Towards secure and sustainable supply chains: a multi-perspective risk assessment for photovoltaics

Gervais, E.

Chapter 4

Risk-based due diligence in supply chains: The case of silver for photovoltaics

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Abstract

Supply concentration and environmental, social, governance (ESG) issues constitute important supply risks. With strategic autonomy and sustainable sourcing high on the political agenda these risks are especially relevant for the EU. This paper proposes an approach to conduct risk-based due diligence. Using a trade-linked material flow analysis, ESG and dependency hotspots along supply chains can be identified. Silver supply chains for photovoltaics (PV) are taken as case-study. The model traces silver from mining to PV module manufacturing, from 1995 to 2021.

The supply of silver powder, paste, PV cells, and modules is found to be highly concentrated. These supply chains are linked to substantial ESG risks, mostly nested in fabrication and manufacturing, some of which have worsened over time. Over 85% of the silver used in PV transits through at least one country with a very high risk factor. Reshoring the PV industry to the EU can partially de-risk supply.

4.1. Introduction

Raw material supply chains are crucial for the world economy and specifically for the energy transition. As supply chains have become more complex, concerns over their resilience have been raised (Szczepański, 2021). In order to avoid and prepare for disturbances, companies and countries must be aware of their exposure to supply risks. These risks are manifold. For example, the political stability of mining countries, by-product dependency, recyclability, and diversity of supply are common indicators in material criticality assessments (Helbig et al., 2021, Schrijvers et al., 2020). A mismatch between projected material demand and current production levels has frequently been identified in literature (Liang et al., 2022, Marscheider-Weidemann, 2021, Watari et al., 2020). Although the threat of shortages due to mineral depletion has been disputed, it is widely acknowledged that environmental, social, and governance issues (ESG) are a main limiting factor to the development of mining projects (Jowitt et al., 2020, Lèbre et al., 2019, Valenta et al., 2019).

Placing supply risks in the context of sustainability concerns is further necessary over the entire supply chain, i.e., beyond extraction. This is becoming ever more important in view of the package of EU regulations under preparation or in force, e.g., Directive on Corporate Sustainability Due Diligence (European Commission, 2022a), Regulation on prohibiting products made with forced labor on the Union market (European Commission, 2022b), Corporate Sustainability Reporting Directive (European Commission, 2021), and the Sustainable Finance Disclosure Regulation (European Commission, 2019). These policies require companies to identify and manage social and environmental adverse impacts along their supply chains. Companies are also facing increasing pressure from investors and public banks (European Investment Bank, 2022) to disclose satisfactory ESG performance. Procuring products from unsustainable sources will pose litigation and reputational issues as well as the risk to be excluded from the investment ecosystem. Additionally, ensuring a secure, diversified supply for critical and strategic materials is at the core of the European Critical Raw Materials Act (European Commission, 2023). Adequate supply chain risk analyses can support companies in identifying hotspots and prioritize in-depth due diligence monitoring and risk management.

The photovoltaics (PV) industry provides an interesting case-study for the assessment of supply chain risks. Market concentration and limited ESG due diligence remain shortcomings which could impede a secure and sustainable material supply for a large-scale PV deployment. The quasi-monopoly of China over manufacturing has rendered PV component buyers vulnerable to local market conditions. In 2021, power rationings in Chinese provinces and maintenances led to PV material price surges (IEA, 2022). The Uyghur Forced Labor Prevention Act, under which solar panels presumably produced by forced labor were seized by customs in the USA, further sets a precedent on how sustainable sourcing and PV upscaling goals can collide (U.S. Department of Energy, 2022). Such occurrences can be unpredictable. Nevertheless, supply chain risks need to be assessed for all materials and in all processing stages to enable proactive mitigation strategies, instead of reactive decisions.

This paper presents a systematic approach for risk-based due diligence. It assesses the supply chain risks related to ESG issues and supply concentration for the case study of silver in the PV industry. It builds upon a global trade-linked material flow analysis model to map the supply chain of silver, from mining to module installation, and from 1995 to 2021. The supply routes are analyzed against 21 country-level ESG indicators provided by the Environmental Performance Index, the Social Hotspot Database, and the Worldwide Governance Indicators. Supply concentration is assessed with the Herfindahl-Hirschman Index. As a result, supply patterns and risks over time are identified and characterized. The amount of silver embedded in PV transiting through countries with high ESG risks is estimated. Finally, the impact of alternative supply routes on the supply risks can be quantified. The consequences of reshoring PV manufacturing to the EU are assessed.

The novelty of this paper is hereby twofold. First, it develops a methodology for a fact-based ESG risk assessment from a supply chain perspective. While past work, most notably from Lèbre et al. (Lèbre et al., 2020), focused on the ESG risks linked to metal extraction, the proposed approach extends the scope of analysis to engage all supply chain stakeholders in taking appropriate risk mitigation measures, as recommended by EU policy.
Second, this paper fills the research gap on the supply chain risks related to silver for PV. Several studies have applied supply chain mapping methods to identify material specific supply vulnerabilities. For instance, Nakatani et al. developed a graph theory-based supply chain modelling and applied it to the case-study of Japanese synthetic resins (Nakatani et al., 2018), Liu and Müller developed a trade-linked material flow analysis for aluminum (Liu and Müller, 2013), and van den Brink et al. applied network analysis to cobalt and antimony (van den Brink et al., 2020, van den Brink et al., 2022). A detailed understanding of silver supply chains, at the core of solar cell metallization, is however missing. Current silver usage has been pointed out as a limiting factor to a terawatt-scale annual PV growth, which is expected by 2030 (Goldschmidt et al., 2021, Zhang et al., 2021). As PV manufacturers consider silver thrifting or substitution over availability concerns, this paper invites a complementary broader analysis of supply risks: Beyond supply versus demand comparisons, towards more detailed PV supply chain mapping.

4.2. Material and methods

4.2.1. General approach

In this paper we define risk-based due diligence as the process through which companies, industrial sectors, or countries can identify, prioritize, and address environmental, social, governance, and economic risks in their supply chains to prevent or mitigate adverse impacts associated with their activities. This is in line with the OECD guidance (OECD, 2018), with an extended scope.
The methodological framework consists of three main stages. First, the material supply chains are mapped. Process locations are determined, material flows are quantified, and trade links between countries are identified. Second, each step along the supply chain is assessed in terms of concentration and ESG risks. The production shares s by country c for each process step p are known from the first stage. The Herfindahl-Hirschman Index (HHI) is applied to determine the supply concentration (Herfindahl, 1950), as shown in Eq. 1:

$$HHI_p = \sum_c {s_{c,p}}^2 \quad (1)$$

For each process step, the risk score by ESG indicator i $Score_{p,i}$ is calculated as a weighted sum of the country-level indicator scores $Score_{c,i}$ as shown in Eq. 2:

$$Score_{p,i} = \sum_c (s_{c,p} \times Score_{c,i}) \quad (2)$$

This weight-averaging approach is often used in supply risk assessments to calculate material risk scores describing the social, regulatory, or governance situation of producing countries (Helbig et al., 2021). Third, the probable distribution routes from mining to end-product are identified. This is done by multiplying the end-product material use by the suppliers' production share for each process step (See online Supplementary materials[1]). The ESG risk assessment can thereby be conducted at the supply route level. Because a proportional trade distribution assumption is necessary to close data gaps the uncertainties are relatively high. Nevertheless, it enables a rough estimating of the amount of material "contaminated" by upstream unsustainable production practices.

4.2.2. Material flow analysis model

The trade-linked journey of silver from mining to PV module installation results from a material flow analysis (MFA) model that covers the period 1995-2021 and 238 world regions. The system definition is shown on **Fig. 2**. The model is programmed in python and builds upon the open-source framework ODYM (Open Dynamic Material Systems Model) (Pauliuk and Heeren, 2020). The trade-linked perspective on MFA stems from (Liu and Müller, 2013). All flows are quantified in silver content equivalents. The list of countries for the MFA, the system parameters with data sources, and system flows are provided in the online Supplementary materials.

4.2.3. Trade data

The procedure for trade data compilation depends on the commodity considered. For silver in concentrate and refined form, the trade database BACI for the Harmonized System (HS) 1992 was used (Gaulier and Zignago, 2010). The routines applied for the detection and handling of outliers are described in the online Supplementary materials. They are based on a kernel density estimation approach (Jiang et al., 2022).
The aggregation level of trade data does not allow to identify flows of PV products alone. A market analysis was therefore conducted to map the locations of the PV related process steps. The silver powder and paste market was inferred from press releases, initial public offering documents, company and institutes reports, as well as interviews with industrial stakeholders (see online Supplementary materials). While the market analysis was deemed as robust for the year 2021, data on silver powder and paste were not sufficient to model market variations over the years. Thus, the year 2021 shows the highest level of detail. The silver demand for the PV sector was only examined at the cell and module stages from 2010 to 2020. A proportional trade distribution, adjusted with real trade relationships, was assumed for PV products. For example, no trade was registered under the code HS711590 between Taiwan and India in 2020. This means that metallization silver paste was not exchanged between these countries. It was therefore assumed that all paste producers, except Taiwan, supply to India for cell manufacturing, in the same proportions as their respective market shares.

4.2.4. ESG indicators

Environmental, social, and governance issues in supplier countries can have multiple effects on value chains. Poor national performances can be an indicator of lax policy instruments regulating production, social unrest or political instability might lead to supply interruptions, and overall, a lack of sustainability puts companies at risk for reputational, legal, and financial damages.

The ESG risks were characterized with the following country-level indicators:

- **Governance** (Kaufmann and Kraay, 2022): Voice and Accountability, Political Stability and Absence of Violence/Terrorism, Government Effectiveness, Regulatory Quality, Rule of Law, Control of Corruption.
- **Environmental** (Wolf et al., 2022): Air Quality, Biodiversity and Habitat, Climate Change Mitigation, Heavy Metals, Waste Management, Water Resources.
- **Social** (SHDB, 2019): Wage Assessment, Child Labor, Forced Labor, Excessive Working Time, Freedom of Association/Collective Bargaining/Right to Strike, Social Benefits, Labor Laws and Conventions, Discrimination and Equal Opportunity, Occupational Toxics and Hazards.

The full definition of the indicators and reasoning for their selection is given in the online Supplementary materials. The ESG scores of selected key countries are shown on **Fig. 1**.

[1]https://doi.org/10.1016/j.resconrec.2023.107148 (Supplementary materials - Excel data)

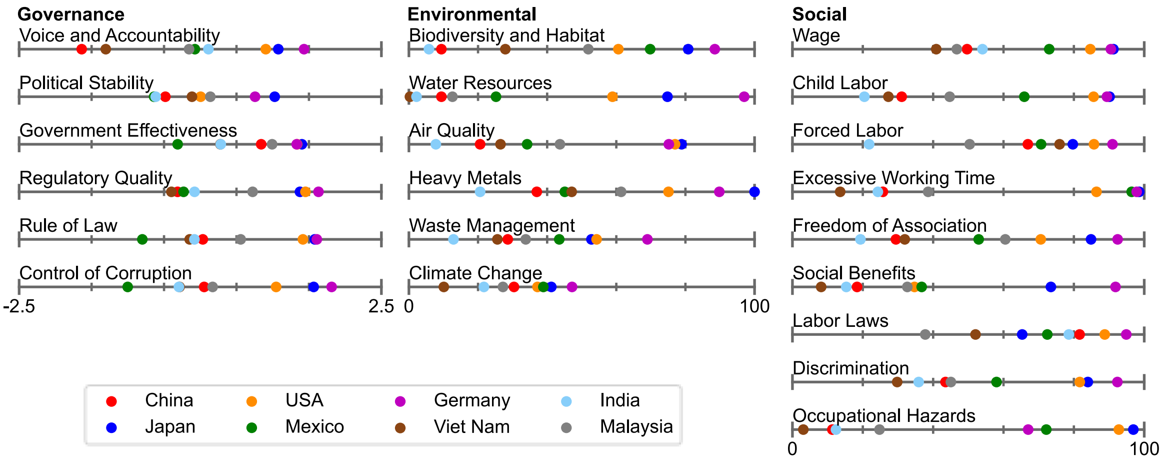

Fig. 1 Comparison of the ESG scores of selected countries for the year 2021, based on (Kaufmann and Kraay, 2022, SHDB, 2019, Wolf et al., 2022). The governance scores are rated from -2.5 (worst) to +2.5 (best). The environmental scores are rated from 0 (worst) to 100 (best). The social scores are averaged over the economic sectors considered and scaled by percentile rank for visualization purpose, from 0 (worst) to 100 (best) (See Appendix for a more detailed global distribution of social risks).

For the social dimension, the Social Hotspot Database (SHDB) supports the quantification of social risks for 244 world regions and 57 economic sectors. Out of the 26 social impacts subcategories considered in the SHDB, those relevant for the stakeholder category "Workers" were selected. Upon modelling, some subcategories such as *Injuries and Fatalities* were discarded due to the lack of data. The sectors in the SHDB of interest for our case-study are "Minerals not elsewhere classified" for silver mining, "Metals not elsewhere classified" for silver refining, powder and paste fabrication, and "Electronic equipment" for cell and module manufacturing. It should therefore be noted that, similarly to the governance and environmental indicators, data from the SHDB are used as a proxy for risk analysis, and do not depict the specificities of the silver industry.
The SHDB provides information on the social risk level (low, medium, high, very high, no data) and labor intensity (in worker hours per unit of process output) by country-specific sector. The social risk for a country c and sector x was calculated as shown in Eq. 3 from the number of worker hours Wh and a characterization factor CF associated with the risk level (0.1 for low risk and no evidence, 1 for medium risk, 5 for high risk, 10 for very high risk) (Benoît Norris et al., 2019). The social risk is given in medium risk hour equivalent (mrh), as it is expressed relatively to the medium risk level.

$$Social\ risk_{c,x} = CF_{risklevel_{c,x}} \times Wh_{c,x} \quad (3)$$

All data for the ESG risk assessment were indexed for management in python. The data coverage for the risk assessment is given in the online Supplementary materials.

The governance, environmental, and social dimensions are assessed on different scales. A score comparison on a shared risk scale can facilitate the communication of the results to decision-makers. In this paper, a binning procedure described in the online Supplementary materials was proposed to attribute a risk level from very low to very high to each quantitative score. This classification introduces subjectivity and is therefore only used for visualizing final results.

4.3. Results

4.3.1. Market concentration, stocks, and flows

Fig. 2 shows the silver flows from mining to PV module installation, cumulated on a global level over 238 countries and from 1995 to 2021. In the production phase, silver ore is extracted and concentrated.

The concentrate is separated from its parent materials – mostly lead/zinc, silver, copper, or gold ores – through smelting or leaching, and processed into refined silver to be used for fabrication.

Out of the 739 kt silver mined from 1995 to 2021, an estimated 27% left the economy as tailings (148 kt) and slag (51 kt) (Johnson et al., 2005). Concentrates are not a highly exchanged commodity compared to refined silver. This indicates that miner countries are often also refiners (see Appendix for the world refined silver production by country).

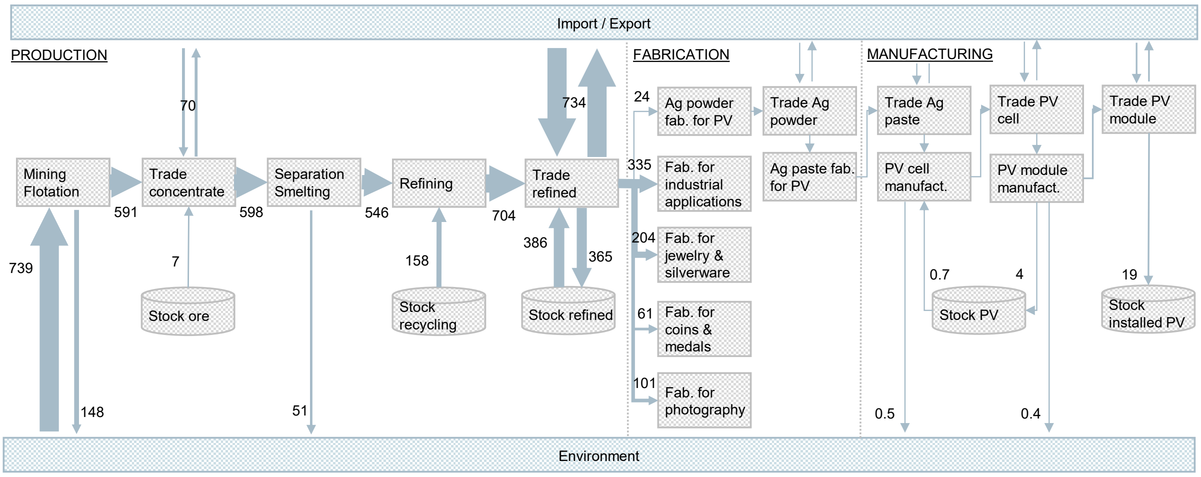

Fig. 2 Global silver flows cumulated over the period 1995-2021, in kilotons of silver. The width of the arrows is proportional to the magnitude of flows. Flows from and to the stocks of silver ore, refined silver, and manufactured cells and modules are derived from mass-balance at country-level. Trade flows from silver powder to PV module were calculated from a proportional trade distribution assumption and are therefore not detailed here.

As shown on **Fig. 3**, the silver market has fluctuated between periods of shortage and oversupply. Stocks of refined silver and recycling have played a key role in closing the gap between supply and demand. The demand for fabrication is led by industrial applications and jewelry and silverware (World Silver Survey). Silver-based photography dropped, whereas silver use for PV showed an average annual growth rate of 15% over the period 2014-2021.

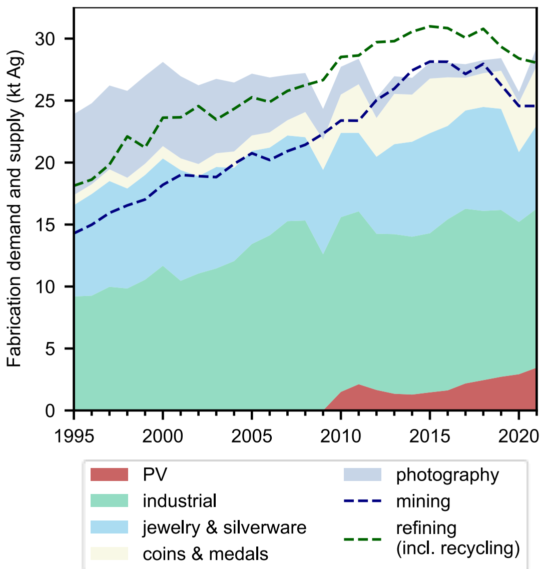

Fig. 3 Historic evolution of supply and refined silver demand for fabrication.

The fabrication of silver powder and silver paste are key processes for PV electrode contact pastes. The powder, made of silver particles by chemical reduction, is dispersed in a mixture of organic binders, additives, and leaded glass frit, thus forming a highly conductive paste. The paste is deposited by screen-printing on the top and bottom of solar cells. The cells are then assembled in a PV module.
We estimate the refined silver demand for global PV production at 12% (3,500 t) of the total demand in 2021. This includes silver losses from cell breakages in the cell and module fab (Brailovsky et al., 2022). In total, and under consideration of the historic evolution of silver loading per cell (see online Supplementary materials), over 19,000 tons of silver are embedded in installed PV modules and could become potentially available upon end-of-life recycling. For comparison, global mine production in 2020 was around 25 kt (Idoine et al., 2022).

Fig. 4 shows the results of the market analysis for PV related process steps. A more detailed market description for silver powder and paste is provided in the Appendix. The formulation and fabrication process of silver paste for PV varies with the base doping of the cell material (p-type or n-type), the side of the contact layer on the cell (front or back), and the metallization temperature – low temperature (LT) or high temperature (HT). Chinese localization is in full swing for most paste types: Chinese companies provided 63% of the global p-type, front, HT paste in 2021 against 17% in 2016 (BloombergNEF, 2021). Japan also shows a strategic advantage as it focuses on n-type paste production, which will become central to achieve higher PV efficiencies.

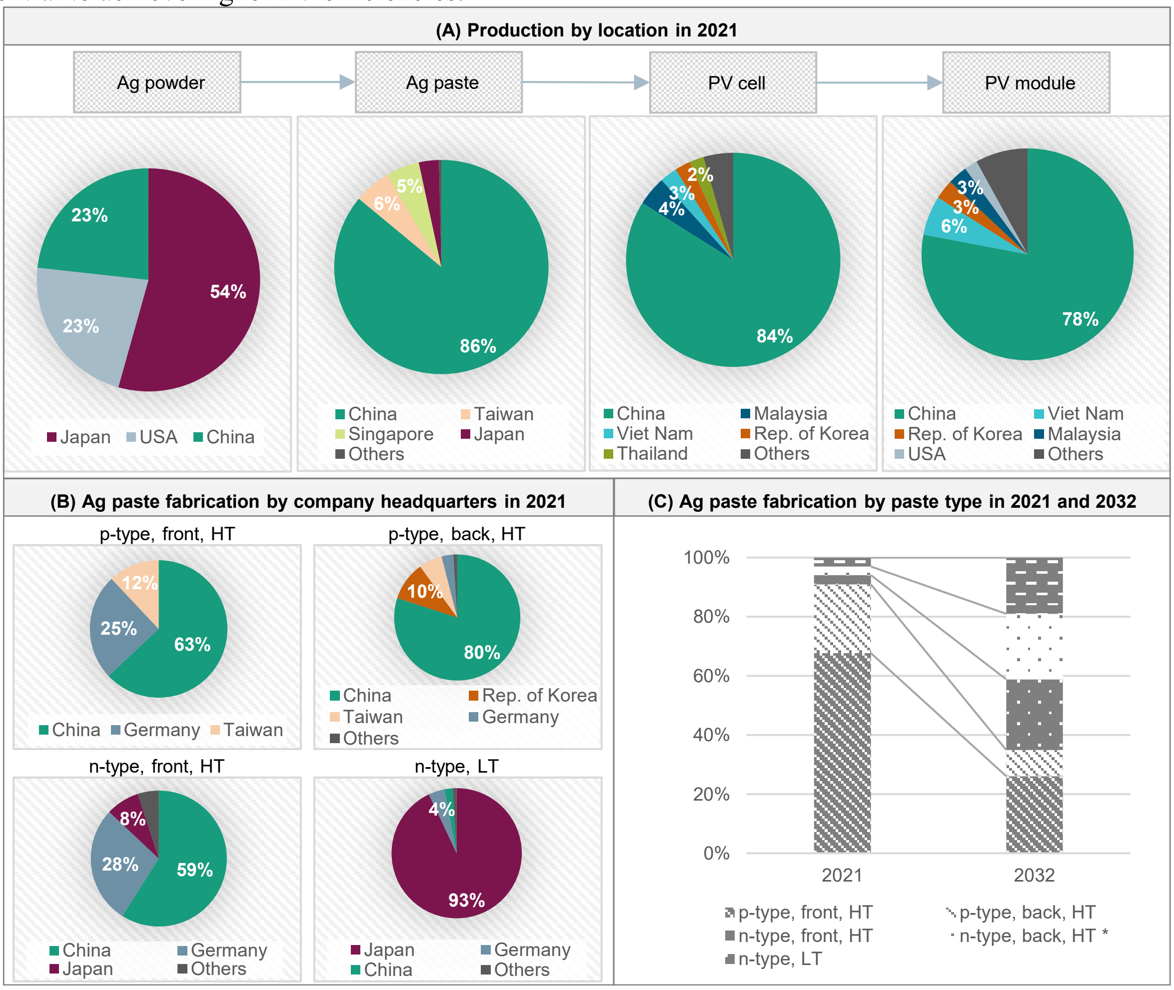

Fig. 4 (A) Production location of PV related process steps in 2021. (B) Company headquarters location of the main silver paste types for PV in 2021. The silver paste market for PV was inferred from press releases, initial public offering documents, company and institutes reports, as well as interviews with industrial stakeholders (see online Supplementary materials). (C) Silver paste market projections for 2032, estimated from (CPIA, 2022, ITRPV, 2022), showing that n-type is expected to become mainstream over the next decade. * The n-type, back, HT paste is assumed similar to the p-type, front, HT paste.

The favorite location for paste fabrication remains China for Chinese and Non-Chinese companies alike, as they seek a proximity to PV cell manufacturers. This provides the advantage of limiting transportation costs.

As shown on **Fig. 5**, supply concentration for cell and module has exacerbated over time as the industry moved to China. Their HHI reached record values in 2021. On the contrary, silver mining and refining – which includes recycling – have consistently shown a low concentration, despite some changes among suppliers. Among these changes, China has become a key supplier of concentrates and refined silver, increasing its market share from 6% and 5% respectively in 1995 to 14% and 18% in 2020, as well as the second global recycler behind the United States. Mexico has further consolidated its position of first mining country at the expense of Canada and the United States. While PV installation shows a moderate geographical concentration, it has led to the accumulation of important silver reservoirs (see Appendix). China concentrates by far the most secondary silver embedded in installed PV, with 6,300 tons of silver. It is followed by Germany (3,000 t), the United States (2,200 t), Japan (2,000 t), Italy (1,200 t), and India (990 t).

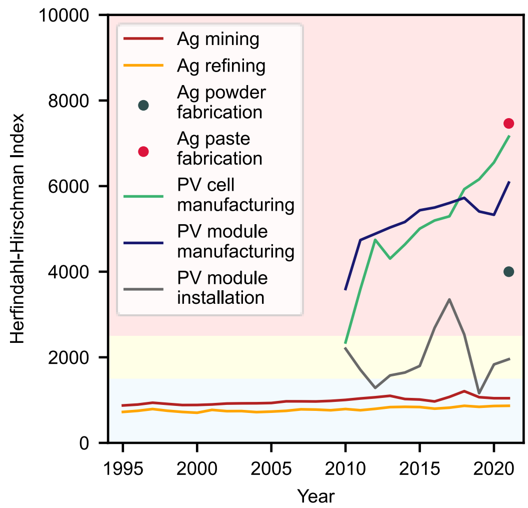

Fig. 5 Herfindahl-Hirschman Index (HHI) scores along the silver supply chain and over time. HHI < 1,500: Competitive marketplace (blue range); 1,500 ≤ HHI < 2,500: Moderately concentrated market (yellow range); HHI ≥ 2,500: Highly concentrated market (red range); HHI = 10,000: Monopoly.

The global PV industry is reliant on a handful of countries for the supply of silver powder, paste, PV cell, and module. This low diversity of suppliers can translate into a global shock propagation along supply chains. ESG issues can trigger such disruptions.

4.3.2. ESG risks by process step

Fig. 6 shows the historic governance performances by process step, rated from -2.5 (worst) to +2.5 (best). The global governance score remains zero over time. Silver supply chains are linked to below global average scores for all indicators except *Government Effectiveness*. *Political Stability* is the most prominent shortcoming for silver mining and refining. Paste fabrication, and cell and module manufacturing show particularly poor performances for *Voice and Accountability*. Powder fabrication, largely located in Japan, is the process step with the highest governance score in 2021.

Over time, a negative slope has established in mining and refining for all governance indicators. This worsening trend also applies to cell and module manufacturing. Exceptions are observed for *Government Effectiveness* for cell and module manufacturing, and for *Rule of Law* for module manufacturing. The factors of the governance decline are further analyzed. A combination of two main developments is at play.

First, a global market shift. Silver supply chains have concentrated in countries with, on average, lower governance scores. This has been the most important driver for all governance indicators in mining and refining, as the shares of Canada, Japan, Australia, and the United States have receded to the benefit of China, Mexico, Russia, and India. Similarly, the PV cell and module industry has increasingly relied on China, Viet Nam, Thailand, and India, instead of Germany, Taiwan, Japan, and the United States. This has been associated with a steep decline in *Voice and Accountability* and *Regulatory Quality*.

Second, a governance shift at country-level. Countries have exhibited improvements and/or deteriorations in their governance scores. This has been the most important factor behind the increase of *Government Effectiveness* and *Rule of Law* in cell and module manufacturing. Large progress in *Government Effectiveness*, especially in China since 2014, has led to an upward trend for the PV industry. This progress has cancelled out the negative effects of market changes, meaning that the current *Government Effectiveness* score is at a similar level as it would have been if the manufacturing countries for cell and module had stayed the same since 2010. Similarly, progress in *Rule of Law* over the last decade in Asia has started to reverse the negative effects of PV market changes. A positive trend is also emerging for *Control of Corruption*, as China showed improvements in 2020 and 2021. On the contrary, the *Political Stability* score for the PV industry has declined since 2018, mirroring the evolutions in China, Viet Nam, and the United States.
As of 2021, China contributes the most to the governance scores from paste fabrication to module manufacturing due to its market dominance. For silver mining and refining, Mexico and China present the highest risks (See Appendix).

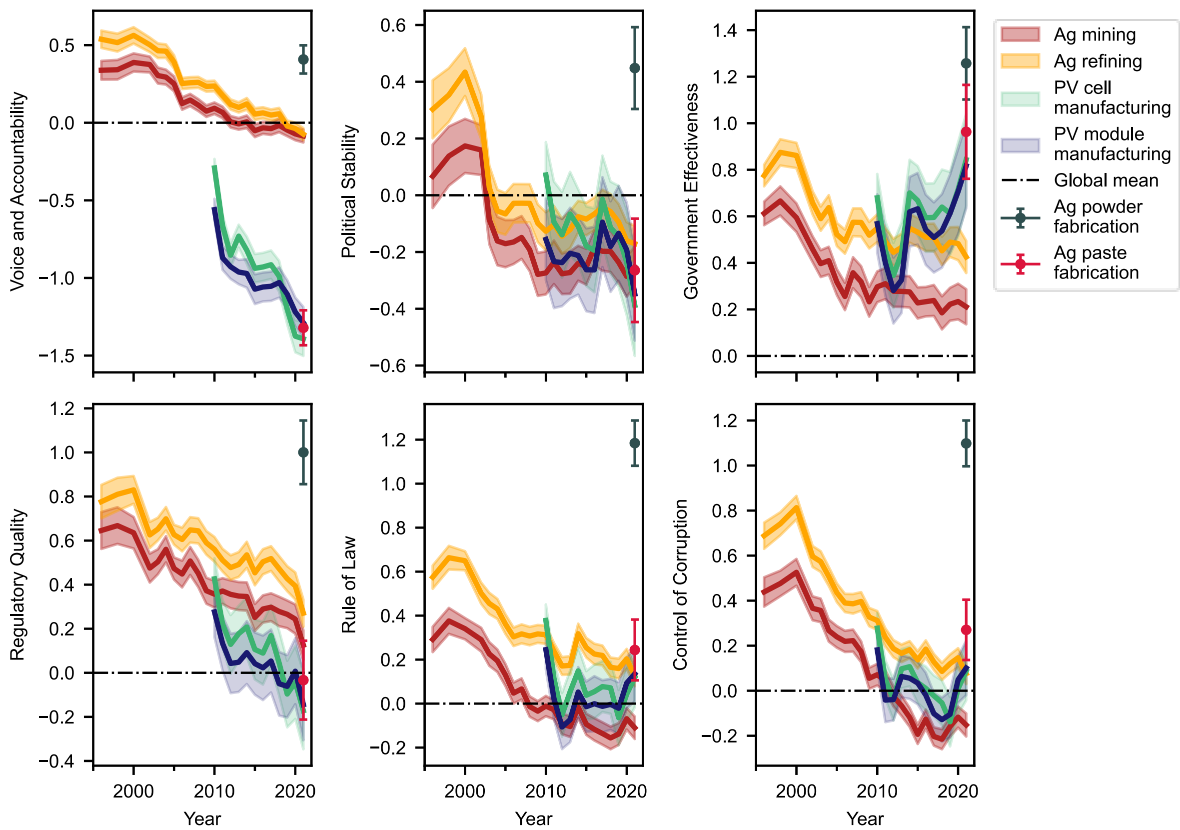

Fig. 6 Governance performance from -2.5 (worst) to +2.5 (best) along the silver supply chain and over time. The country scores have a margin of error, represented on the figure with continuous error bands or whiskers for single point data.

Fig. 7 shows the social risk results. A high value in medium risk hour equivalent (mrh) is representative of a country-specific sector where the social risk is elevated and might concern many workers.

Cell and module manufacturing show the highest aggregated social risk, followed by mining, and paste fabrication. For all process steps considered, social adverse impacts are most likely to arise from a lack of worker's rights of freedom of association, collective bargaining, and right to strike. *Occupational Toxics and Hazards* are prominent along the entire supply chain as well. The U.S. Department of Labor flagships reports of children forced to produce electronic components in China, e.g., under cover of internships (U.S. Department of Labor, 2022). All products belonging to the Chinese sector "Electronic equipment" such as printed circuit boards, semiconductors, cell phones, laptops, or solar panels, are therefore attributed a very high risk of *Child Labor* in the SHDB. While cell and module manufacturing might not be directly concerned, this calls nevertheless for caution on a PV system level. *Excessive Working Time* is also linked to cell and module manufacturing. Risks of *Forced Labor* are mostly identified in the upstream supply chain. The countries where social issues are most likely to occur are shown in **Table 1**.

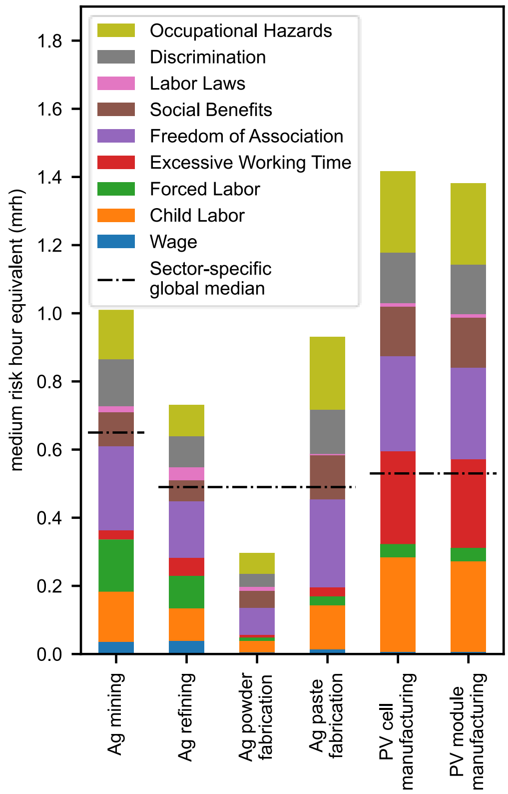

Fig. 7 Social risks along the silver supply chain. The risks are given for one year, representative of the status-quo.

The social risk assessment is not normative: Scores in mrh cannot be interpreted alone as good or bad. A comparison with the worldwide social risk distribution by sector (see Appendix) can give an indication on how well the countries involved in silver supply chains perform compared to peers. With aggregated social risk scores between 0.7 and 1.4 mrh, all process steps are rated relatively poorly: They take place in countries which perform on average worse than 50% to 75% of the world regions considered. The exception is silver powder fabrication for which the aggregated social risk score lies in the 25th percentile.

Table 1 Most prominent social hotspots in silver supply chains by process step.

Process step	Social risk, Location (Contribution to the aggregated social risk by process step)
Ag mining	*Freedom of Association*, China (8%); *Occupational Hazards*, China (6%); *Child Labor*, China (4%); *Social Benefits*, China (4%); *Discrimination*, China (4%); *Child Labor*, India (3%), *Forced Labor*, India (3%), *Freedom of Association*, India (3%); *Freedom of Association*, Mexico (3%); *Occupational Hazards*, Kazakhstan (3%)
Ag refining	*Freedom of Association*, China (8%); *Occupational Hazards*, China (6%); *Child Labor*, Peru (5%); *Child Labor*, China (4%); *Social Benefits*, China (4%); *Discrimination*, China (4%); *Wage*, Argentina (3%); *Freedom of Association*, Mexico (3%); *Forced Labor*, Russia (3%)
Ag powder fabrication	*Freedom of Association*, China (23%); *Occupational Hazards*, China (20%); *Child Labor*, China (12%); *Social Benefits*, China (12%); *Discrimination*, China (12%); *Social Benefits*, USA (5%); *Labor Laws*, Japan (4%); *Forced Labor*, China (2%); *Excessive Working Time*, China (2%); *Freedom of Association*, USA (2%)
Ag paste fabrication	*Freedom of Association*, China (28%); *Occupational Hazards*, China (23%); *Child Labor*, China (14%); *Social Benefits*, China (14%); *Discrimination*, China (14%); *Forced Labor*, China (3%); *Excessive Working Time*, China (3%); *Wage*, China (2%)
PV cell manufacturing	*Child Labor*, China (18%); *Excessive Working Time*, China (18%); *Freedom of Association*, China (18%); *Occupational Hazards*, China (15%); *Social Benefits*, China (9%); *Discrimination*, China (9%); *Forced Labor*, China (2%)
PV module manufacturing	*Child Labor*, China (17%); *Excessive Working Time*, China (17%); *Freedom of Association*, China (17%); *Occupational Hazards*, China (14%); *Social Benefits*, China (9%); *Discrimination*, China (9%); *Occupational Hazards*, Viet Nam (2%); *Forced Labor*, China (2%)

The environmental performances, rated from 0 (worst) to 100 (best), are presented in the Appendix. Over the last decade, the global average has shown minimal improvements for most of the environmental indicators. Silver mining and refining perform relatively closely to this global average. Powder fabrication shows the highest environmental scores, ranging from 38 for *Climate Change* to 80 for *Heavy Metals* in 2021. Paste fabrication, cell and module manufacturing are the process steps with the highest country-level environmental risks. *Water Resources* is hereby the most prominent issue in 2021, due to the below 20 score of China, India, Malaysia, Thailand, Taiwan, and Viet Nam. Policies in *Biodiversity and Habitat* are insufficient as well, especially in China. As for *Climate Change*, progress could be noticed over the last decade. This indicator captures the country projected greenhouse gas emission levels by 2050 and whether they comply with a zero-emission target, as well as past trends in greenhouse gas emissions growth (Wolf et al., 2022). The *Climate Change* score in China increased from 9 to 30. Still, silver supply chains locate in countries which are not on track for net-zero greenhouse gas emissions by 2050.

It is important to note that the ESG risk assessment is performed at country-level and does not account for corporate conducts or differences in specific industries, processes, or regions. It provides a basis for companies to flag potential issues which may be the basis for enquiries to their suppliers at the identified hotspots.
It can further be of interest to estimate the ramifications of ESG risks. This is done by adopting a supply route perspective, i.e., by estimating the amount of silver used in PV which transits through countries with high ESG risks.

4.3.3. ESG risks by supply route

The trade-linked journey of silver from mining to module manufacturing for the year 2021 is shown on **Fig. 8**. Trade flows were corrected for re-exports: Concentrate trades from non-mining countries were discarded. Refined silver trades from countries which are not recyclers or have less than 200 kg concentrates from trade balance in a given year were discarded as well.

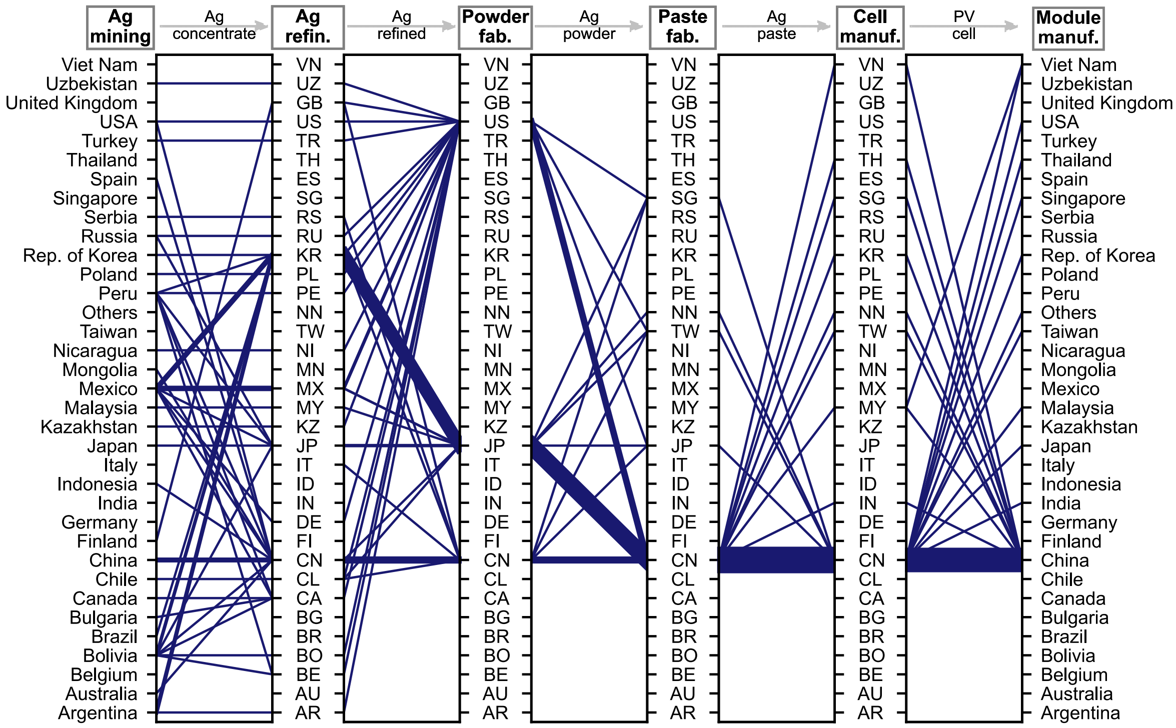

Fig. 8 Trade-linked global journey of silver containing products for PV in 2021, from mining to PV module manufacturing. The width of the links is proportional to the magnitude of flows. Flows smaller than 1 ton and losses are omitted for visualization. Representation type from (Liu and Müller, 2013).

The model provides insight in the probable distribution routes a unit silver can take. As an example, the 5 most important supply routes for silver used in PV, among over 200,000 probable supply routes assessed in the model, are listed in **Table 2**. Retracing the silver journey enables to uncover key suppliers for the PV industry. Thus, 43% of the silver for PV transit through the Republic of Korea. Although, on a global level, the Republic of Korea plays a minimal part in silver production, it is the main refined silver trade partner for Japan which supplies most of the silver powder for PV. The reasons behind the preference of Korean refined silver (e.g., transportation costs, trade relationship, silver quality) is beyond the scope of this paper. Russia and Poland represent each over 5% of the global silver mining and refining. Their participation in PV related silver supply is however estimated at only 1% because they trade outside of the silver powder and paste industry. China is an inevitable PV component supplier.

Table 2 Most probable supply routes for silver used in PV module manufacturing in 2021, and estimated quantity of silver in tons.

Supply route	Ag mining	Ag refining	Powder fabrication	Paste fabrication	Cell manufacturing	Module manufacturing	t Ag
1	Mexico	Rep. of Korea	Japan	China	China	China	260
2	China	China	China	China	China	China	240
3	Argentina	Rep. of Korea	Japan	China	China	China	200
4	Bolivia	Rep. of Korea	Japan	China	China	China	160
5	Mexico	Mexico	USA	China	China	China	160

Each route was evaluated against the 21 ESG indicators. To facilitate comparison between the ESG dimensions, the risk scores were attributed a risk level from very low to very high. The binning procedure is described in the online Supplementary materials. The highest risk level among all process steps for a given indicator provides the risk level of the supply route for this indicator. It is hereby argued that virtuous production at a point in the supply chain does not cancel out sustainability negligence elsewhere. As opposed to a risk averaged over the entire supply chain, this avoids for hotspots to be masked. Because threshold values were defined to convert the quantitative risk scores in qualitative levels, the approach is somewhat subjective and simplified. It remains however useful for visualization purposes. Results are shown on **Fig. 9**.

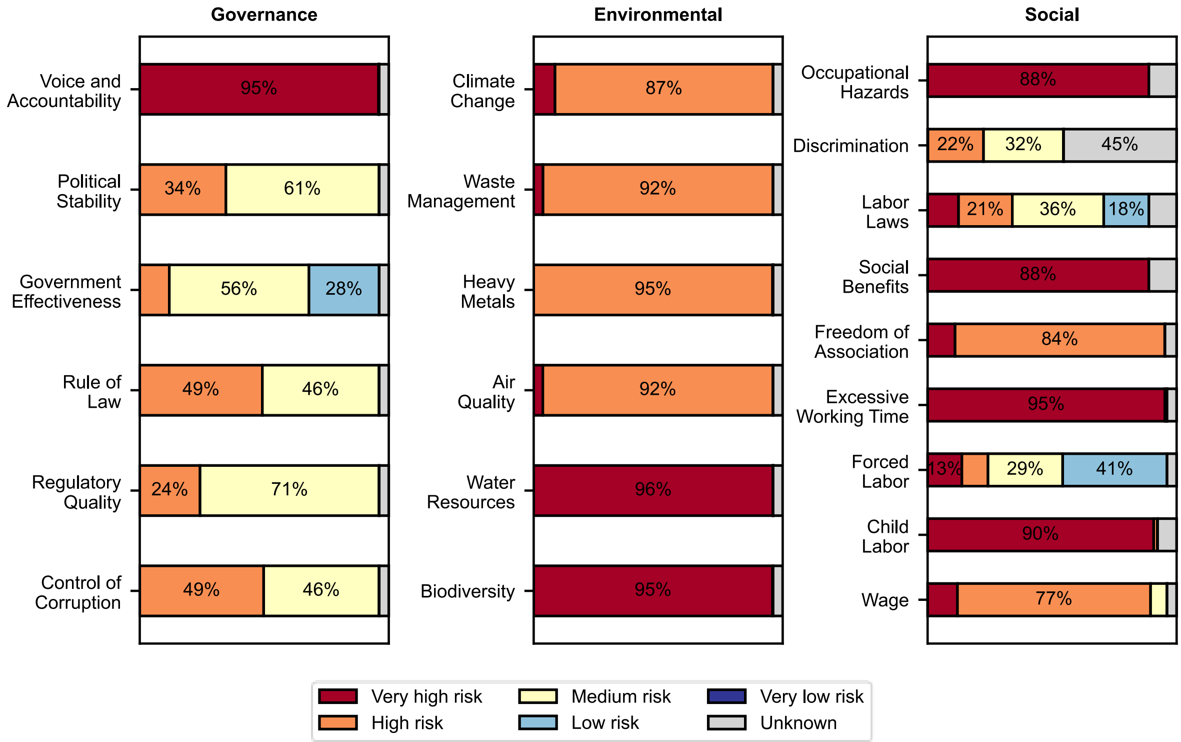

Fig. 9 ESG assessment of the silver supply routes for PV. For each ESG indicator considered, the percentage shows the share of silver used in PV associated with a given risk level. For example, 34% of the silver used in PV is associated with a high risk regarding Political Stability, 61% with a medium risk, and for the remaining 5% no data were available.

Over 88% of the silver used in PV transit through at least one country with a very high risk of poor performance for *Voice and Accountability*, *Water Resources*, *Biodiversity and Habitat*, *Occupational Toxics and Hazards*, *Social Benefits*, *Excessive Working Time*, and *Child Labor*.
Particular attention should also be paid to *Freedom of Association*, *Wage*, *Climate Change*, *Waste Management*, *Heavy Metals*, and *Air Quality*. No supply route with a low risk over all ESG dimensions is identified. The social dimension shows the most missing data.

The risk assessment applied to supply routes has two main advantages. First, the assessment is conducted for the supply chains specific to the product considered, meaning it is less generic than an assessment at process step level. Second, it enables decision-makers to appreciate the magnitude of potential ESG issues and how much downstream products are concerned. For our case-study, the current supply routes are associated with significant ESG risks, which, if not rebutted after business examination, contaminate nearly all silver used in PV.

The trade-linked model further enables to examine how different sourcing strategies reduce or increase the ESG risks.

4.3.4. Impact of alternative supply routes on ESG risks for the EU

Bringing PV production back to the EU, or reshoring, has become a central topic for strategic autonomy. The EU Solar Energy Strategy targets 30 GWp of PV manufacturing capacity in the EU by 2025 (European Commission, 2022c). The annual EU PV market size is estimated at 49.7 GWp by then

(Medium Scenario) (SolarPower Europe, 2021). The impact of reshoring on the ESG risks is assessed. The following potential supply patterns are compared:

- **Status-quo**: The EU demand for PV is covered by the global silver and PV market in 2021, as detailed previously.

- **Cell to Module reshoring**: 60% of the EU demand for PV is covered by local cell and module manufacturing. This target is in accordance with the EU Solar Energy Strategy. EU manufacturing locates in the EU countries with the most ambitious PV plans by 2025 (see online Supplementary materials). From cell to module, trades within the EU are preferred.

- **Powder to Module reshoring**: 60% of the EU demand for PV is covered by local manufacturing from silver powder to module. This target is in accordance with the EU Solar Energy Strategy. EU cell and module manufacturing locates in the EU countries with the most ambitious PV plans by 2025 (see online Supplementary materials). EU powder and paste fabrication locates in Germany, based on the headquarter location of the leading paste producer Heraeus. From powder to module, trades within the EU are preferred.

- **PV Autarky**: 100% of the EU demand for PV is covered by local manufacturing from silver powder to module. The EU Solar Energy Strategy does not advocate for self-sufficiency. This supply pattern is solely defined for comparison purposes and is not intended to depict a desirable outcome.

The supply routes for each supply pattern are evaluated against the ESG indicators. **Fig. 10** shows the share of silver used for PV installation in the EU, transiting through at least one country with a high or very high ESG risk.

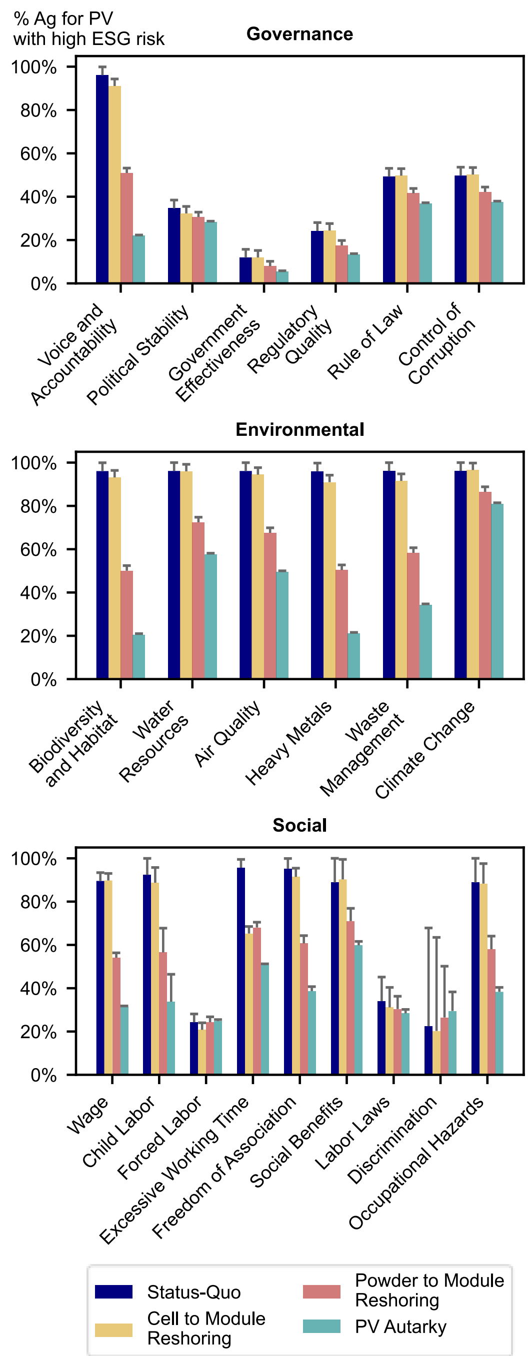

Fig. 10 Share of silver used for PV installation in the EU associated with a high or very high ESG risk, under consideration of different sourcing strategies. Missing data are represented as error bars.

Locally manufacturing 60% of the cells and modules for the EU has a relatively limited impact on alleviating governance and environmental supply chain risks. The risk of *Excessive Working Time* and *Forced Labor* are reduced by 32% and 14% respectively compared to the status-quo. For the other ESG indicators, this reduction does not exceed 10%.
Reshoring further upstream, from the powder fabrication onwards, substantially de-risk supply chains. Risks are reduced by 35% to 50% for *Biodiversity and Habitat*, *Heavy Metals*, *Voice and Accountability*, *Wage*, *Waste Management*, *Child Labor*, and *Freedom of Association*.
Reshoring in the EU appears as an efficient risk reduction strategy. This also has limits. As highlighted by the supply pattern PV Autarky, even a fully European PV industry will not entirely de-risk the upstream silver supply chains. For example, over 80% of the silver delivered to the European PV market

would still be associated with a high risk for *Climate Change*. Risks of *Forced Labor* also remain because they mainly arise by silver production. Collective action with supplier countries and due diligence further upstream, up to mining, remain therefore crucial.

4.4. Discussion

The MFA model used to assess silver supply chains is only as robust as its underlying data. Estimated tailings and slags are particularly uncertain and could be improved if mine-specific data and details on silver separation methods were available. Findings on the social risks are limited because social progress over time is not available in the underlying SHDB. They only provide a snapshot at country-level based on data sources which, in some cases, are not regularly updated. A further disaggregation of the product groups in trade statistics would also facilitate the monitoring of material flows.

This paper contributes to research on raw material criticality and provides guidance for systematic and transparent due diligence for industrial sectors. While ESG imperatives have been identified as a main limiting factor for mineral extraction, this paper suggests that adverse ESG impacts along the entire supply chain create further, and immediate, supply risks. The modelling of multiple supply-chain stages and the extension of the risk analysis to the social dimension (the environmental and governance dimensions being already standard) could be integrated in criticality assessments. The historic perspective on risks provides additional valuable insights. Assessing ESG trends over time and for disaggregated indicators enables to highlight progress in developing countries, thus avoiding a simplified opposition between “bad” and “good” suppliers, or, on the contrary, identify worsening situations.

The mapping exercise and hotspot identification carried out here is the first step required from companies to fulfill their due diligence (OECD, 2018). The risks are identified at country-level and need to be confirmed or infirmed with higher resolution approaches, i.e., under consideration of corporate conducts and regions (Lèbre et al., 2020, RMF, 2022). Findings of this paper can also be of interest for policymakers: Supply concentration and some ESG risks such as systemic forced labor are rather addressed through high-level dialogues and international cooperation than by individual companies.

For the case of silver, ESG risks from paste fabrication to PV module manufacturing are mostly located in China due to its market dominance, and in Mexico and China for mining and refining. Due diligence and traceability in collaboration with the local actors there need to be strengthened in priority. A continuous ESG risk monitoring could further be helpful as the PV industry increasingly turns towards other producing countries. For instance, Viet Nam and India are PV growing markets associated with their own high environmental, social, and governance risks (see **Fig. 1**). Establishing alternative supply routes can also de-risk sourcing. This has been exemplified by showing the ESG risk decrease resulting from reshoring PV manufacturing to the EU. It should however be noted that the economic pros and cons of reshoring are beyond the scope of this paper. More research is needed to understand to what extent reshoring can increase supply chain resilience, how internalizing ESG risks contributes to a level-playing field in PV and how this translates in terms of consumer prices. Other instruments for a sustainable sourcing in PV, such as establishing partnerships, consolidating standards beyond environmental aspects, and strengthening international governance should be examined as well.

4.5. Conclusion

This paper explores supply chain risks related to supply concentration and ESG issues, for the case-study of silver for PV.

It proposes a methodology for a transparent, fact-based ESG risk assessment from a supply chain perspective. All supply chain actors can therefore identify hotspots and take appropriate risk mitigation measures, as recommended by EU policy.

For silver used in the PV industry, a high supply concentration from powder to module was found. The benefits and barriers to a supply diversification for these processes need closer examination. The amount of silver embedded in installed PV was estimated at 19 kt. This will be of interest for recyclers to assess how much silver could become available and where. It is further recommended for PV stakeholders to clarify in priority the risks related to *Voice and Accountability*, *Water Resources*, *Biodiversity and Habitat*, *Occupational Toxics and Hazards*, *Social Benefits* (for paste to module) as well as *Excessive Working Time* and *Child Labor* (for cell to module). Virtually all silver used in PV is associated with very high ESG risks upstream. Reshoring could potentially reduce risk exposure to a large extent for the EU.

Findings of this paper call for the differentiation of materials by supply chains: A material is not inherently sustainable or not, it depends on its distribution route. The need for more material efficiency in PV and other energy technologies is established knowledge. The energy transition will however not only be about using less materials, but also about sourcing them better – both strategically and responsibly.

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