry show that the exports and imports of semiconductors of Asian countries increased substantially over the observed period, growing at a faster rate compared to that of the EU and the U.S. Asian countries have seen substantial expansion in the semiconductor trade, indicating increasing interdependence with the EU and the U.S.

The choice of business model, such as Integrated Device Manufacturers (IDMs) or foundries, can impact the level of interdependence and specialization within the semiconductor industry.

The Interdependence Index provides valuable insights into the global semiconductor landscape. China has the highest index, signifying its crucial role as both a consumer and producer in the global semiconductor value chain. Taiwan and South Korea are specialized foundry service providers with lower Interdependence Index values. The U.S. maintains moderate dependence on semiconductor imports, driven by its strong presence in manufacturing and research, particularly with IDMs. In contrast, the EU exhibits a relatively higher level of interdependence, emphasizing its reliance on semiconductor imports, especially in advanced semiconductors. Japan’s low Interdependence Index showcases self-sufficiency in semiconductor manufacturing, reducing dependence on imports. The Grubel-Lloyd Index highlights the U.S. and EU’s specialization, while China’s business model leans towards importing semiconductor-related goods, mainly for fabless design firms and foundries.

The EU’s Interdependence Index and the Grubel-Lloyd Index reveal diverging trends in raw materials, particularly the dominance of the EU, U.S., and Japan in the gallium arsenide industry. Taiwan and South Korea are key destinations for EU manufacturing machines, but export controls on lithography machines may alter the semiconductor trade dynamics between the EU and China. Namely, export controls, while aiming to secure and diversify the semiconductor supply chain, can have economic consequences for Dutch companies, particularly ASML, by limiting their sales to Chinese customers, which could potentially impact their profits and market position.

The EU’s Interdependence Index in semiconductor devices exceeds 1, indicating a high reliance on imports from China. A similar pattern is seen in the EU’s dependence on advanced chips from Taiwan. However, the EU’s Interdependence Index and the Grubel-Lloyd Index in manufacturing equipment, silicon wafers, and raw materials demonstrate significant interdependence and trade between the EU, China, and Taiwan, reflecting a mutual flow of dependencies and collaboration.

In general, the EU, the U.S. and Japan specialize in exporting upstream components of the semiconductor value chain, including silicon wafers, specialty gases, and chemicals, equipment. Similarly, the EU Japan are significant exporters of lithography machines. In contrast, China is a major importer of semiconductors and devices, which it incorporates into electronics, while South Korea and Taiwan import silicon wafers and equipment for chip production in their semiconductor foundries.

Cooperation in the semiconductor industry offers unique opportunities and challenges for regions such as the EU, US, Asian countries (e.g., South Korea, Taiwan, China), and Japan. To capitalize on their respective strengths, strategies encompass cross-border R&D collaboration, the establishment of common standards, education and sustainability investments, public-private partnerships, and supply chain security. These efforts may collectively enhance global semiconductor industry stability and sustainability through international cooperation.

Ultimately, the forces of interdependence within the globalized semiconductor industry should be seen as a positive, as they can act as a stabilizing counterweight to potential geopolitical turbulence. However, it is crucial to address the national security challenges and find the right balance in the complex semiconductor supply chain.

Conflict of interest: The author declares no conflict of interest.

References

ACEA. (2022). Economic and market report: State of the EU auto industry—Full-year 2022. Available online: https://www.acea.auto/files/Economic-and-Market-Report_Full-year-2022.pdf (accessed on 9 November 2023).

Alfaro, L., Chor, D. (2023). Global supply chains: The looming "Great Reallocation". Available online: https://www.kansascityfed.org/documents/9747/JH_Paper_Alfaro.pdf (accessed on 9 November 2023).

BCG & Semiconductor Industries Association. (2021). Strengthening the global semiconductor value chain in an uncertain era. Available online: https://www.semiconductors.org/wp-content/uploads/2021/05/BCG-x-SIA-Strengthening-the-Global-Semiconductor-Value-Chain-April-2021_1.pdf (accessed on 9 November 2023).

Ciani, A., Nardo, M. (2022). The position of the EU in the semiconductor value chain: Evidence on trade, foreign acquisitions, and ownership. Available online: https://joint-research-centre.ec.europa.eu/publications/position-eu-semiconductor-value-chain-evidence-trade-foreign-acquisitions-and-ownership_en (accessed on 9 November 2023).

Chan, I. (2023). Impacts of China's gallium export control on the supply chain. DIGITIMES Asia. Available online: https://www.digitimes.com/news/a20230711PD201.html (accessed on 12 July 2023).

European Commission. (2021). 2021 Strategic Foresight Report: The EU's Capacity and Freedom to Act. European Commission.

Eurostat. (2022). China-EU—International trade in goods statistics. Available online: https://ec.europa.eu/eurostat/web/international-trade-in-goods/database (accessed on 9 November 2023).

Farrell, H., Newman, A. (2019). Weaponized interdependence: How global economic networks shape state coercion. International Security, 44(1). 42–79.

Funke, M., Wende, A. (2022). Modeling semiconductor export restrictions and the US-China trade conflict. Available online: https://papers.ssrn.com/sol3/papers.cfm?abstract_id=4307050 (accessed on 9 November 2023).

Ji, K., Nauta, L., Powell, J. (2023). Mapping global supply chains—The case of semiconductors. Available online: https://www.rabobank.com/knowledge/d011371771-mapping-global-supply-chains-the-case-of-semiconductors (accessed on 9 November 2023).

Kleinhans, J. P., Lee, J. (2021). China's rise in semiconductors and Europe. Available online: https://www.stiftung-nv.de/sites/default/files/chinas_rise_in_semiconductors_and_europe.pdf (accessed on 9 November 2023).

Martin, B., Baldwin, L. H., DeLuca, P., et al. (2023). Supply chain interdependence and geopolitical vulnerability: The case of Taiwan and high-end semiconductors. Available online: https://www.rand.org/pubs/research_reports/RRA2354-1.html (accessed on 9 November 2023).

Mönch, L., Uzsoy, R., Fowler, J. W. (2018). A survey of semiconductor supply chain models part I: semiconductor supply chains, strategic network design, and supply chain simulation. International Journal of Production Research, 56(13), 4524–4545.

OECD. (2019). Measuring distortions in international markets: The semiconductor value chain. Available online: https://www.oecd-ilibrary.org/trade/measuring-distortions-in-international-markets_8fe4491d-en (accessed on 9 November 2023).

Ricardo, D. (1817). On the Principles of Political Economy and Taxation. Liberty Fund, Inc. pp. 160–162.

Platzer, M. D., Sargent, J. F., Sutter, K. M. (2020). Semiconductors: U.S. industry, global competition, and federal policy. Available online: https://crsreports.congress.gov/product/pdf/R/R46581 (accessed on 9 November 2023).

Silber, J., Broll, U. F. (1990). Trade overlap and trade pattern indices of intra-industry trade: Theoretical distinctions versus empirical similarities. Available online: https://www.econstor.eu/bitstream/10419/101755/1/770157408.pdf (accessed on 9 November 2023).

Semiconductor Industry Association. (2021). State of the US semiconductor industry. Available online: https://www.semiconductors.org/wp-content/uploads/2021/09/2021-SIA-State-of-the-Industry-Report.pdf (accessed on 9 November 2023).

Thadani, A., Allen, G. C. (2023). Mapping the semiconductor supply chain: The critical role of the Indo-pacific region. Available online: https://csis-website-prod.s3.amazonaws.com/s3fs-public/2023-05/230530_Thadani_MappingSemiconductor_SupplyChain.pdf?VersionId=SK1wKUNf_.qSF3kzMF.aG8dwd.fFTURH (accessed on 9 November 2023).

UN Comtrade. (2023). International trade statistics. Available online: https://comtrade.un.org/data/ (accessed on 9 November 2023).

Appendix

Table A1. HS classification reference for semiconductor industry.

Categories	HS classification		Brief info	Traded products
Raw materials	280461		Silicon high purity	Silicon; containing by weight not less than 99.99% of silicon
	284920		Silicon carbide	Carbides; of silicon, whether or not chemically defined
	282560		Germanium	Germanium oxides and zirconium dioxide
	811292		Gallium	Gallium, germanium, indium, niobium (columbium) and vanadium; articles thereof, unwrought, including waste and scrap, powders
Wafers	3818		Silicon Wafers	Chemical elements doped for use in electronics, in the form of discs, wafers or similar forms; chemical compounds doped for use in electronics
Semiconductor manufacturing equipment	8479		Machines and mechanical appliances having individual functions.	Machinery and mechanical appliances; having individual functions for semiconductors.
	8486	848620	Machines and apparatus of a kind used solely or principally for the manufacture of semiconductor devices or of electronic integrated circuits.	Machines and apparatus of a kind used solely or principally for the manufacture of semiconductor boules or wafers, semiconductor devices, electronic integrated circuits or flat panel displays.
		848640	Machines and apparatus of a kind used solely or principally for the manufacture or repair of masks and reticles, assembling semiconductor devices or electronic integrated circuits.	
	8443		Printing machinery, including lithography machines used in the production of semiconductors.	Printing machinery; used for printing by means of plates, cylinders and other printing components of heading 84.42; other printers, copying machines and facsimile machines, whether or not combined; parts and accessories thereof.
	9010		Apparatus and equipment for photographic purposes.	Photographic (including cinematographic) laboratory apparatus and equipment, including lithography machine; projection screens.