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# **Silicon solar cells with Low Environmental footprint and Advanced interfaces**



## **SiLEAN - Deliverable report**

### **D6.4– Final result on the safety of supply and SiLEAN targets**



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#### Project Scientific Abstract

The SiLEAN project deals with the development of advanced innovations to tackle the major drawbacks of silicon heterojunction solar cell technology, namely the high energy and material demand for Si wafer manufacturing, limited current generation, and the consumption of scarce materials like silver, bismuth and indium. Within the scope of the project, we will directly grow the wafers from the gas phase with low temperature processes, apply alternative passivation concepts that show higher optical transparency, develop indium-free contact layers and apply silver and bismuth-free metallization with all-in-one cell interconnection and encapsulation. The project aims to achieve >25.5% solar cell efficiency and >23.5% module efficiency with 50% lower costs for Si wafers and contacting, as well as up to 75% lower carbon footprint. All processes applied allow upscaling to larger sizes as well as high manufacturing throughput. Eventually, the developments of SiLEAN will pave the way for a new, lean, generation of heterojunction solar cell technology that will both increment the energy conversion efficiency and unlock production at terawatt-scale.

## Public summary

The SiLEAN project is developing the next generation of silicon heterojunction solar cells with lower manufacturing costs, a lower carbon footprint, and reduced critical raw material content. By replacing energy-intensive Czochralski-grown wafers with NexWafe epitaxially-grown ones and substituting indium, silver, and bismuth with abundant materials, the SiLEAN technology will enable a more resilient, supply secure, and sustainable photovoltaic (PV) value chain in Europe.

In this report, TU Delft examined the supply chains of six raw materials, silver, silicon, copper, bismuth, aluminium, and silica sand, from mine production to EU PV module imports, using bilateral global trade data for the year 2024. The Herfindahl-Hirschmann Index and the Worldwide Governance Indicators were used to evaluate supply concentration and the governance standards at each step of the raw material supply chains examined. The results confirm that the silicon supply chain carries the greatest supply risk, with doped wafer production and its upstream stages exhibiting the highest supply concentration and lowest governance standards of all materials examined. In contrast, copper has the best governance scores and more diverse mining origins of the materials examined. Furthermore, domestic EU silver production was determined to contribute to only 1% of silver in inbound PV modules. Major silver producing EU countries export a large share of their production in refined form to the United States and the United Kingdom. Bismuth global supply is concentrated in China and the Republic of Korea, although domestication potential exists within the EU as Bulgaria produces bismuth as a byproduct of lead ore processing, and Belgium hosts significant refining capacity. The supply chains of bulk materials, aluminium and glass, are strongly concentrated in China due to high levels of domestic mine production and processing.

There is strong potential to strengthen the supply chains of PV raw materials within the EU, but development is uneven across materials and processing stages. Notably, Norway, as a member of the European Economic Area, contributes significantly to the EU supply of metallurgical-grade silicon production, while sourcing considerable quantities of natural quartz from Spain and France. Within the EU, countries such as Lithuania (doped wafers), Hungary (PV cells), Bulgaria (bismuth by-product of lead mining), Belgium (silver and bismuth refining), and Netherlands (silica sand production) each provide concrete starting points within the value chain. However, these strengths remain fragmented, and without sufficient intermediate processing capacity, they do not translate into meaningful influence over the final supply of PV modules. In practice, most modules entering the EU still arrive as fully manufactured products from China, thereby bypassing existing European refining and processing capacities and limiting their contribution to supply security.

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## Abbreviations

Abbreviation	Explanation
Cz	Czochralski
GW	Gigawatt rated power capacity
HHI	Herfindahl-Hirschmann Index
WGI	Worldwide Governance Indicators
PV	Photovoltaic
NBSC	Net Bilateral Supply Contribution
SHJ	Silicon heterojunction
SoA	State-of-the-art
USGS	U.S. Geological Survey

# 1 Introduction

In deliverable 6.2 [1], a multicriteria method was developed to evaluate the criticality of raw materials, which are important to photovoltaic (PV) modules. The scores of the different materials were aggregated at the technology level based on defined bill of materials from literature, which served as a basis for comparing the SiLEAN technology resource-use to other state-of-the-art (SoA) technologies. The results were calculated in kilograms of silicon equivalent per kilowatt-peak, and the SiLEAN technology model demonstrated a resource-use criticality of 5.2 kilograms of silicon equivalent. This value represents an 80% reduction in resource-use criticality when compared to SoA silicon heterojunction (SHJ) cells. The main drivers for this decrease were determined as the replacement of indium and silver with more abundant performing materials, specifically zinc and copper. Furthermore, an elasticity-based sensitivity analysis identified improvements in cell efficiency, reduced wafer thickness, and the use of bismuth-free solder alloys as key parameters for lowering PV technologies' total resource-use criticality.

The analysis performed in deliverable D6.2 relied on a simplified representation of processing stages for each raw material. As a result, it was not possible to accurately model epitaxially grown wafers, which are produced directly from metallurgical-grade silicon, in a way that is comparable to conventional Czochralski (Cz) wafers, which must be produced from polycrystalline silicon. In addition, the challenge that each step of the raw material supply chain can have different suppliers with different supply concentration and governance standards was not considered in the previous analysis. As such, an updated security of supply assessment is needed to address these gaps from the previous analysis. Recent analyses have shown that European manufacturing "falls considerably behind" the Net-Zero Industry Act targets, especially in polysilicon, ingots, wafers, and cells, with existing capacity far below the 76 Gigawatt rated power capacity (GW)/year required for domestic supply chain sovereignty by 2030 [2]. Given this widening gap between policy ambition and industrial capability, a more granular and supply chain-oriented assessment is essential to identify where capacity expansion should be prioritised across the raw material supply chain. In particular, differentiated attention is required for stages where European production capacity is marginal and where supply is heavily concentrated in countries with weaker governance standards, thereby increasing exposure to disruption and geopolitical risk.

The objectives defined for this deliverable are as follows: (i) to trace the most significant supply routes through which raw materials reach EU PV modules; (ii) to quantify the GW-equivalent of PV module enabled production resulting from domestication or restructuring of important supply routes; and (iii) to contextualize these findings in relation to the project's material substitution targets. In this deliverable, TUD uses global trade data-linked material flow analysis, similar the methodology presented in the work of Gervais et al. [3], to analyse the supply chain of six key raw materials used in crystalline silicon PV manufacturing:

- Silver: the main material used in screen-printed front-contact metallization.
- Silicon: the bulk wafer material.
- Bismuth: the key alloying element in low-temperature solders for cell interconnection.
- Copper: modelled here for cell metallisation.
- Aluminium and glass, which are the bulk module materials, and whose weights are strongly influenced by cell and module efficiencies.

Indium is intentionally excluded, despite its relevance to transparent conductive oxide layers, because its trade is aggregated with multiple raw materials under the Harmonized System (HS) code classification. HS codes are internationally standardized six-digit codes developed by the World Customs Organization and used by more than 200 countries to classify goods consistently [4]. This aggregation precluded a sufficiently granular trade flow assessment. For each step of the raw material supply chain, security of supply is evaluated using three metrics: (i) supply country concentration measured by the Herfindahl-Hirschmann Index (HHI); (ii) the net bilateral supply contribution of the 27 countries of the EU; and (iii) the Worldwide Governance Indicators (WGI) developed by the World Bank [5].

## 2 Methodology

As presented in Figure 1, the methodology presented in this study traces how raw materials from PV modules imported by EU countries move through processing stages and across the countries involved at each stage. First, bilateral country trade data are collected for the relevant processing stage. These data are then converted from kilograms of different product forms into raw-material-equivalent kilograms, such that different products can be compared. Second, domestic production is determined by estimating what each country could have produced to balance its import inflows at one processing stage with its export outflows from the subsequent stage. In countries where successive processing stages are carried out domestically, it may be necessary to balance the inflows of multiple processing stages with the outflows of a later stage.

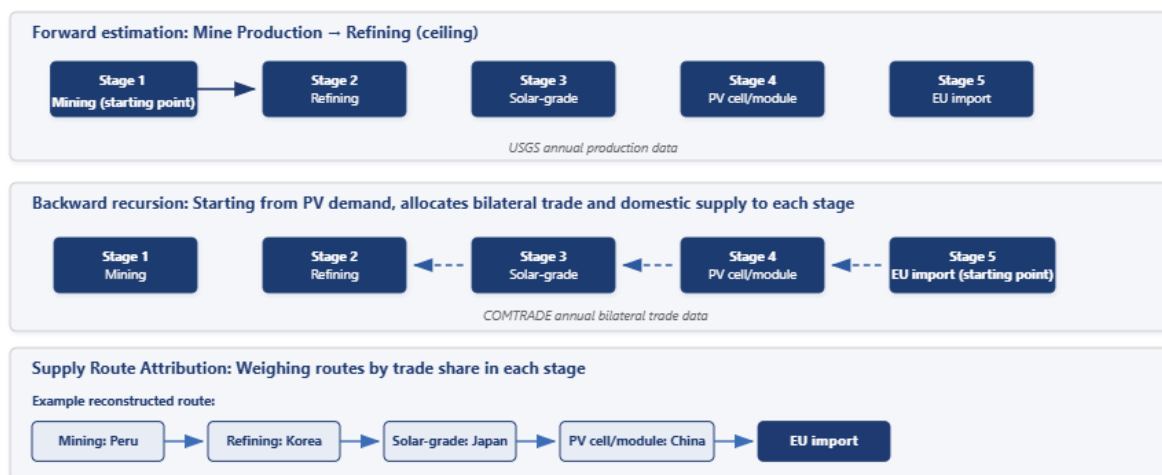


Figure 1: Schematic of the methodology used in this study to reconstruct PV material supply chains

Once trade flows and domestic production are determined at every stage, the raw material content of each EU country's inbound PV modules is traced backward through upstream countries stage by stage. At each stage, each supplier receives a share proportional to its contribution to total supply. This yields a set of complete supply routes that can be ranked by their contribution to the raw material content of EU-bound PV modules. Finally, three metrics for evaluating the security of supply are calculated for the PV raw materials considered in this study.

### 2.1 Bilateral country trade data source: UN COMTRADE and commodity classification

A simplified methodological framework is adopted from the work of Gervais et al. [3] to construct bilateral trade flows of raw material-equivalent content across successive processing/manufacturing stages. Bilateral country trade data are obtained from the UN Commodity Trade Statistics Database (COMTRADE) [6], which provides harmonized international trade quantities in metric tons and covering over 200 reporting economies. **Data from the year 2024 are used, as data for the year 2025 were not yet available at the time this study was prepared.**

The HS codes selected for each product in the raw material supply chains investigated are listed in Table 8-1 in Appendix B. The study adopted the HS codes from the Gervais et al. [3] study for silver products. As bismuth is mostly recovered as a by-product from the processing of several base metal ores [7], this limits traceability at earlier extraction stages. Consequently, modelling is initiated at the stage classified as “Bismuth and articles thereof, containing ≤ 99.99% bismuth by weight,” as upstream flows cannot be separated within the HS system. Stage-specific raw material content factors ( $\phi_k$ ) are assigned to convert physical trade quantities into equivalent raw material tonnage. The assumed raw material content in PV cells and modules is mainly derived from the life cycle inventory published in the work of Frischknecht et al. [8]. **Based on the estimated market share for the silicon heterojunction**

technology in global PV sales in 2024 from the International Technology Roadmap for Photovoltaics (ITRPV) report [9], a 5% share is attributed to this technology, with all assumed to contain bismuth in their solder alloys to estimate bismuth content in global PV module exports.

## 2.2 Domestic production estimation

To ensure material balance across processing stages, the model reconstructs supply chains using a hybrid approach that combines backward and forward recursion. Processing stages are ordered from ore or concentrate production (stage 1) through refining and intermediate processing to PV module manufacturing (stage  $n$ ), with the final stage representing the destination country receiving traded modules. For the downstream stages directly linked to PV module trade, domestic production requirements are estimated using backward recursion. Starting from the final stage and moving upstream, the domestic production requirement of country  $i$  at stage  $n$  is calculated as shown in equation 1.

$$D(i, n) = D(i, n + 1) + \sum_j E(i, j, n + 1)\phi_{n+1} - \sum_j I(i, j, n)\phi_n \quad (1)$$

where:

- $D(i, n)$  denotes domestic production at stage  $n$  available for stage  $n + 1$  in metric tons,
- $E(i, j, n)$  and  $I(i, j, n)$  denote the exports and imports in between country  $i$  and  $j$  at stage  $n$  in metric tons,
- $\phi_n$  denotes the raw material content factor for stage  $n$  [%].

The first two stages of the supply chain, typically mining and primary refining, are estimated using forward accounting based on mine production data reported by the U.S. Geological Survey (USGS) Mineral Commodity Summaries annual report for the year 2024 [10]. For these stages, the available material flow in country  $i$  at stage  $n$  for the following stage is calculated as:

$$D(i, 1) = M(i) - \sum_j E(i, j, 1)\phi_1$$

$$D(i, 2) = D(i, 1) + \sum_j I(i, j, 1)\phi_1 - \sum_j E(i, j, 2)\phi_2 \quad (2)$$

where  $M(i)$  is the domestic mine production of country  $i$  in 2024. The forward accounting from mine production will result in material estimates at the refining stage which exceed those from the backward recursion due to the fact that refined materials serve multiple downstream applications other than PV manufacturing, whereas the backward recursion identifies only the share of upstream production attributable to the PV supply chains. However, in some cases the forward estimation may yield lower values than the backward recursion, as observed for refined silver in China. This discrepancy could be explained by incomplete trade reporting in the UN COMTRADE database from major producing countries, such as Russia for silver or the Democratic Republic of Congo for copper, despite evidence of significant silver trade flows from Russia to China [11]. Furthermore, the model assumes no processing losses between successive stages in order to avoid introducing additional uncertainty through further assumptions, particularly given the substantial regional variation in processing efficiencies.

## 2.3 Mapping EU-Bound Supply Routes

To trace the upstream origins of raw materials in EU-bound PV modules, each destination EU country's total imports are allocated proportionally across its supplying countries, and these shares are propagated upstream through chain multiplication. The dimensionless contribution factor ( $\alpha_j$ ) of

country  $k$  to the total supply (bilateral trade flow + domestic production) of country  $i$  at that stage is given by equation 3.

$$\alpha_{i,k,n} = \frac{I(i,k,n)\phi_n}{\sum_j I(i,j,n)\phi_n} \quad (3)$$

For each EU country  $e$ , terminal inflows ( $Q_{\text{terminal}}$ ), in metric tons, consist of all bilateral PV module flows entering  $e$  at the terminal stage  $s$ :

$$Q_{\text{terminal}}(e) = \sum_j I(e,j,s)\phi_s \quad (4)$$

For a complete upstream route  $r$ , consisting of sequential bilateral flows, the cumulative route weight ( $W_{e,r}$ ), in %, is calculated as the product of the stage-level shares:

$$W_{e,r} = \prod_n \alpha_{i,j,n} * 100 \quad (5)$$

The weight  $W_{e,r}$  represents the share of the EU country  $e$ 's total terminal imports attributable to that upstream configuration. The physical quantity ( $Q_r$ ) allocated to route  $r$ , in metric tons, is then calculated as given by Equation 6.

$$Q_r(e) = W_{e,r} \cdot Q_{\text{terminal}}(e) \quad (6)$$

## 2.4 Security of supply indicators

First, to identify primary suppliers to the EU and filter out re-export effects, a Net Bilateral Supply Contribution (NBSC) is calculated at each processing stage. This metric expresses, as a percentage, the net contribution of a trading partner to the EU's total supply. It adjusts gross imports from a partner against reciprocal exports to that same partner and normalises the result against total net supply from all trading partners. This ensures that the indicator reflects actual material reliance rather than transit volumes. The NBSC is defined as:

$$\text{NBSC}_{i,j,n} = \frac{I(i,j,n)\phi_n - E(i,j,n)\phi_n}{\sum_j (I(i,j,n)\phi_n - E(i,j,n)\phi_n)} \times 100 \quad (7)$$

Second, the Herfindahl–Hirschman Index (HHI), expressed in points between 0-10,000, is used to evaluate country concentration of PV-related raw material production and is calculated using the formula shown below.

$$\text{HHI} = s_1^2 + s_2^2 + s_3^2 + \dots + s_n^2 \quad (8)$$

where  $s_n$  is the market share percentage of country  $n$ . It is generally accepted that an HHI value below 1500 is an indication of a competitive market, while a value above 2500 is an indication of a highly concentrated one [12].

Third, the aggregated Worldwide Governance Indicators (WGI) developed by the World Bank [5] are used to evaluate governance stability of countries relevant to PV-related raw material production. The indicators are scaled from 0 to 10, following the EU Study on Critical Raw Materials (2023) [13], where a higher score indicates weaker governance and a higher supply risk. Governance stability for stage  $n$  is calculated as shown in Equation 8.

$$\text{Governance stability}_n = \sum_{i \text{ countries}} s_{i,n} \times \text{WGI}_i \quad (9)$$

## 2.5 Reshoring potential

To assess reshoring potential, current EU domestic production and exports are added together, assuming these materials stay within the EU. This potential supply is then compared to the material content in EU-bound PV modules to see how much of its own demand the EU could meet with existing capacity. This potential supply is then compared to the material content embodied in EU-bound PV modules to evaluate the extent to which existing capacity could meet internal demand. First, potential supply ( $S_{EU,n}^{pot}$ ) is calculated as shown in equation 10.

$$S_{EU,n}^{pot} = \sum_{e \in EU} D(e, n) + \sum_{e \in EU} \sum_j E(e, j, n) \phi_n \quad (10)$$

Then the reshoring ratio ( $R_n$ ) is calculated as:

$$R_n = \frac{S_{EU,n}^{pot}}{\sum_{e \in EU} Q_{terminal}(e)} \quad (11)$$

A key limitation of this approach is that PV materials are also used in other sectors with growing demand, so not all production could be redirected to PV. Furthermore, the analysis assumes that exports to non-EU countries could be retained within the EU, which may not be realistic in practice. It also does not account for differences in material quality or specifications, which may limit their use in PV applications. Finally, the results are based on current trade and production patterns and do not capture future changes in technology, capacity, or supply chains.

## 3 Results & discussion

### 3.1 Silver

The Silver supply chain stages considered span silver ores and concentrates, refined silver, silver powder, and silver paste.

The NBSC calculations for the silver stages indicate that, **at the aggregate EU level, silver powder production has the highest reliance on non-EU suppliers of 45%**, as shown in Figure 2. According to the COMTRADE database, Japan contributes to 70% of global silver powder exports, followed by the United States with more than 10%. At the EU level, these two countries together represent 40% of the net bilateral supply contribution, while 55% comes from EU countries. **The production of silver ores and concentrates in the EU has the least reliance on non-EU suppliers**, with marginal supply from Canada and Peru reported in 2024, in contrast to significant contributions from **Poland, Sweden, Portugal, and Spain within the EU**.

While the NBSC results suggest relatively low reliance on non-EU suppliers at the silver mining and refining stages, this does not translate into supply security for PV manufacturing. In practice, silver is incorporated into a wide range of downstream products, including PV modules, which are predominantly imported into the EU as finished goods. As a result, a significant share of silver enters the EU already embedded in these products, effectively bypassing domestic refining and intermediate processing stages. The relevance of this becomes clear when compared with the supply chain mapping results, which will be presented in Figure 3 and discussed in the coming section.

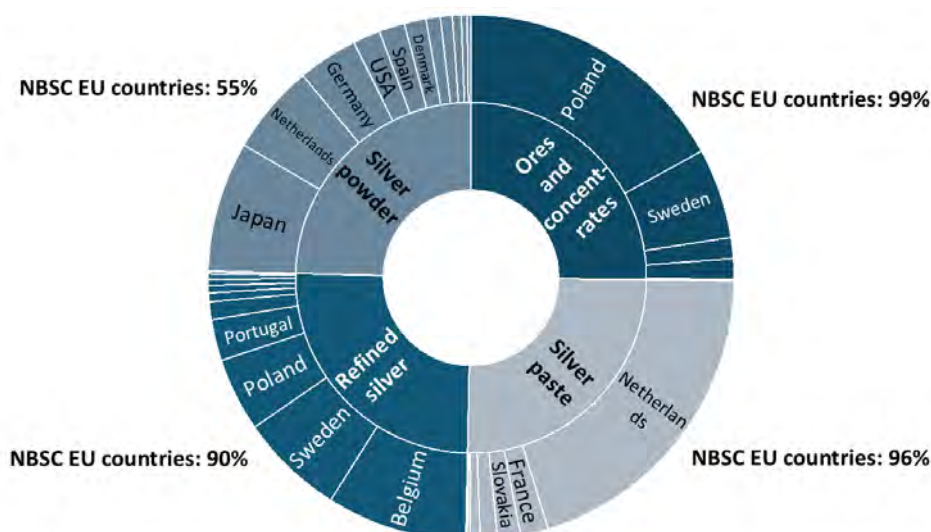


Figure 2: the net bilateral supply contribution of the relevant silver stages in the EU.

Figure 3 illustrates the mapped flows of EU-bound silver in PV modules. Based on the sum of EU-bound silver flows, roughly 1600 metric tons of silver were present in PV modules traded in the EU in 2024. **China dominated supply across nearly all silver processing stages, with the exception of ores and concentrates, where Peru contributed 53% of silver supply to EU-bound PV modules, followed by China (28%)**. China's high concentration in downstream stages is due to the backward allocation of domestic production, which is driven by PV module exports that far exceed silver product imports. The figure also shows that **the stage of silver paste production has the highest HHI and WGI indices, with China accounting for more than 98% of the silver paste in EU-bound PV modules**. The supply of PV cells is also strongly concentrated in China, whereas the PV module stage is slightly less concentrated (89% in China). However, this estimate is strongly influenced by the re-export of Chinese PV modules through the Netherlands, which accounts for 6% of EU-bound PV module flows [14]. The China-Netherlands PV module trade represents the largest bilateral PV module trade flow globally as the port of Rotterdam is the largest in Europe.

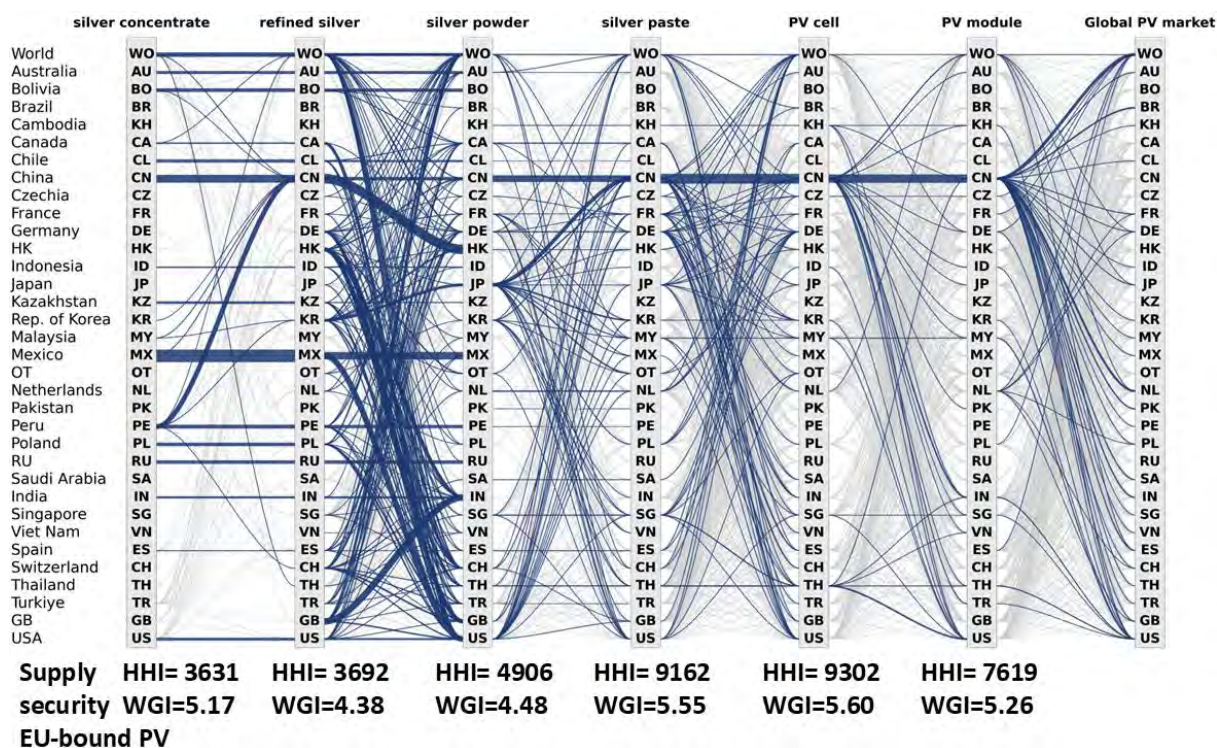


Figure 3: The global trade flows of silver products for PV in 2024 analysed from mining to PV module manufacturing and exporting. Blue curves represent domestic production and large bilateral trade flows (20% top percentile by silver-equivalent volume); grey curves represent smaller bilateral trade flows (80% bottom percentile). Line thickness is proportional to silver-equivalent volume.

Table 3-1: The five most important EU-bound silver supply routes for PV in 2024 counting for 72% of all PV modules supply.

Ores and concentrates	Refined silver	Powder	Paste	PV cell	PV module	Contribution to EU-bound silver in PV modules
China	China	China	China	China	China	24%
Peru	Republic of Korea	Japan	China	China	China	21%
Peru	China	China	China	China	China	14%
Peru	China, Hong Kong	China	China	China	China	9%
Armenia	China	China	China	China	China	4%

Table 3-1 lists the most important supply routes for silver in EU-bound PV modules and that this supply is concentrated in a limited number of routes. **At the ores and concentrates stage, Peru and China are the principal origin countries.** As shown in Table 3-1, the two dominant trade routes from these countries alone account for approximately 43% of traced supply, **while all configurations originating from Peruvian and Chinese silver ores and concentrates account for 85% of EU-bound silver in PV modules.** Refining and powder production are highly concentrated in the Republic of Korea and Japan, respectively, with limited contribution from Hongkong that is largely exporting its imports of Chinese silver, as shown in Figure 3. Armenia also appears as an origin country at the ores and concentrates stage, contributing approximately 4% of EU-bound silver in PV modules. **This may partly indicate Armenia's well-documented role as a transit country for Russian-origin precious metals following**

the 2022 sanctions [15], [16], [17], and given that Russian silver trade data are absent from COMTRADE.

Compared to Gervais et al. [3], who identified Mexico as the dominant mining supplier using 2021 data, the 2024 results indicate a shift: Peru now emerges as the primary upstream source, accounting for 53% of EU-bound silver at the mining stage versus 3% for Mexico. As shown in Figure 3, limited Mexican silver ores and concentrates are exported to China and the Republic of Korea, whereas refined silver is now predominantly exported to the United States that has limited contribution to the PV value chain. For the global supply, Malaysia and Thailand account for 7% of global PV module exports, of which more than 95% is destined for the United States. It is estimated that **silver from mine producing countries in the EU contributes to a mere 1% of silver in EU-bound PV modules**, despite the fact that their combined annual mine production exceeds the estimated silver content in PV modules traded in the EU in 2024. This suggests that EU-mined silver is predominantly directed toward other downstream applications rather than the PV supply chain.

### 3.2 Silicon

The silicon supply chain stages considered span quartz, metallurgical-grade silicon, polysilicon, and doped substrates.

Based on the NBSC indicator proposed in this study, **the metallurgical-grade silicon stage is identified as the most vulnerable at the aggregate EU level**. As shown in Figure 4, Norway, China, and Brazil together account for 66% of the net EU supply; globally, China dominates with 49% of exports, followed by Norway and Brazil at 12% each. On the contrary, the least vulnerable stage is doped wafer production, with Lithuania (35%) and Hungary (24%) as the leading net suppliers, based on trade flows under HS codes 381800 and 854142, which capture both PV and semiconductor-grade doped wafers. The contributions of both countries are largely attributed to Lithuania's doped wafer exports and the domestic production allocated to Hungary due to PV cell exports at the downstream stage.

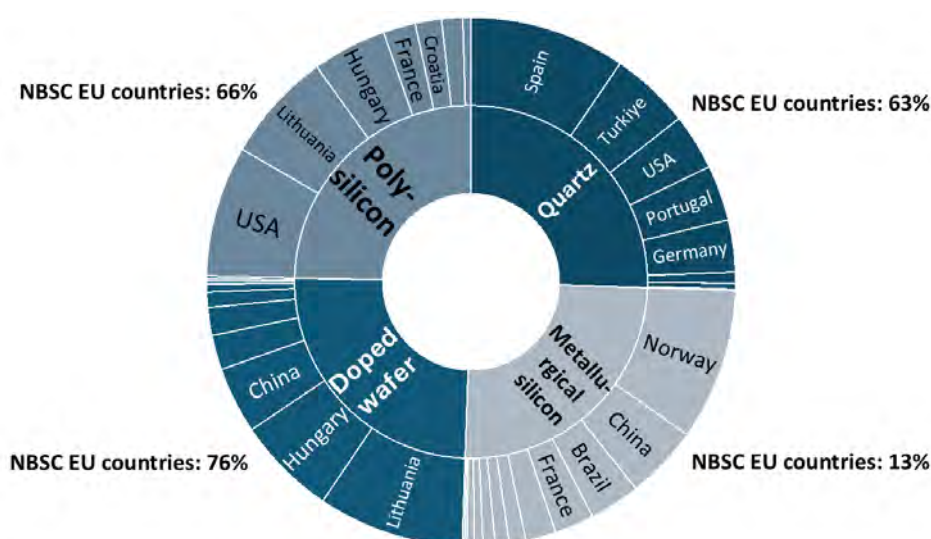


Figure 4: the net bilateral supply contribution of the relevant silicon stages in the EU

Figure 5 illustrates the global trade flows of silicon for EU-bound PV modules, which are **even more concentrated in China than all other PV raw materials investigated in this study** due to China's strong reliance on domestic production of natural quartz sands. **This concentration is evident from the earliest stage: China accounts for 90% of natural quartz sand supply for EU-bound PV modules**. At the metallurgical-grade silicon stage, China accounts for 95% of EU-bound supply and only 3% from EU

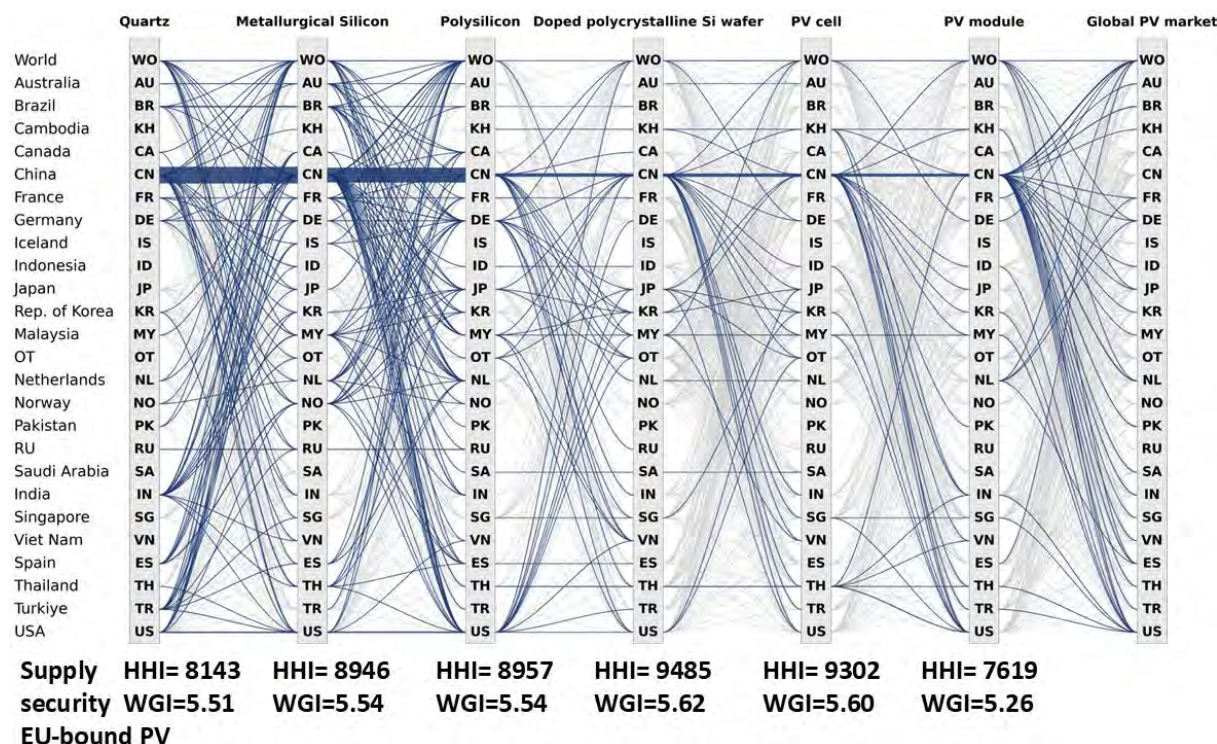


Figure 5: The global trade flows of silicon products for PV in 2024.

countries. However, this minor contribution entirely almost phases out entirely at downstream stages. Furthermore, doped wafer production represents the most vulnerable stage, combining the highest supply concentration (97% from China) with the lowest governance standards, as measured by the HHI and WGI indices.

The NBSC results are best interpreted alongside the supply chain mapping. At the EU level, Lithuania and Hungary have potential domestic capacity at the doped wafer stage. However Lithuania's capacity for doped wafers is dedicated to other applications, such as printed circuit boards and optoelectronic devices, rather than PV [18], [19]. Ecosolifer in Hungary has an operational 100 MW heterojunction cell production line [20]. Furthermore, the global supply chain mapping indicates that most of the silicon used in PV modules installed in the EU actually enters the market already embedded in finished modules imported from China. As a result, these domestic processing stages are largely bypassed in practice. Even so, the existing capacity at the doped wafer and cell production stages still provides a concrete starting point for greater supply chain domestication.

Table 3-2 shows the most important supply routes for silicon in EU-bound PV modules. Unlike silver, no countries other than China make a significant contribution beyond the stage of quartz production. Nevertheless, **EU-origin quartz accounts for more than 3.5% of silicon in EU-bound PV modules, though intermediate processing remains absent in Europe**, with no subsequent stage exceeding a 3% EU contribution.

Table 3-2: The four most important EU-bound silicon supply routes for PV in 2024 accounting for 87% of all EU PV module supply

Quartz	Metallurgical grade silicon	Polysilicon	Doped wafer	PV cell	PV module	Contribution to EU-bound silicon in PV modules
China	China	China	China	China	China	79%
China	China	China	China	China	Netherlands	5%
India	China	China	China	China	China	2%
USA	China	China	China	China	China	1%

### 3.3 Bismuth

The bismuth supply chains stages considered span bismuth-containing materials (less than 99.99%), and refined bismuth (more than 99.99%).

Figure 6 shows that **the EU countries are vulnerable to external NBSC for the two intermediate bismuth processing stages considered in this study**. For bismuth products with content below 99.99%, the United States supplies 68% of net supply to the EU, followed by Bulgaria (25%), where bismuth is produced as a byproduct of lead ore processing [21]. For refined bismuth, China supplies 70%, followed by Belgium (21%), which functions as a refining hub through Umicore [21], [22]. Globally, Germany and Belgium together account for 22% of global bismuth exports despite having no primary mine production (re-export)[10], following the United States (51%). Belgium alone ranks third globally with 10% of the exports, behind China (61%) and the Republic of Korea (14%). This makes Belgian refining capacity a foundation for EU supply chain domestication.

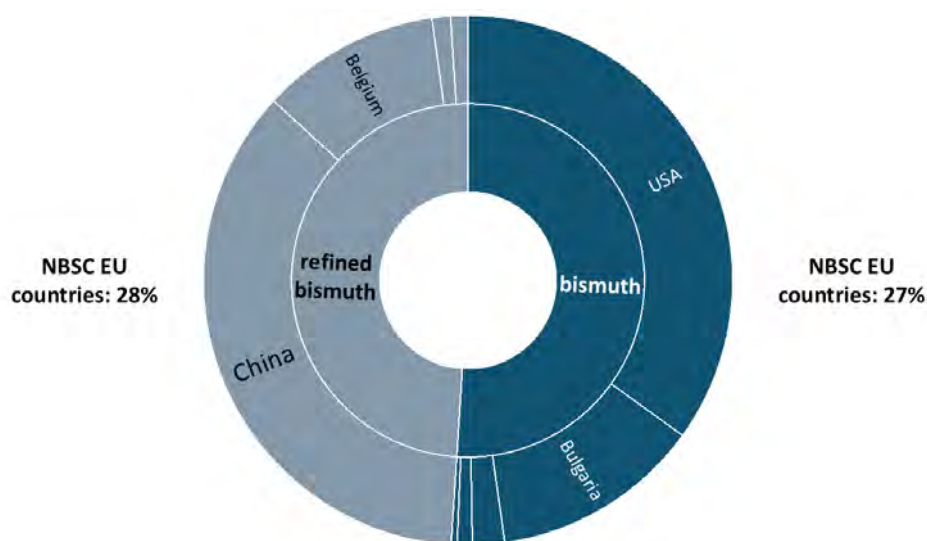


Figure 6: the net bilateral supply contribution of the relevant bismuth stages in the EU

Figure 7 illustrates the global trade flows of **bismuth for EU-bound PV modules**. According to the mapping methodology, 45 metric tons of bismuth are estimated to have been contained in PV modules traded in the EU in 2024. As China is currently the largest global producer of bismuth, HHI values above 7000 are estimated for both intermediate processing stages, and China is estimated to supply 85% of bismuth in EU-bound PV modules. At the first processing stage, the United States and Germany each contribute 5%, while at the refined bismuth stage, the United States, Portugal, and Belgium each account for just over 2%. The important supply routes are listed in Table 3-3.

Table 3-3: The four most important EU-bound bismuth supply routes for PV in 2024 accounting for 86% of all EU PV module supply

Bismuth, <99.99%	Refined bismuth, >99.99%	PV module	Contribution to EU-bound bismuth in PV modules
China	China	China	80%
China	China	Netherlands	3%
Germany	USA	China	2%
USA	China	China	1%

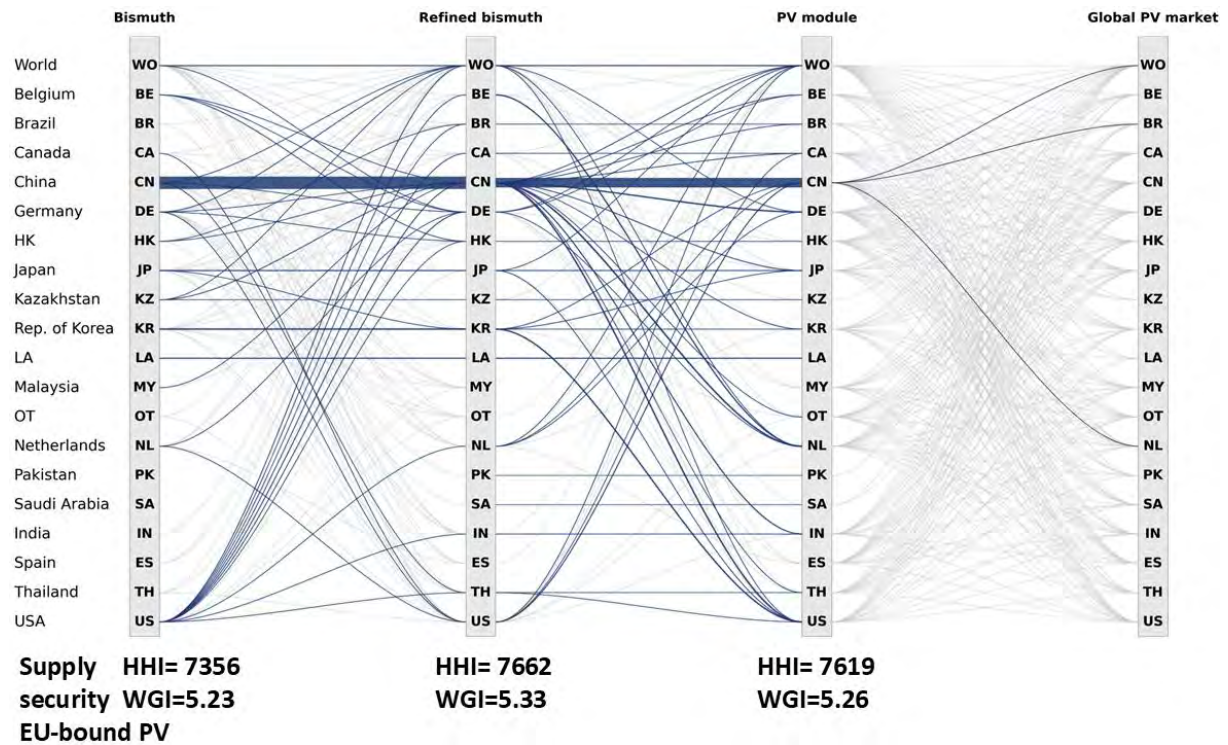


Figure 7: The global trade flows of bismuth products for PV in 2024.

### 3.4 Copper

The copper supply chain stages considered span copper ores and concentrates, refined copper, copper wire rods, and copper foil.

The NBSC indicator determines the **copper foil stage as the most vulnerable for EU countries, as Malaysia and the Republic of Korea together contribute to 60% of the net bilateral supply**. The results presented in Figure 8 also show that **refined copper is the next critical stage, with Chile contributing to 23% of the net bilateral supply**. Poland and Portugal are the main suppliers within the EU for ores and concentrates (81% in total), and for refined copper Poland, Belgium, and Finland are the main net suppliers (47% in total).

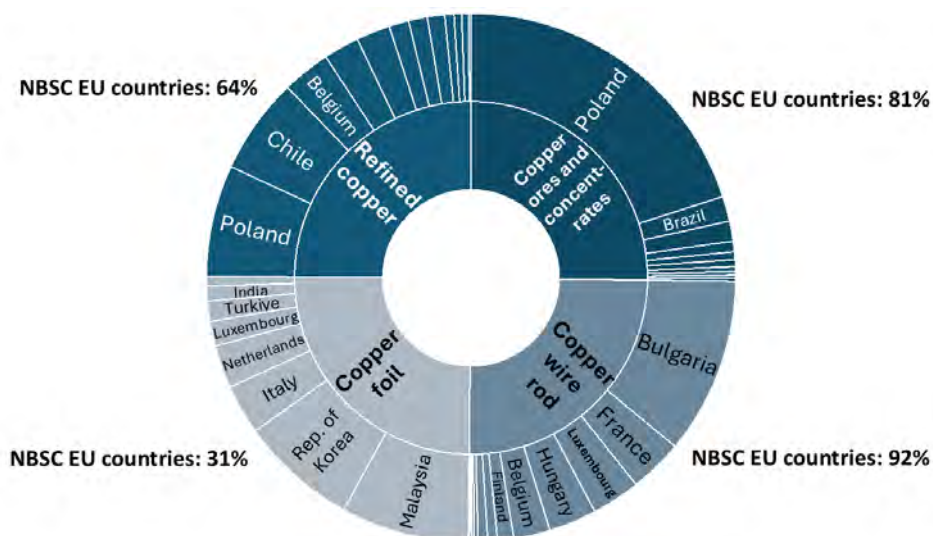


Figure 8: the net bilateral supply contribution of the relevant copper stages in the EU

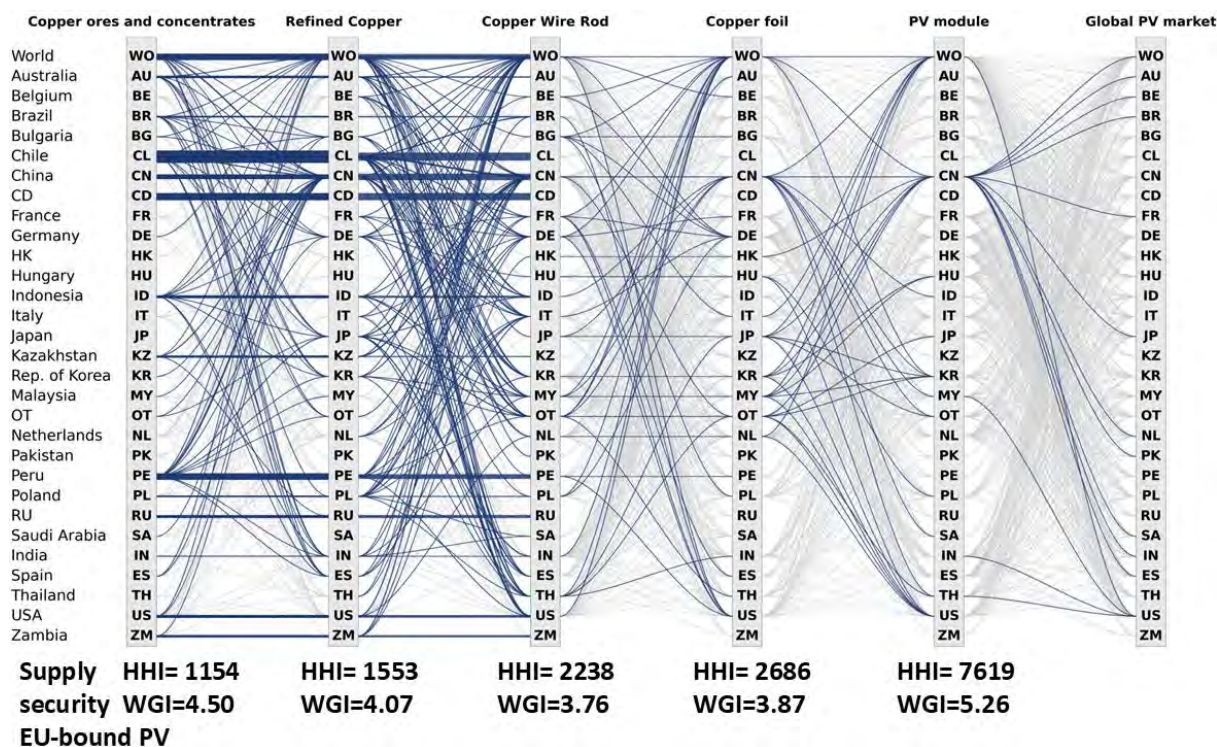


Figure 9: The global trade flows of copper products for PV in 2024.

Figure 9 shows the global trade flows of copper products for PV modules in 2024. According to the mapping methodology, **more than 47,000 metric tons of copper were present in PV modules traded in the EU in 2024 as cell interconnections**. Approximately 70% of the copper for EU-bound PV modules is sourced from ores and concentrates from China, Chile, Peru, Indonesia, and Australia. For refined copper, supply to EU-bound PV modules mainly originates from China (32%), Japan (14%), and Chile (12%). **Taiwan emerges as the biggest supplier of copper foil to EU-bound PV, given that the Taiwan-China trade of copper foil is the largest global bilateral trade, and is 25% higher than the estimated domestic production for China.** The important supply routes are listed in Table 3-4.

Table 3-4: The seven important EU-bound copper supply routes for PV in 2024 accounting for 35% of all EU PV module supply with all other supply routes having <3% contribution.

Ores and concentrates	Refined copper	Copper wire rod	Copper foil	PV module	Contribution to EU-bound copper in PV modules
China	China	China	China	China	8%
China	China	Taiwan	Taiwan	China	8%
Australia	Australia	Taiwan	Taiwan	China	5%
Peru	Japan	Taiwan	Taiwan	China	4%
Chile	Chile	Taiwan	Taiwan	China	4%
Zambia	Zambia	Hong Kong	Hong Kong	China	3%
Indonesia	Indonesia	Malaysia	Malaysia	China	3%

### 3.5 Aluminium and Glass

For aluminium, the supply chain stages considered include aluminium ore and concentrate, aluminium oxide, unwrought aluminium alloy, and aluminium profile. For glass, these stages are natural silica sand production, and non-wired polished glass.

An important limitation for aluminium is the absence of documentation in COMTRADE for the exports of Guinea, the world’s largest producer of bauxite. For EU-bound PV modules, the data available

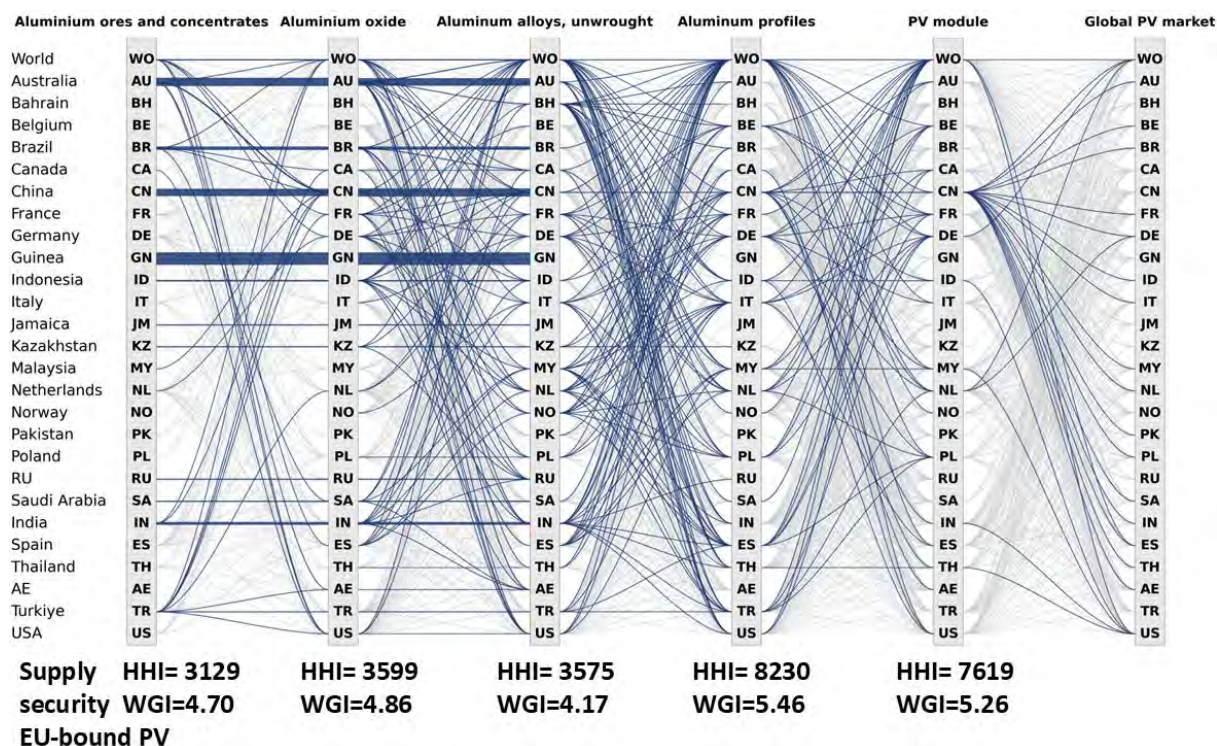


Figure 10: The global trade flows of aluminium products for PV in 2024.

indicate the strong concentration of the mining stage in China (50%), Australia (18%), and Indonesia (17%). The important supply routes are listed in Table 3-5, indicating Malaysia as an important hub for alloys production and its contribution to 23% of the EU-bound supply. The global trade flows are illustrated in Figure 10.

Table 3-5: The three most important EU-bound aluminium supply routes for PV in 2024 accounting for 70% of all EU PV module supply

Ores and concentrates	Aluminium oxide	Alloy, unwrought	Profile	PV module	Contribution to EU-bound copper in PV modules
China	China	China	China	China	48%
Indonesia	Indonesia	Malaysia	China	China	16%
Australia	Australia	Malaysia	China	China	6%

For glass, China's dominance reflects its strong domestic production base across both silica sand and glass manufacturing, supplying 83% of glass in EU-bound PV modules. The EU collectively ranks as the second largest supplier at 12%, driven by direct and indirect exports of silica sand and glass to China. Furthermore, there is strong potential for domestication given that Netherlands is among the top three

global producers of silica sand [10], and the broader EU silica sand production base could in principle support a more integrated supply chain in Europe. The global trade flows are illustrated in Figure 11.

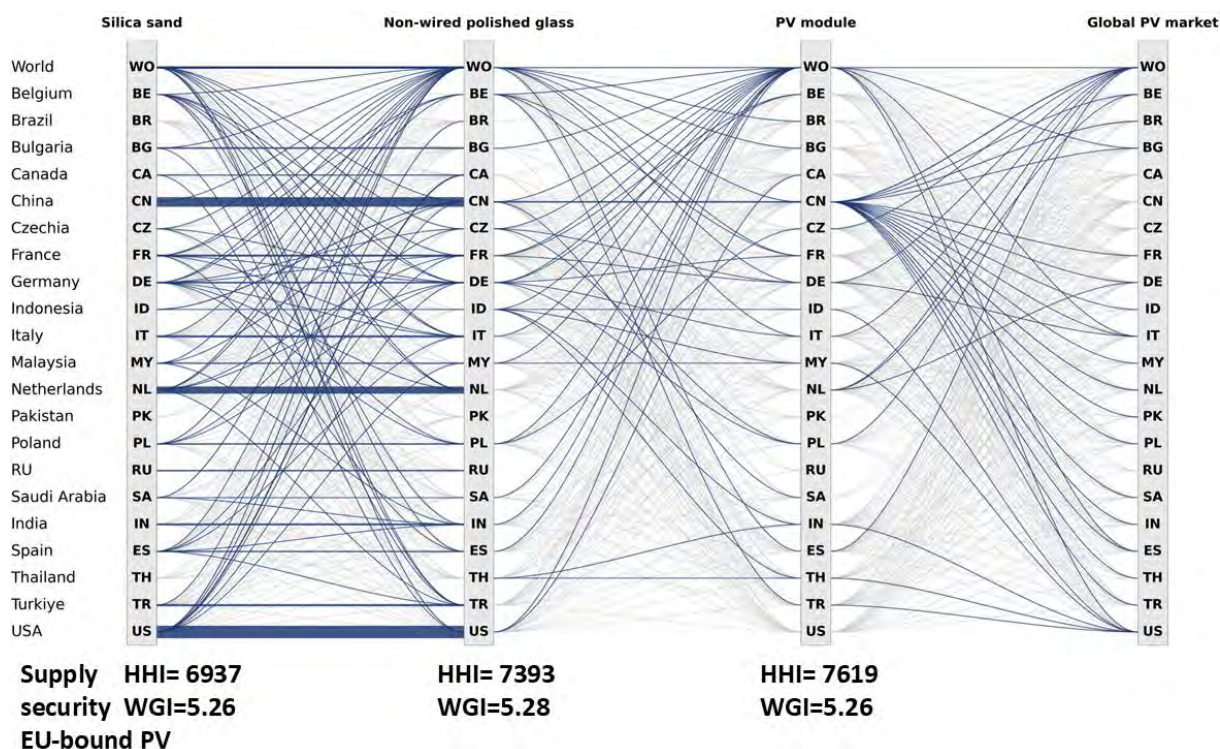


Figure 11: The global trade flows of glass for PV modules in 2024.

### 3.6 Reshoring potential

The results for the reshoring potential of the different process steps in the supply chain of PV materials are illustrated in Figure 12. Silicon has the lowest overall reshoring potential across its entire value chain. In the last two stages, reshoring potential drops sharply to 0.18 for polysilicon and 0.02 for doped wafers. The SiLEAN technology, which uses Epiwafers from NexWafe to convert metallurgical-grade silicon directly into wafers while bypassing the polysilicon stage, offers a pathway to greater supply chain resilience by relying on metallurgical-grade silicon instead. Nevertheless, the 65% reshoring potential for metallurgical-grade silicon should be treated with caution, given its additional uses in aluminium alloys, steel, chemicals, and other applications.

Powder production has the lowest reshoring potential in the silver value chain, followed by paste production. This suggests that capacity expansion should focus on these downstream stages, as upstream stages already have relatively higher reshoring potential. Foil production is the most vulnerable stage in the entire copper value chain, also suggesting a need to prioritize capacity expansion. However, due to COMTRADE data limitations, copper examined in this study is restricted to cell interconnections at the module level. A system-level analysis that includes copper for cabling and inverters could therefore expose further vulnerabilities in the EU's potential to reshore copper for PV production.

Aluminium and bismuth are the PV materials with reshoring potential above 1 at every stage. However, the bismuth content in EU-bound PV modules was estimated assuming only a 5% market share for SHJ technologies, a share that could change significantly in the future. Aluminium is classified as a critical raw material by the EU, with economic importance driving its criticality more than supply risk [13]. This raises concern for PV manufacturing as well, even though current demand is relatively low, because demand is anticipated to increase in line with targets set by the Net Zero Industry Act [2]. For glass, the second stage shows low reshoring potential. However, this finding should be interpreted with caution. The glass value chain was modelled as a two-step process due to limitations in data



Figure 12: The reshoring potential for PV materials examined across the different mining/processing steps

granularity, and glass has numerous downstream applications beyond PV. Therefore, these findings represent a lower-bound estimate of reshoring potential rather than a definitive limit.

### 3.7 Discussion of Contribution to project Objectives

The raw material supply chains examined in this deliverable relate to the following SILEAN project objectives:

- Development of epitaxially grown ultra-thin epitaxially-grown silicon wafers from the gas phase
- Development of copper-based fingers
- Reduction of silver and bismuth in a foil-based copper cell interconnection

**With a HHI of 9485 and a WGI of 5.62 doped crystalline silicon wafers and their upstream processing stages exhibit the highest supply concentration and the lowest governance standards of all materials examined in this study.** PV cells and modules (excluding re-exports) show even higher concentration, though this is attributed to China's dominance in manufacturing capacity, which according to the IEA operates at a 55% utilization rate, as well as its leading share of annual module output [23]. **According to this analysis, epitaxially-grown wafers benefit from the bypass of the polysilicon process step, where China supplies 95% of the polysilicon in EU-bound PV modules. Metallurgical-grade silicon, the new upstream boundary, has more diverse sourcing: Norway and Brazil together contribute to 23% of global metallurgical-grade silicon exports.** Furthermore, there is strong potential for supply chain domestication given that Norway is an established EU trading partner within the European Economic Area, while Lithuania and Hungary are involved in the semiconductor and PV sectors.

**EU silver mining countries, Poland, Sweden, Spain, and Portugal, contribute less than 1% of silver in EU-bound PV modules in 2024,** despite their combined annual mine output exceeding this amount, which was estimated at 1600 metric tons. This indicates that domestically mined silver is predominantly directed toward other sectors. Moreover, **Poland exports more than two-thirds of its mined silver in refined form to the United Kingdom and the United States which have limited contribution to the global PV value chain.** The results also suggest a potential contribution of Russian-origin silver, either through transit countries or as direct exports to China, though this cannot be accurately quantified due to the absence of Russian bilateral trade data in COMTRADE.

China supplies more than 85% of refined bismuth in EU-bound PV modules due to the large domestic production. Reduced bismuth content/bismuth-free solder alloys would therefore effectively reduce

this dependency. **Nevertheless, domestication potential exists within the EU as Bulgaria produces bismuth as a byproduct of lead ore processing, and Belgium's refining capacity positions it as a global refining hub.** Another non-EU alternative with higher governance standards could be the Republic of Korea, the second largest global producer of bismuth.

**Copper has the best governance scores and more diverse mining origins among the raw materials considered in this study.** A notable supply route for copper runs from Australia to Taiwan, accounting for 5% of copper supply in EU-bound PV modules. Both countries offer high governance standards, with Australia contributing 6% of global refined copper exports and Taiwan contributing 30% of global copper foil exports. **Bulk materials, aluminium and glass, exhibit high concentration due to high levels of domestic mine production in China, although EU countries are leading global producers of silica sand.**

## 4 Conclusion and Recommendation

This study presents an assessment of the raw material supply chains related to EU-bound PV modules, using bilateral trade mapping from the UN COMTRADE database. To maintain mass balance across processing stages, a hybrid approach was adopted combining backward recursion from global PV module exports and forward recursion from mine production data to estimate domestic production at each stage of the supply chain. The Herfindahl-Hirschmann Index and the Worldwide Governance Indicators were used to evaluate supply concentration and the governance standards involved in the supply of PV raw materials.

The results confirm that the silicon supply chain carries the greatest supply risk, with doped wafer production and its upstream stages exhibiting the highest supply concentration and lowest governance standards of all materials examined. China is leading the global supply of nearly all silicon intermediate products, from natural quartz to polysilicon, and is reinforced by its leading share of global PV manufacturing capacity. At the EU level, metallurgical-grade silicon production is the most exposed stage to external supply critical, and thus a critical bottleneck for scaling wafer manufacturing within Europe. Without a secure and diverse supply of metallurgical-grade silicon, downstream EU capacity at the wafer stage remains structurally vulnerable.

There is strong potential to strengthen PV supply chains within the EU, but it remains uneven across materials and processing stages. Notably, Norway, as a member of the European Economic Area, contributes significantly to the EU supply of metallurgical-grade silicon production, while sourcing much of its natural quartz from Spain and France. Within the EU, countries such as Lithuania (doped wafers), Hungary (PV cells), Bulgaria (bismuth), Belgium (refining), and Netherlands (silica sand) each provide concrete starting points within the value chain. However, these strengths remain fragmented, and without sufficient intermediate processing capacity, they do not translate into meaningful influence over the final supply of PV modules. In practice, most modules entering the EU still arrive as fully manufactured products from China, effectively bypassing existing European capabilities and limiting their contribution to supply security.

The findings of this study also highlight the supply chain relevance of SiLEAN technology. Silver-free copper metallization, reduced silver and bismuth in cell interconnections, and epitaxial wafer growth each offer not only performance and cost benefits but also meaningful reductions in exposure to high-concentration, low-governance supply routes. Accelerating the deployment of these technologies would therefore contribute directly to the raw material supply security of the EU PV sector.

## 5 Data availability

Data obtained from the United Nations Comtrade Database are subject to copyright and redistribution restrictions imposed by the United Nations. Accordingly, bilateral trade records are not disclosed in full detail in this report.

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#	Partner short name	Partner Full Name
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2	IMEC	INTERUNIVERSITAIR MICRO-ELECTRONICA CENTRUM
3	TUD	TECHNISCHE UNIVERSITEIT DELFT
4	UNR	UNIRESEARCH BV
5	NXW	NEXWAFE GMBH
6	PVW	PV Works B.V.
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## 7. Appendix A - Quality Assurance Review Form

The following questions should be answered by all reviewers (WP Leader, reviewer, Project Coordinator) as part of the Quality Assurance procedure. Questions answered with NO should be motivated. The deliverable author will update the draft based on the comments. When all reviewers have answered all questions with YES, only then can the Deliverable be submitted to the EC.

NOTE: This Quality Assurance form will be removed from Deliverables with dissemination level “Public” before publication.

Question	WP Leader	Reviewer	Project Coordinator
	Malte Vogt (TUD)	Giuliana Giuliano (3SUN)	Karsten Bittkau (FZJ)
1. Do you accept this Deliverable as it is?	Yes	Yes	Yes
2. Is the Deliverable complete? - All required chapters? - Use of relevant templates?	Yes	Yes	Yes
3. Does the Deliverable correspond to the DoA? - All relevant actions performed and reported?	Yes	Yes	Yes
4. Is the Deliverable in line with the SiLEAN objectives? - WP objectives - Task Objectives	Yes	Yes	Yes
5. Is the technical quality sufficient? - Inputs and assumptions correct/clear? - Data, calculations, and motivations correct/clear? - Outputs and conclusions correct/clear?	Yes	Yes	Yes
6. Is created and potential IP identified and are protection measures in place?	N/A	N/A	N/A
7. Is the Risk Procedure followed and reported?	Yes	Yes	Yes
8. Is the reporting quality sufficient? - Clear language - Clear argumentation - Consistency - Structure	Yes	Yes	Yes

## 8. Appendix B - Commodity Classification and Material Scope

Table 8-1: assumed HS codes for the different commodities and the equivalent raw material content

Raw material, $k$	Product	HS code	Raw material-equivalent content, $\varphi_k$ [%]
<b>Silver</b>	silver ores and concentrates	261610	0.5
	refined silver	710691	99.9
	silver powder	710610	85
	silver paste	711590	70
	PV cells	854142	0.8
	PV modules	854143	0.03
<b>Silicon</b>	quartz	250610	46.7
	metallurgical silicon	280469	99.9
	polysilicon	280461	100
	doped wafer	381800	100
	PV cells	854142	98
	PV modules	854143	5.2
<b>Bismuth</b>	bismuth	810690	100
	refined bismuth	810610	100
	PV modules	854143	0.0008
<b>Copper</b>	copper ores and concentrates	260300	7
	refined copper	740311	100
	copper wire rod	740710	100
	copper foil	741011	100
	PV modules	854143	0.9
<b>Aluminium</b>	aluminium ores and concentrates	260600	20
	aluminium oxide	281820	52.9
	aluminium alloy, unwrought	760120	95
	aluminium profile	760429	95
	PV modules	854143	15.2
<b>Glass</b>	natural silica sand	250510	100
	non-wired polished glass	700510	100
	PV modules	854143	67