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A case study of photovoltaics diversification

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Tracing the propagation of disruptions in supply chain scenarios: A case study of photovoltaics diversification

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ABSTRACT

Diversifying supply chains through reshoring and friendshoring is increasingly proposed as a key strategy for supply security and resilience. Quantitative analyses characterizing to what extend diversification shield countries from supply disruptions remain however scarce. In this paper, we present a methodology to assess the supply risk exposure of countries in different supply diversification scenarios – business-as-usual, reshoring, friendshoring. For each scenario, the propagation of three types of upstream disruptions – supply shortage, export restriction, bilateral trade conflict – is simulated. A fragility ratio metric is introduced to quantify the potential downstream shortages caused by these disruptions. A novel friendshoring modelling approach is also proposed. It consists in determining risk-optimized trade relations based on criteria such as supply concentration and UN voting similarity.

The Python-based model is tested on the case of diversified photovoltaics supply chains, e.g., if the US, EU, and India increase domestic production from polysilicon to module. Beyond building up manufacturing capacities, choosing between vertical integration and trade is highly determinant in risk exposure. Each diversification scenario shows pros and cons depending on the country and process considered.

Overall, this paper underlines the need for supply risk research to nuance diversification recommendations. It would be particularly helpful to improve indicators accounting for a region's technical and economic ability to supply a given product, and to realistically model the challenges of reshoring.

1. Introduction

Supply chain disruptions can severely harm companies, and potentially even paralyze entire countries. Some disruptions can be anticipated, but many – even extremely large disruptions such as a global pandemic – can catch actors across supply chains by surprise, not only because the disruption itself is unexpected, but because knock-on effects are very difficult to predict (Sprecher et al., 2017). There is a widespread recognition that the impact of disruptions needs to be mitigated to ensure access to essential products and technologies. Supply diversification is often recommended (Carrara et al., 2023; van den Brink et al., 2020). Policymakers increasingly see reshoring and friendshoring as viable strategies. Reshoring is the focus of the US Inflation Reduction Act, the Indian Production Linked Incentive scheme, and the European Net Zero Industry Act, which all aim at boosting domestic production for strategic goods. Friendshoring encourages trade partnerships with "like-minded" countries (European Commission, 2023b) or with "allies and partners who share our values" (U.S. President, 2021), and is also on the political agenda, although the practicalities of identifying friends are unclear.

Recommendations to diversify remain mostly qualitative: supply chain diversification is a risk mitigation instrument, but its benefits are rarely quantified. It is often unclear to what extend diversification would shield countries from deliberate or undeliberate supply disruptions. Such an exercise implies to i) construct scenarios representing diversified supply chains, and ii) assess the impact of supply disruptions. Both aspects are addressed in this paper. We present and discuss a methodology to assess the exposure of countries to different types of upstream disruptions – supply shortage, export restriction, bilateral trade conflict – and for various supply chain scenarios – business-as-usual, reshoring, friendshoring. To this end, a Python-based model is built to simulate the propagation of a supply disruption and the resulting downstream

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shortage.

The focus is hereby not on the “how” to diversify supply, but on the “what if” we do: how could country interlinkages look like and how would alternative trade relations reduce risk exposure? Specifically, “exposure” is defined in accordance with the terminology on disaster risk from the United Nations. Risk is a function of hazard, exposure, and vulnerability (UNDRO, 1980). From a supply chain perspective, the hazard is the supply disruption of a component, exposure is a country’s direct or indirect dependence on failing suppliers, and vulnerability is a country’s ability to withstand the supply disruption based on its market power, underutilized production capacity, or thrifting ability. The adaptation of the supply chain in face of disruptions, or resilience analysis, are out of the scope of this paper. “Disruptions” refer to short-term supply disturbances in the remainder of this work, as defined by Sprecher et al. (2015).

We test our approach on the case of solar photovoltaics (PV) supply chains. PV is recognized as a cost effective, available, and key decarbonization technology. High-end predictions for PV deployment, from 1 TWp cumulative installed capacity in 2022 to over 50 TWp by 2050, are widely accepted (Haegel et al., 2023). The quasi-monopoly of China over PV supply chains has however raised concerns, and India, the EU, and the US are looking to (re)build domestic PV manufacturing capacities. Taking these ambitions into account, we simulate the propagation of disruptions in PV supply chains and assess the exposure of the PV installation goals in the main markets US, EU, India, China, and Rest-of-World.

This paper addresses two research gaps. A first gap is the lack of impact assessment of reshoring and friendshoring on risk exposure. Modelling risk propagation in material trade networks has gained traction in the literature (Sun, 2022). Notably, Wang et al. simulated Indonesia’s export reduction on nickel ore and its impact on the nickel industry (Wang et al., 2022), and the spread of a graphite supply crisis (Wang et al., 2018). Hu et al. showed the potential impacts of China’s import ban on copper waste and scrap (Hu et al., 2020). Such contributions have underlined the potential bottlenecks downstream and provided the methodological ground for simulating cascading failures in supply chains. Past works have however focused on current material trade networks without comparing risk exposure for different supply chain scenarios. Modelling alternative supply chains is key to better understanding the risk mitigation potential of supply diversification. A main novelty of this paper is the approach proposed to build a friendshoring scenario, i.e., by finding the optimal combination of trade relations to minimize the disruption potential between partner countries.

A second research gap is the lack of in-depth PV supply chain mapping, from quartz mining to module installation. A growing body of literature is dedicated to supply risk assessments beyond the mining stage. Disruptions can occur throughout the entire supply chain and material processing often shows a high degree of geographical and/or corporate concentration, as has been exemplified for antimony (van Brink et al., 2022), cobalt (Ericsson et al., 2024), or tin (Li et al., 2021). High-resolution studies including a full supply chain mapping are needed to uncover and effectively manage hidden supply risks (Ku et al., 2024). In the context of the energy technologies, efforts are ongoing to extend risk monitoring. For example, supply risks were assessed at each processing stage of lithium-ion battery (Sun et al., 2019) and fuel cell vehicles materials (Xun et al., 2021). For silicon in PV, past studies only investigated the trade of a single component, such as PV cells (Wang et al., 2021) and polysilicon (Liu et al., 2019), or analyzed trade dependencies from polysilicon to module, but only from the US perspective (Smith and Margolis, 2019). A more comprehensive mapping for PV is essential to understand the propagation of a disruption to the entire network and identify the most disruptive spreaders.

2. Material and methods

2.1. General approach

The methodological framework consists of three main stages, namely mapping current supply chains, constructing supply chain scenarios, and simulating the propagation of supply disruptions. All underlying models are programmed in Python for easier data management and quick calculations.

The mapping of current supply chains (business-as-usual scenario) is the result of a trade-linked material flow analysis. It relies on trade and production data. As data availability highly fluctuates from product to product, a mix of data from trade databases, national customs statistics, sector-specific reports, is used and complemented with outlier detection procedures and, when inevitable, assumptions.

The supply chain scenarios are constructed relatively to the business-as-usual scenario. The reshoring scenario assumes given countries to cover a share of their domestic demand along the supply chain with ramped up local production. The rest of the demand is covered as in the business-as-usual scenario. This scenario is constructed by linear optimization with PuLP (Mitchell et al., 2011). The friendshoring scenario also assumes given countries to ramp up local production along the supply chain but, contrary to the reshoring scenario, does not impose a domestic use. Global trade flows are determined based on supply risk criteria: market concentration, ability to supply, and willingness to supply. The Herfindahl-Hirschman Index is used to assess market concentration (Herfindahl, 1950), meaning that the allocation of trade flows is a non-linear optimization exercise. This scenario is therefore constructed with a differential evolution algorithm.

The propagation of supply disruptions in the supply chain follows a cascade failure model. It simulates three types of supply disruptions – supply shortage, export restriction, bilateral trade conflict – of different magnitude and points of origin in the supply chain. For each supply chain scenario, the supply disruptions can then be compared based on their potential downstream shortage. This makes a total of nine sub-results.

In the subsequent sections, the supply chain scenarios and the supply disruption propagation model are described in more detail. The data used for the PV case study are also presented.

2.2. Business-as-usual scenario

The business-as-usual (BaU) scenario assumes current supply chains remain unchanged by 2030. The journey of a material from upstream to end-product is mapped by determining trade flows and production output at country-level. Results are shown on Fig. 1**A** for BaU. The reader is referred to existing papers on trade-linked material flow analysis for more methodological details (Gervais et al., 2023; Liu and Müller, 2013).

For the PV case study

A Python-based model is used to map the trade-linked journey of silicon for crystalline silicon PV. It covers 239 world regions and the following process steps: (1) high purity quartz mining – referred to as ‘quartz’, (2) refining into metallurgical-grade silicon – ‘SiMe’, (3) refining into polysilicon – ‘poly-Si’, (4) ingot crystallization and wafer slicing – ‘wafer’, (5) PV cell manufacturing – ‘cell’, (6) PV module assembly – ‘module’, (7) PV module installation – ‘installation’.

Production data

Production output data for poly-Si, wafer, cell, and module in 2021 are taken from (IEA, 2022b) and corrected to remove thin-film production (First Solar, 2021). For the EU, 0.8 GWp/a cell production and 2.2 GWp/a module production are assumed by cross-checking (SolarPower Europe, 2021) and (IEA, 2022b). Non-Chinese wafer production is uncertain, but it is less than 3% of the global production. Viet Nam is added as a wafer producer due to its high capacity of 1.5 GWp as of 2021. Other wafer producers are aggregated. The production

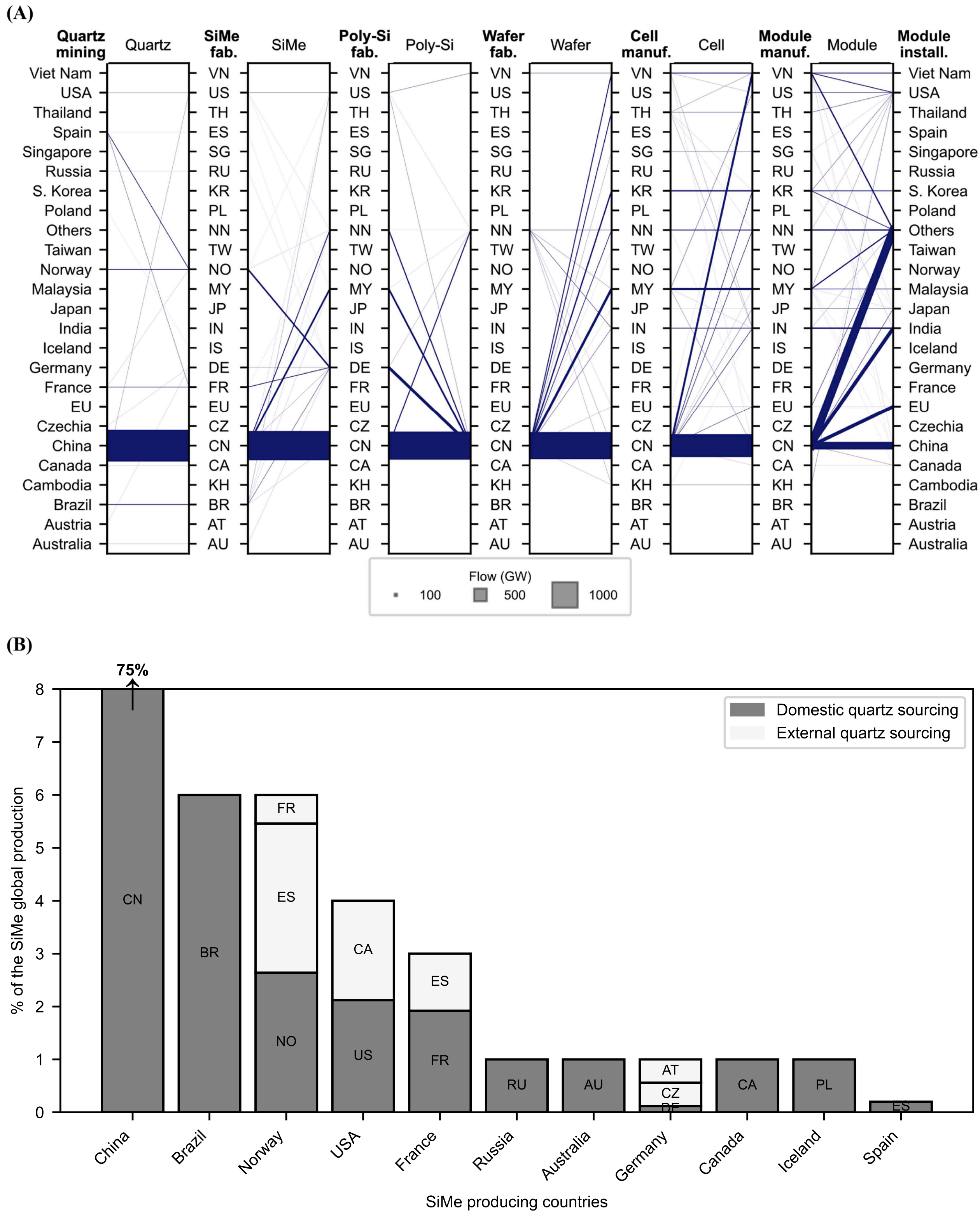

Fig. 1. (A) Supply routes of silicon containing products for PV, from mining to installation, in the business-as-usual scenario. The year 2030 is taken as reference (1.4 TW added installed capacity). Flows smaller than 1 GW and losses are omitted for visualization.
(B) Active metallurgical-grade silicon production locations in 2021 and their sources of quartz. China accounts for 75% of the global production (out of scale). Details by company, production capacity, and literature references are provided in the Annex.

locations of SiMe and quartz are shown on Fig. 1**B**. They are compiled from (Bauer, 2022; Guangzhou Futures Exchange, 2022; Idoine et al., 2023; U.S. Geological Survey, 2023) and companies' documents. Quartz is found to be typically supplied from closely located mines.

The material flow analysis tracks both energy and material flows: conversion parameters used to translate GWp PV in tons of input materials are based on (Brailovsky et al., 2023; Frischknecht et al., 2020) and provided in the Annex.

Trade flows

The procedure for trade data compilation depends on the commodity examined. The BACI trade database is used for SiMe (HS code 280469) and poly-Si (HS code 280461) in 2021 (Gaulier and Zignago, 2010). We further detect and handle outliers by applying a kernel density estimation approach (Jiang et al., 2022). Only trades from known producers to consumers are considered to limit the significance of re-exports. New trade codes for cells and modules have been introduced in the 2022 Harmonized System revision, which is not yet available in BACI. As described in the Annex, national data are therefore used for wafer, cell, and module trade flows.

The year 2030 is taken as reference in the BaU scenario. The collected production and trade data for 2021–2022 are therefore translated into shares of origin by country and multiplied with local PV demand in 2030 estimated by (Bogdanov et al., 2021; Personal communication, 2023).

2.3. Friendshoring scenario

The friendshoring scenario assumes a restructuring of global supply chains based on supply risk concerns. The supplier selection depends entirely on supply risk criteria, namely market concentration, ability to supply, and willingness to supply. Overall, the friendshoring scenario depicts a world where countries collectively strive for de-risking supply through diversification and preference for trade relations based on non-pricing criteria. In practice, the friendshoring scenario determines the best combination of trade flows to minimize the global disruption potential DP, defined as follows:

$$DP = \sum_j \sum_i S_{ij}^2 \ . \ ASI_i \ . \ WSI_{ij}$$

Where, for a given product, S_{ij} is the share of producing country i in the sourcing of consumer country j, ASI_i is the Ability to Supply Index of i, and WSI_{ij} is the Willingness to Supply Index from i to j. The DP indicators come from the work from Nassar et al. (2020) for the revision of the U.S. Critical Minerals List. To our knowledge, their Willingness to Supply Index is the first composite metric quantifying the affinity between countries in the context of supply risk assessments. The sum of the squared production shares mimics the Herfindahl-Hirschman Index, which is commonly used to measure market concentration (Helbig et al., 2021). As a proxy for ASI, the Policy Perception Index (Yunis and Aliakbari, 2022) was used by Nassar et al.. It measures a country's attractiveness in terms of mining policies. Our focus lies however not only on the mining stage but on the entire supply chain. Therefore, we use the World Bank's World Governance Indicators (*WGI*) instead (Kaufmann and Kraay, 2022). The *WSI* was originally composed of three elements: Trade Ties (*TT*), Shared Values (*SV*), and Military Cooperation. Their calculation was however conceived from the perspective of the US, and not fully applicable to other countries. We propose the following changes to provide a proxy for the likelihood that a country i may deliberately disrupt its supplies to country j.

Shared Values: We define Shared Values as the degree to which a pair of states is aligned over foreign policy. We use data on recorded voting behavior in the United Nations General Assembly (UNGA) to reveal similarities in political preferences. UNGA voting data have been used in research on international relations (Bailey et al., 2017; Kleinman et al., 2020; Voeten, 2012) and more recently to simulate the polarization of the world in trading blocs (Métivier et al., 2023). The General Assembly is the only universally representative UN voting body. All 193 UN member states are represented, each getting one vote: yes, no, or abstain. Absences are also recorded. UN votes do not capture how much state i like state j, but rather how states position themselves on a resolution on a global issue such as human rights, nuclear issues, or disarmament (Voeten, 2012). One way to measure voting similarity between actors is to translate their voting behavior into a spatial position on a one-dimensional political spectrum (e.g., liberal-conservative ideology). These spatial positions are referred to as ideal points estimates. The greater the absolute distance between ideal points, the more political divisions between two actors. Bailey et al. (2017) proposed to apply the ideal points approach to UN votes. Their model generates a score for each state and each UNGA session, which represents their position on a political spectrum spreading from negative to positive values. A dataset of all roll-call votes at the UNGA with ideal point estimation from 1946 to 2021 is publicly available on the Harvard Dataverse and regularly updated (Voeten et al., 2009). If regular updates continue, this constitutes a directly usable data source of ideal points estimates for supply risk researchers. We compute Shared Values between i and j as the absolute distance between their mean ideal points θ from 2017 to 2021.

$$SV_{ij} = \left| \overline{\theta_i} - \overline{\theta_j} \right|$$

Trade Ties (similar to (Nassar et al., 2020)): Trade Ties capture the importance of a trade relationship for a state's economy. It is hereby argued that a state less dependent on trade has greater freedom to initiate conflict because its economic damages would be less (Oneal and Russet, 1997).

$$TT_{ij} = \frac{\sum (I_{ji}, \ E_{ij})}{GDP_i}$$

Where, I_{ji} and E_{ij} are the total imports and exports in monetary terms between countries i and j, and GDP_i is the supplier's gross domestic product in current US dollars. For the numerator, the median of the BACI trade flows from 2017 to 2021 (Gaulier and Zignago, 2010) is used to limit outliers and pandemic effects.

Interstate Conflict: The Military Cooperation metric from (Nassar et al., 2020) captures whether a country has a collective defense agreement with the US. To suit the global scope of our work, we rather determine whether two states are currently involved in a conflict. This includes all kinds of conflicts ranging from non-violent crisis to war, as recorded by the Heidelberg Institute for International Conflict Research (HIIK, 2023). UN votes at the General Assembly only concern global issues, and fail at capturing rivalry between some countries (Voeten, 2012). For example, India and Pakistan tend to align on UNGA votes. Interstate Conflict provides a complementary correcting factor.

Each DP indicator is normalized on a scale of 0 to 1, with higher values corresponding to higher risks (Nassar et al., 2020).

WSI is calculated as the average of *TT* and *SV*, plus 0.1 for pairs of countries involved in a conflict. *DP* is computed for both external ($i \neq j$) and internal ($i = j$) product flows to account for domestic overreliance. The usefulness and limitations of the indicators used to construct the friendshoring scenario are discussed in Section 4.

Finding the best combination of trade flows S_{ij} to minimize DP is a non-linear problem due to the Herfindahl-Hirschman Index. We solve it with a differential evolution (DE) method, using the SciPy library. DE is an evolutionary algorithm, originally introduced by Storn and Price (1997). This optimizer has become widely used due to its excellent search performances, i.e., it can consistently converge to the global minimum of a function, and ease of use, i.e., little input is required from the user to steer the search procedure. The reader is referred to the extensive literature on differential evolution for more detail (e.g., (Gaemperle et al., 2002)). Setting the adequate input parameters for the DE is highly problem dependent. In our case, the algorithm must deal with many variables, and therefore significant computation time is required. For instance, we consider 13 PV cell producing countries and 14 potential consumers, i.e., module producers, in the case study. The algorithm needs to solve a 182-dimensional problem for cell trade (13 × 14 trade flows). We tune the DE parameters to achieve an acceptable convergence time while trying to cover a search space as large as possible.

Fig. 2**A** summarizes our DE solving framework for constructing the friendshoring scenario.

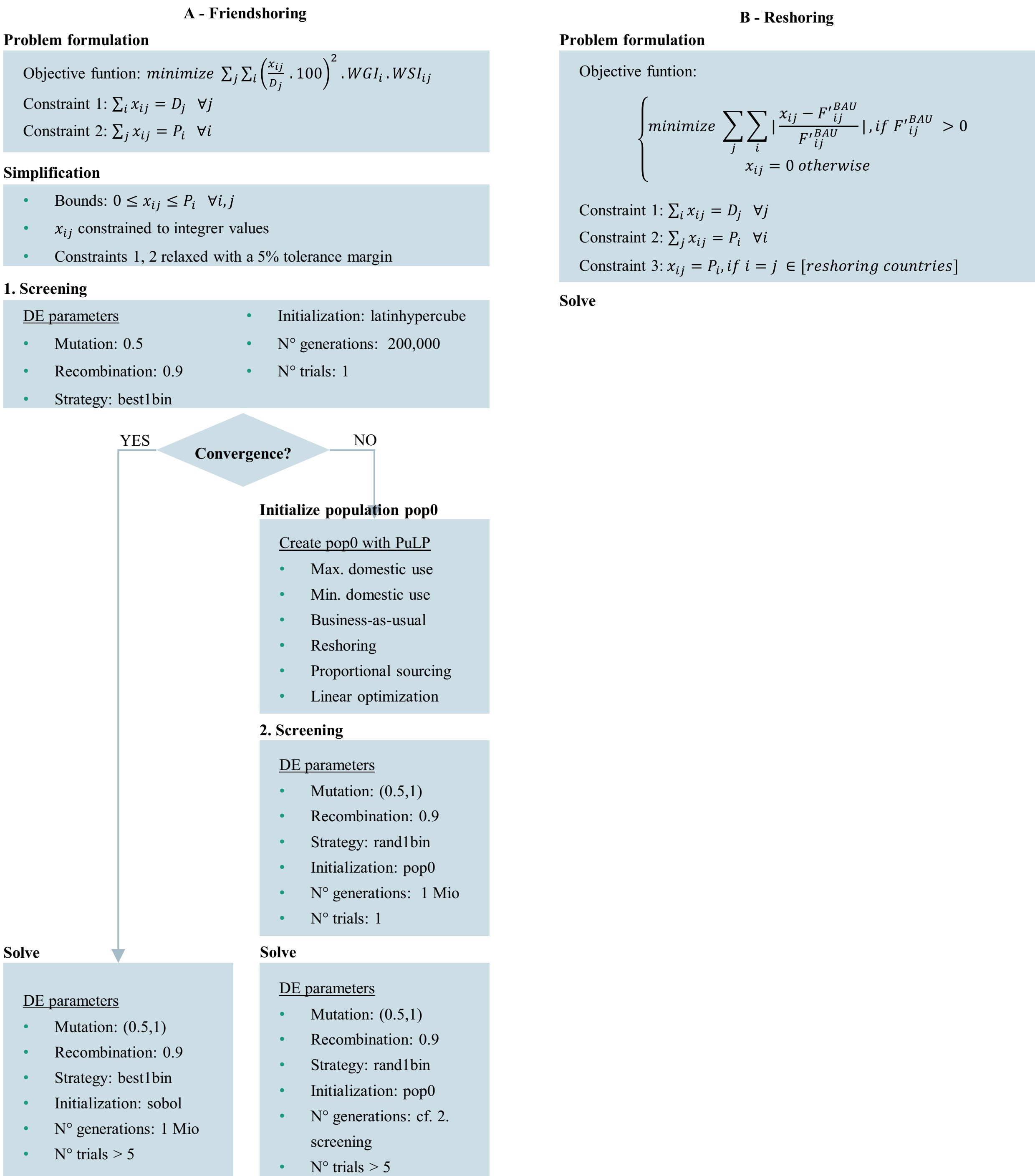

Fig. 2. Solving frameworks used to construct the trade flows in the friendshoring (A) and reshoring (B) scenarios. For a given product, the variable x_{ij} is the flow from producer country i to consumer country j to be determined. F_{ij}^{BAU} is the flow from i to j in the BaU scenario (including non-zero dummy values for reshoring flows), D_j is the total demand of j, and P_i is the total production of i.
(A) The friendshoring scenario is based on a (non-linear) differential evolution algorithm (DE). If DE does not converge with standard parameters (1st screening), an initial population of solution guesses is built to reduce computation time. These guesses are found with the PuLP library in different locations: trade flows maximizing or minimizing domestic use, close to the BaU or reshoring scenario, close to a proportional trade distribution, or minimizing the objective function in a linear setting. Generations are stopped when asymptotic behavior is observed (2nd screening). Solving is repeated (N° trials) to increase statistical confidence in the optimum found. Nevertheless, there is no guarantee that the solution found is the global optimum and not a local optimum.
(B) The reshoring scenario is based on linear programming with PuLP, which allows a simplified modelling process.

For the PV case study

Production data

The friendshoring scenario assumes that the EU, US, and India will ramp up domestic manufacturing from poly-Si to module by 2030. The net-zero domestic production target set by the EU Net-Zero Industry Act is taken as a minimum (European Commission, 2023b). By 2030, domestic manufacturing capacity should represent at least 40 % of the EU, India, US PV deployment needs. Regional PV annual demand in 2030 is estimated from (Bogdanov et al., 2021; Personal communication, 2023). Manufacturers announcements on cell and module capacity expansion in the US, and module expansion in India already exceed this 40% threshold, and the latest available projections are used (JMK Research and IEEFA, 2023; SEIA, 2023). Remaining global PV demand is covered by the same producers as in the BaU scenario.

It should be noted that the friendshoring and reshoring scenarios are not designed to depict a radical reshuffling among the leaders of PV manufacturing. China is currently dominating the global PV industry with over 75% market shares from metallurgical-grade silicon to module production. The domestic manufacturing capacities assumed to be added in the EU, US, and India by 2030 are not in the same order of magnitude. Considering their current low to inexistant PV manufacturing capacities, and the typical lead times to set up poly-Si plants of over 2 years (IEA, 2022a), their primary objective is, on a short-term, to be able to locally fulfill part of their own PV demand of 100 to 200 GWp/a.

Trade flows

It can be expected that quartz and SiMe trade flows are mostly determined by geographical proximity to poly-Si producers, as is currently the case. The DE solving framework to find risk-optimized trade flows is therefore only applied from poly-Si to module. The optimization process is constrained by the fact that the demand of each consumer should be met (Constraint 1), and that the shipments from each producer should total to its production (Constraint 2).

2.4. Reshoring scenario

The reshoring scenario assumes supply chains to be shaped by "inward looking" policies. Countries not only ramp up their domestic production capacity, but also rely on vertical integration. Vertical integration indicates that the produced goods are meant to remain on the same industrial site for further processing or for local markets, instead of being shipped to and from external suppliers. Fig. 2**B** summarizes the solving framework for constructing the reshoring scenario.

For the PV case study

Production data

As in the friendshoring scenario, the EU, US, and India are assumed to ramp up domestic manufacturing from poly-Si to module by 2030 to cover at least 40 % of their respective PV deployment needs. Regional PV annual demand in 2030 is estimated from (Bogdanov et al., 2021; Personal communication, 2023). Manufacturers announcements on cell and module capacity expansion in the US, and module expansion in India already exceed this 40 % threshold, and the latest available projections are used (JMK Research and IEEFA, 2023; SEIA, 2023). Remaining global PV demand is covered by the same producers as in the BaU scenario.

Trade flows

Trade flows from poly-Si to module are constructed by linear optimization with the PuLP library. The model imposes the production of poly-Si, wafer, cell, module in the EU, US, and India to be used domestically (Constraint 3) and fulfills the rest of the world demand in alignment with current trade relations. Vertical integration is currently standard in the PV industry.

2.5. Supply disruption propagation model and damage function

We use a simplified cascade failure model (Lee et al., 2011; Wang et al., 2018) to simulate the propagation of a disruption of magnitude α in the supply chain from upstream to downstream. Three types of supply disruptions are defined. Their propagation mechanisms are explained hereafter.

Supply shortage: A given country produces insufficiently of a product. The shortage occurs unintentionally, because of an event such as a plant fire, climate disaster, or energy consumption capping.

(1) In the initial stage, all countries (or nodes) are in a normal state. In each process layer, nodes have a production output and are linked to the next process layer via flows (or edges) of a certain weight.
(2) Suppose that country A is afflicted by a crisis, and reduces production by a fraction α. As a result, the weights of all edges from country A are decreased by α (Fig. 3**A**).
(3) Each node has a capacity to absorb a supply disruption, represented by a fraction β of its production volume. If the total decrement in the volume of imports of any countries connected to the country in crisis exceeds β, then these countries cannot produce at full demand. Hence, they become a source of supply disruption themselves.
(4) The disruption propagation proceeds down to the last process layer or until the disruption is fully absorbed and there are no more newly affected countries.

Export restriction: A given country implements an export restriction on a product.

The propagation mechanism in step (2) is hereby different. Country A reduces all exports by a fraction α, while leaving domestic flows in a normal state. Only the edges to B and C would be disrupted in Fig. 3**A**.

Bilateral trade conflict: A given country restricts exports of a product to a specific partner. This can stem from a conflictual geopolitical relationship.

The propagation mechanism in step (2) is hereby different. In case of an export restriction directed from country A to country C, only their edge would be disrupted in Fig. 3**A**.

The simulation is conducted for α from 10 % to 100 % with 10 % increments, and for all nodes and edges. The threshold β is set at 1 %. This means that countries are assumed to have inventories ready for use, equivalent to 1 % of their production. The propagation model could be further refined by defining country-specific β values depending on national stockpiles and utilizable production capacities on the short-term, should these data be available.

The relationship between the magnitude of a supply disruption α and the associated downstream shortage Δ can be described by a damage function, which we refer to as supply disruption damage function. It mimics damage functions from other research fields. For instance, damage functions are used to link global temperature changes to economic losses, or in the context of natural hazards risk assessments "to translate the magnitude of extreme events to a quantifiable damage" (Prahl et al., 2016).

Each supply disruption is characterized by its damage function, with its own slope and zero values. The magnitude of the supply disruption α is the reduction in production or export volume. The damage Δ is calculated as the relative difference between the end-product demand and the end-product supply. For the case study, the damage Δ is therefore quantified in % of PV deployment at risk, i.e., the share of the regional PV installation target potentially not achieved due to the supply disruption. An example is shown in Fig. 3**B**.

The damage function is not a realistic forecasting tool, as evidenced by its linearity. Nevertheless, the impacts of supply disruptions can easily be compared based on the slope of their damage function: the steeper the function, the more severe the damage Δ. We introduce the metric "fragility ratio" which refers to the slope of the supply disruption damage function. It quantifies the potential downstream shortage resulting from a supply disruption, highlighting indirect dependencies along the supply chain.

In practice, for a given supply disruption, the damage Δ is calculated for a range of disruption magnitudes α. The resulting data points (α, Δ) build the damage function. A linear regression is then performed on the non-zero values and the obtained slope is the fragility ratio. This enables one to estimate the value of the damage Δ from that of the disruption magnitude α. For example, a fragility ratio of 40 % means that 40 % of the initial supply disruption magnitude is translated into a downstream

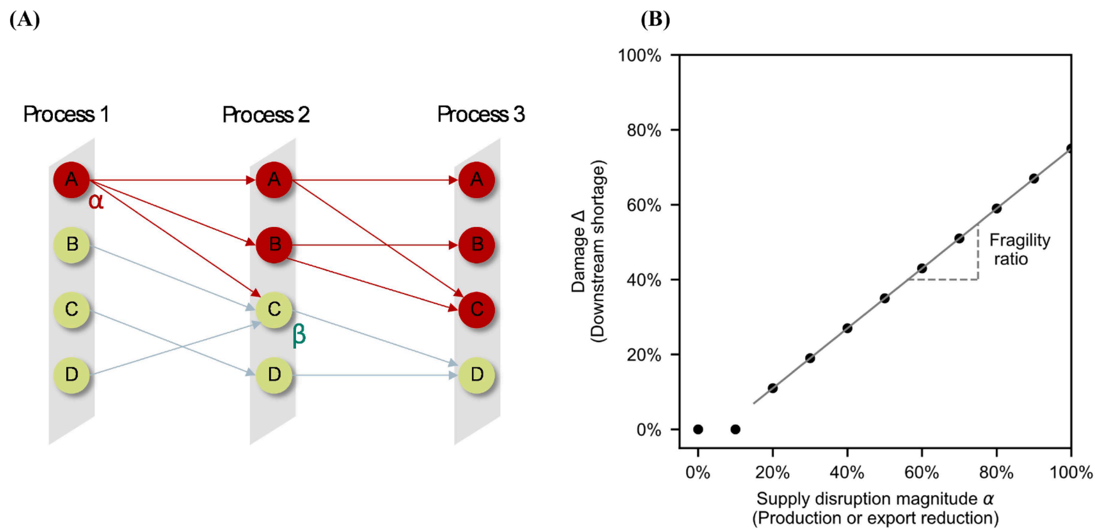

Fig. 3. (A) Schematic representation of a supply disruption propagation from upstream to downstream. Bubbles represent countries, either in normal state (green) or disrupted state (red). Red arrows indicate a decrease in material flow.
(B) Generic supply disruption damage function. The fragility ratio refers to the slope of the damage function. The zeros values indicate that the supply disruption is absorbed along the supply chain (β) and only propagates when of higher intensity.

shortage (or that 60 % of the initial supply disruption magnitude is absorbed through the network). A fragility ratio of 100 % means that a supply disruption is transmitted downstream without any barrier, while a fragility ratio of 0 % means that a supply disruption has no downstream effect.

3. PV case study results

In this section, the key differences between the PV reshoring and friendshoring scenarios are highlighted and results from the simulation of supply disruptions are presented.

3.1. Impact of friendshoring on supply chains

The risk mitigation potential of reshoring is set by design: domestic production in the EU, US, and India to cover their own demand will directly shield them from external supply disruptions but increase exposure to internal supply disruptions. An interesting output of our analysis is rather the comparison with the friendshoring scenario: how could PV supply chains look like if supplier selection was guided by a set of supply risk criteria (supply concentration, shared values, trade ties, interstate conflicts, governance) instead of focusing on self-reliance?

Supply chain differences between reshoring and friendshoring can be visualized in the Annex. The main findings are summarized hereafter:

- Through friendshoring, the EU and India become wafer suppliers for Asia ex-China. Instead of using their wafers domestically (reshoring), they divert around half of their production to Malaysia, Rep. of Korea, Thailand, Viet Nam, and Taiwan, thus replacing former Chinese supply in these countries.
- Japan, India, and Others (unspecified countries aggregated) diversify module imports away from China. The EU and US contribute almost 30 % of their module production to installation in Others. Japan's new suppliers include Thailand and Taiwan, while India increases its sourcing from Viet Nam.
- Viet Nam and the Rep. of Korea are the main beneficiaries of friendshoring for cell trade. They reduce their dependency on Chinese cells and their exports to the US market, to cover their own demand and establish trade with Malaysia, also a former cell supplier to the US. The cell deficit in the US is covered by China and the EU.
- Poly-Si supply in friendshoring turns out to be similar to the reshoring scenario: countries with both poly-Si and wafer capacities retain over 85 % of their poly-Si production. This means that the domestic use of poly-Si is the less risky solution.

Overall, through friendshoring, the EU, US, and India become a supply diversification opportunity for other countries. In particular, Asian producers display the lowest risk ($WSI * WGI$) when sourcing from the EU, compared to China, India, and the US. The EU, US, and India mainly cover their requirements deficit with Chinese supply. While this might seem counterintuitive, the rationale behind it is that, on a global level, the disruption potential *DP* is minimized when the EU, US, and India accept a certain degree of dependency on China.

3.2. Exposure to export restrictions

Fig. 4 shows the maximum fragility ratio in each supply chain scenarios, i.e., the export restriction enforced by a single supplier country with the worst impact for the EU, US, India, and the Rest-of-World (RoW) PV markets. The main finding is that there is no "one-size-fits-all" strategy for diversification. No supply chain scenario provides lower fragility ratios than the others for all process steps and countries.

Friendshoring performs better than reshoring for the US, India, and RoW. No export restriction would impact more than 20 % and 40 % of the US and Indian PV goals. The worst module export restriction for the RoW features a 62 % fragility ratio, instead of 75 % in the reshoring scenario. Still, diversification is a risk transfer mechanism. By becoming a global supplier through friendshoring, the EU must compromise on its own risk exposure. A wafer, cell, or module export restriction causes therefore more damage for the EU in the friendshoring scenario than in the reshoring scenario.

Fig. 5 provides a more disaggregated view of the exposure of the EU, China, US, India, and RoW to export restrictions. This visualization type highlights both the presence and absence of supply risks along the supply chain.

Export restrictions from China cause the highest damage in all scenarios considered. At the same time, China is largely immune to any export restriction.

In the business-as-usual scenario, two market profiles can be recognized. The EU and India are highly dependent on the end-product. Meaning that a module export ban from China would be fatal. Export

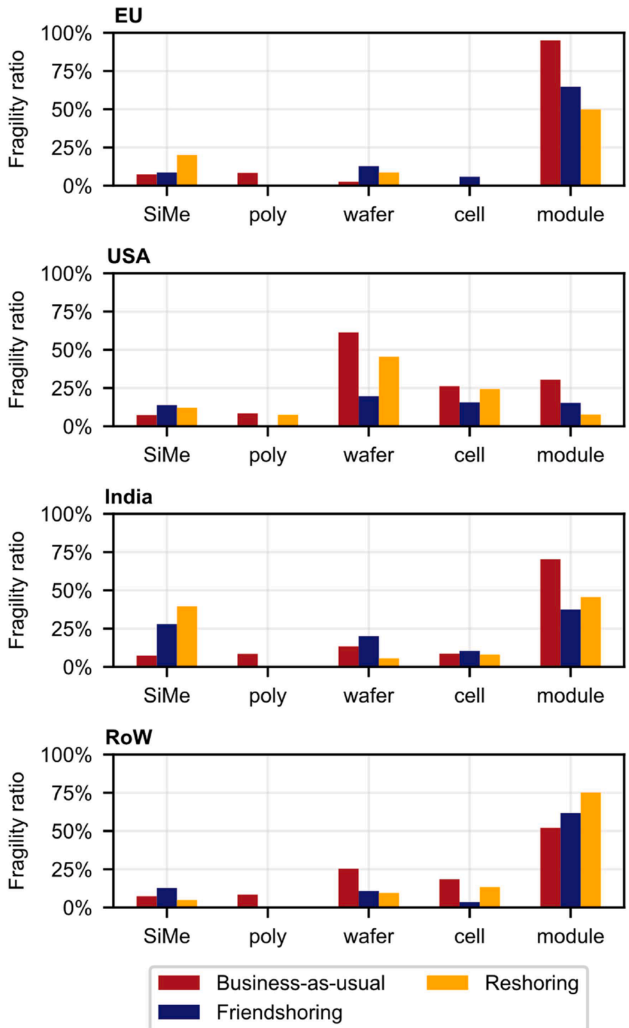

Fig. 4. Most disruptive export restriction by process step, for each supply chain scenario and key PV market, expressed as fragility ratio. For example, the export restriction with the worst impact for US PV deployment is at the wafer stage for all supply chain scenarios.

restrictions on the upstream stages have little impact (fragility ratio < 15 %), which can be explained by a high degree of vertical integration in China. On the contrary, the US already have a diversified module supply and appear overall less exposed to high-impact disruptions than the EU and India. Still, the US show a significant weakness at the wafer stage: without Chinese wafers (α = 100 %), Thailand, Rep. of Korea, Malaysia, Viet Nam, and Cambodia would have a wafer shortage for cell production of respectively 99 %, 99 %, 93 %, 75 % and 42 %. Through a mix of domestic processing in these countries and exports, this would affect over 60 % of US PV deployment down the line.

The EU, US, and Indian PV supply chains are further shown to be largely independent from one another. No export restriction from one of these markets would directly or indirectly impact the others. This is not surprising considering their current low production capacities. German poly-Si is the exception: an export restriction could propagate and have a global impact, however only if the restriction is of high intensity (α ≥ 50 %). Anything less would be absorbed along the supply chain.

The friendshoring scenario leads to more interdependencies between the PV markets. This is reflected by the impact of export restrictions from the EU and India on the US and RoW markets. The impact would however be minimal with fragility ratios of 3–11 %. The friendshoring scenario benefits most markets, but at the expense of the EU which remains highly dependent on China at the module stage. The model favors such a dependency because the trade relations between China and the EU are less likely to deteriorate compared to other partners: the Willingness to Supply Index *WSI* from China to the EU is estimated at 0.26 compared to 0.51 for both China-US (worse in Shared Values *SV*) and China-India (worse in Trade Ties *TT*).

The reshoring scenario shows higher fragility ratios at upstream process stages than the other scenarios. This is because reshoring would increase quartz and SiMe demand in the EU, US, and India for domestic poly-Si production, thus diverting risk exposure from China to mostly regional actors. These risks are rather modest for the EU and US. Germany, sole poly-Si producer in EU, sources SiMe mainly from Norway (50 %), France (23 %), Brazil (11 %), Germany (5 %), and China (5 %). Norway and France produce SiMe from Norwegian, French, and Spanish quartz (see Fig. 1**B**). A quartz or SiMe export restriction from any of these countries impacts up to 20 % of EU PV goals. A quartz or SiMe export restriction from Canada, or Brazil also leads to fragility ratios lower than 15 % in the US reshoring scenario.

Diversification can however introduce more consequent supply risks. For instance, if India started poly-Si production, as assumed in the reshoring and friendshoring scenarios, while relying on the status-quo for SiMe sourcing: a Chinese export restriction on SiMe could impact Indian PV deployment with a 28 % (friendshoring) to 39 % (reshoring) fragility ratio. Indeed, India currently sources 94 % of its SiMe demand (for non-PV applications) from China. Relying on such a concentrated supply poses a risk for the hypothetic Indian poly-Si production, and all its downstream customers. A diversification with local SiMe producers such as Australia and Malaysia should be investigated.

Finally, the supply disruption propagation model uncovers the boomerang effect of some export restrictions. Meaning that these restrictions could end up hurting the countries imposing them. This can be seen by the impact of upstream Chinese export restrictions on the Chinese PV market (5–7 % fragility ratio depending on the scenario). This phenomenon is explained by the highly interconnected nature of supply chains. For instance, in the BaU scenario, an export ban on SiMe from China means that Malaysia does not fulfill 94 % of its SiMe demand for poly-Si production. But China sources around 5 % of its poly-Si demand from Malaysia, thus being also somewhat impacted. Although in this case the damage would not be significant, this calls for careful examination of the countries' interlinkages in more complex supply chains to avoid unintended disruption propagation effects. Similarly (but not covered by our analysis), a wafer export restriction from China could harm the Chinese-owned PV companies manufacturing in South-East Asia, if they are subjected to it.

3.3. Exposure to supply shortages and bilateral trade conflicts

Results from the simulation of supply shortages and bilateral trade conflicts highlight similar trends as for export restrictions. They are presented in the Annex for conciseness. The main findings can be summarized as follows.

Global PV deployment is indissociable from a robust Chinese industrial landscape. A production shortage in China – be it caused by factory shutdown, natural disaster, or accident – for quartz, SiMe, poly-Si, or wafer, impacts all PV markets in the BaU scenario, with a close to 100 % fragility ratio. Reshoring in the EU, US, and India means transferring a part of the shortage risk locally. Notably, US module manufacturing capacity announcements represent over 90 % of US PV demand in 2030. If this capacity is only dedicated to domestic installation, US PV deployment would be largely exposed to local supply

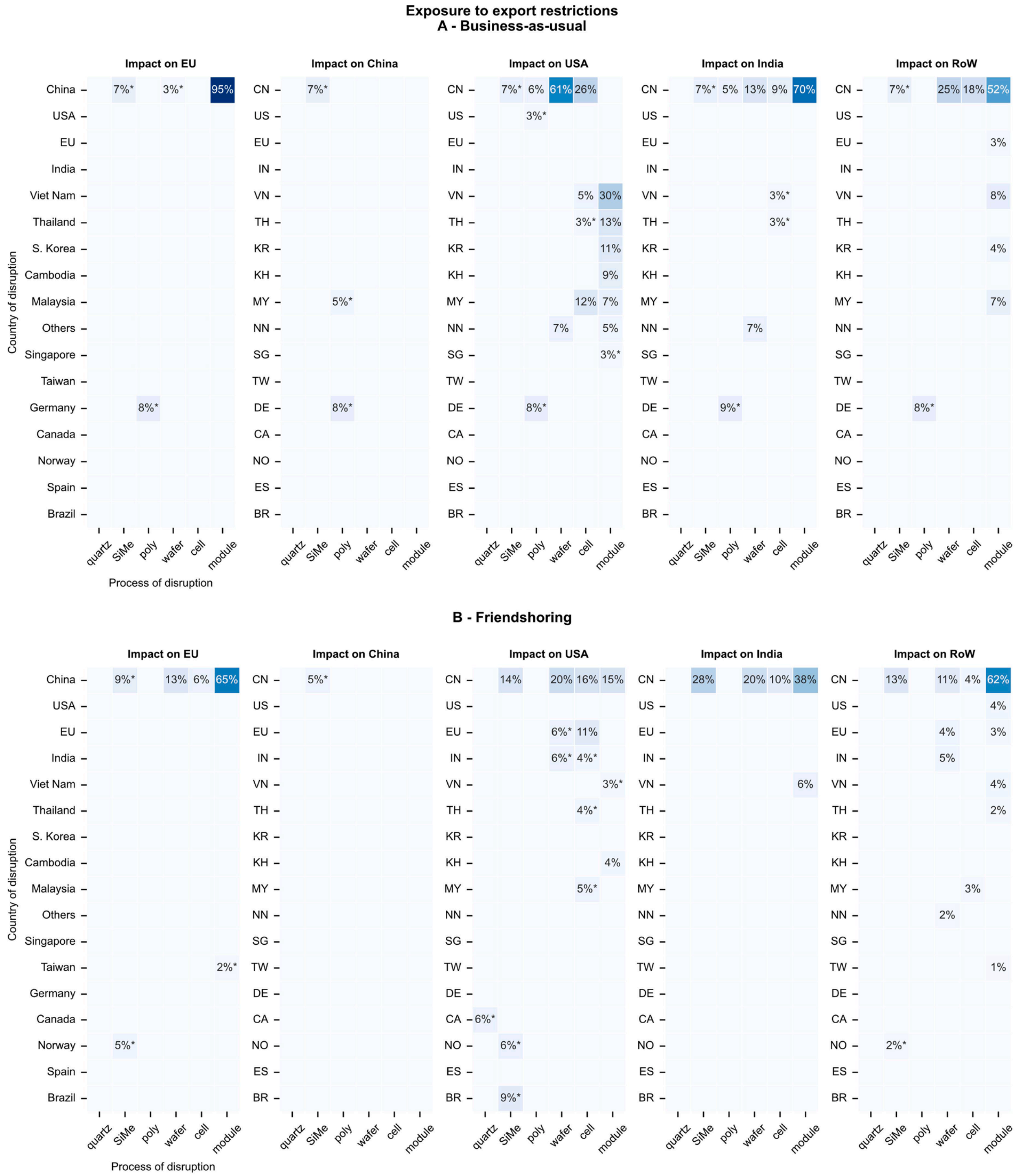

Fig. 5. PV deployment exposure to export restrictions, in (A) the BaU, (B) the friendshoring, and (C) the reshoring scenario. The percentage is the fragility ratio. For example, a wafer export ban ($\alpha = 100$ %) from China would expose 61 % of the US PV deployment goals to failure in business-as-usual. Values with an asterisk indicate that the disruption only propagates when of high intensity ($\alpha > 30$ %) and is otherwise absorbed through national stocks. RoW: Rest-of-World.

crises.

The simulation of bilateral trade conflicts can be of interest for national decision-makers to pinpoint weak links. For instance, trade from China to Viet Nam is found to be of strategic relevance for US PV. A cell trade disruption between these two countries would indirectly impact the US with a 19 % fragility ratio in the BaU scenario. Such key relations should be closely monitored.

4. Discussion

4.1. Proxy indicators

The construction of indicators implies for researchers to first define what they wish to measure before setting out a methodology to measure it. Despite its growing policy relevance, the definition of “friends” in friendshoring is however largely left to interpretation. This paper

Fig. 5. (*continued*).

therefore considers friendshoring as a supplier selection driven by market concentration, ability to supply, and willingness to supply. Our hypothesis that i) the World Governance Indicators are an acceptable proxy for the ability to supply, and that ii) the proposed Shared Values indicator reliably accounts for a country's willingness to supply, can (and should) certainly be debated.

The *WGI* are often integrated in supply risk assessments with the reasoning that poor country governance (e.g., political instability) increases the likelihood of supply disruptions. They have made their way into national mineral strategies (European Commission, 2023a), thus justifying their use in this paper: our results show how country linkages would look like if policymakers further used the *WGI* as a criteria for supplier selection.

While the *WGI* have the merit to exist and be easy to use for risk screening, we argue that alternative indicators are needed for deeper supply chain analyses. The *WGI* lack practical utility because they provide limited guidance on which countries are actual candidates for supply diversification. Also, the assumption that poor governance is a barrier to supply does not hold for all steps in the supply chain. For instance, silver mining has increasingly concentrated in low governance countries over the past 30 years (Gervais et al., 2023). Mines run illegally or by militia are a known issue for cobalt and gold. This is different for highly specialized processes: acquiring the competencies for, e.g., operating a PV wafer factory, requires foreign investments which will probably take the host country's governance into more careful consideration.

Overall, generic recommendations for diversifying supply away from poor governance countries are of little help for industries. More desirable indicators would be those accounting for a country's technical and economic ability to supply. Optimally, they should be technology and process specific. Multidimensional metrics such as the Policy Potential Index aim at addressing this issue for mining but approaches for the rest of the supply chain are missing. For instance, building and maintaining a PV supply chain requires for a country to have certain predispositions such as: proximity to high purity quartz for SiMe production, low electricity prices for poly-Si and ingot production, low costs for water/wastewater treatment for the cell plant, access to skilled operators and technicians, access to production equipment and to special chemicals and gases, acceptable lead times for setting up plants. The existence of similar industries could also be indicative of a country's ability to supply. Using site specific indicators would make supply chain assessments more time-intensive but also more useful.

One novelty of the paper is the calculation of Shared Values based on the United Nations General Assembly voting data. The use of the UN votes to measure states preferences is supported by a substantial body of literature, e.g., related to the probability of a militarized interstate dispute, the voting cohesion of the EU, or the positive impact of trade ties on foreign policy alignment (Bailey et al., 2017). The UNGA voting data cannot be seen as a simple proxy for shared democratic values: strategic voting, and even vote buying, also play a role. For instance, the Trump administration proposed to cut foreign assistance to countries who vote against the US position at the UN. Fig. 6 shows the voting behavior of selected countries in the UNGA.

The ideal points estimates applied by Bailey et al. on UN votes are able to identify critical junctures of post–World War II history, such as the Cold War followed by reconciliation efforts in the 80 s (see the ideal point gap between the US and the USSR/Russia on Fig. 6), the North-South polarization, and the often-isolated position of the US on foreign policy issues. They can also pick up on policy shifts, such as a lower voting alignment between the US and the NATO under Trump administration than under Obama presidency (Mosler and Potrafke, 2020). The UNGA voting data provide a nuanced and time-dependent picture of states positioning (whether it reflects what they truly prefer or how they want to be perceived by others) and, in our opinion, a legitimate approach to identify "like-minded" countries. The UNGA voting data can be used either to construct extreme scenarios, such as the fragmentation of the world in trading blocs based on the votes on a specific resolution (e.g., Aggression against Ukraine), or to reflect a non-binary definition of "friends" as we did. The Shared Values indicator could be refined by only considering the UNGA votes related to specific topics like human rights. This implies however a not straightforward prioritization of vote topics.

Whether the Willingness to Supply Index remains a research exercise or will support practical decisions will depend on policymakers' intent behind friendshoring. If their goal is to exclude specific pre-determined suppliers, it is doubtful that a method for evaluating the closeness of

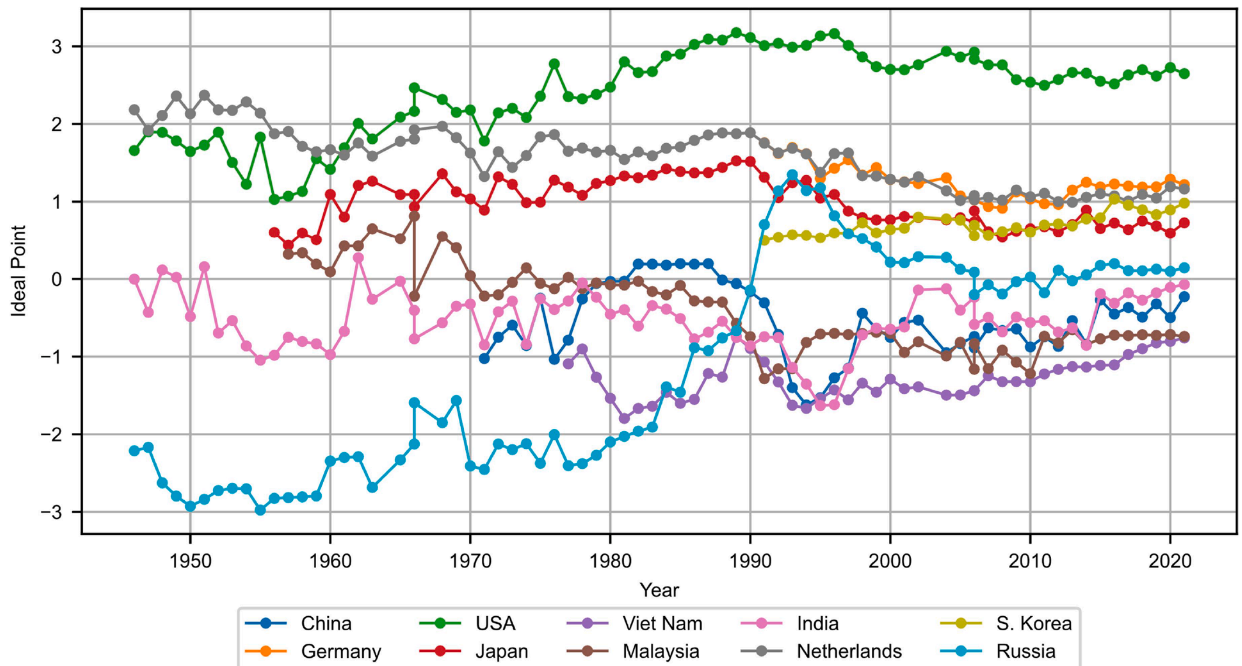

Fig. 6. UN voting behavior of selected countries from 1946 to 2021, measured as ideal points estimates (Voeten et al., 2009). In political science, ideal points estimation consists in the ordinal spatial mapping of states voting behavior on a single dimension (analog to other spatial models used to describe political preferences, e.g., left/right wing).

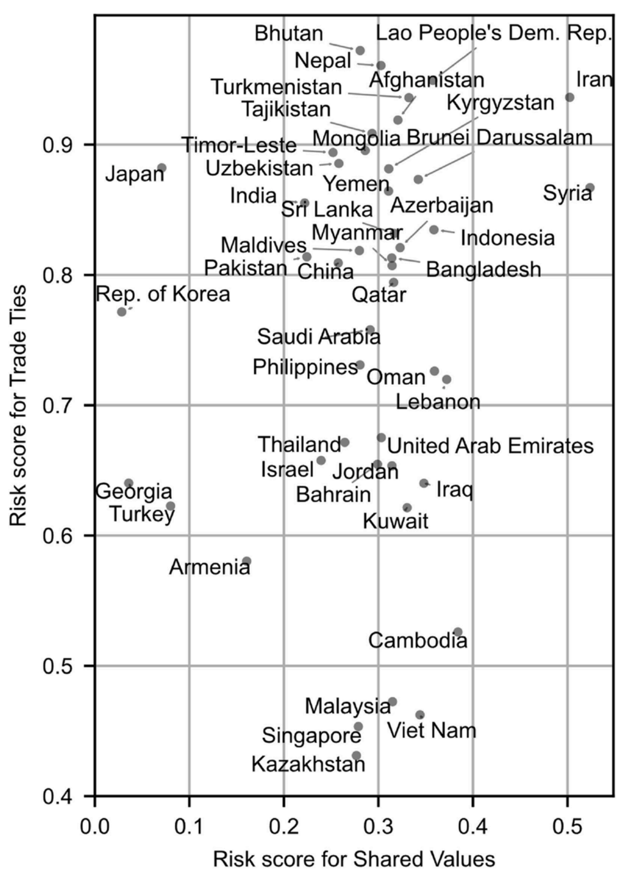

Fig. 7. Comparison of Asian suppliers for the Netherlands. Trade Ties and Shared Values are evaluated on a scale of 0 to 1, with higher values corresponding to higher risks.

countries will be useful.

Overall, further work on friendshoring modelling is required. Nonetheless, it seems that Trade Ties and Shared Values can provide some guidance for trade partnerships. As exemplified for the Netherlands (Fig. 7), different supplier profiles stand out. In particular, Kazakhstan, Singapore, Malaysia, and Viet Nam appear as interesting partners: their trade with the Netherlands represent a non-negligible part of their GDP, and they don't frontally oppose geopolitically. These countries also provide plenty of collaboration opportunities for high-tech industries and energy technologies. For instance, Malaysia has the largest processing capacity for rare earths outside China. Viet Nam and the Netherlands have further recently agreed to strengthen cooperation for the exploration and exploitation of critical minerals.

4.2. Challenges to diversification

Most supply risk assessment papers call for diversification as a mitigation strategy. Nevertheless, analyses comparing the benefits and constraints of diversification are required to provide nuanced and realistic recommendations. After all, supply diversification can be difficult, time-consuming, and costly.

For PV, there is global recognition that China is ahead in terms of cost competitiveness, operational excellence, and technological know-how for most PV and PV equipment production. Non-Chinese cell and module equipment production, and new technologies like perovskite tandems are however still competitive. The gap between China and the rest of the world is the most critical at the ingot/wafer stage. The export restrictions on wafer production equipment currently considered by China would make reshoring particularly difficult for other countries. In the EU, expertise related to semiconductor production is available and could be transferred to an extent to PV wafer manufacturing. Closing the technological gap with China in this way and keeping competitiveness over time would however take some years and financial support. Alternatively, know-how gaps could be closed by contracting key experts or supporting Chinese investments in the form of equities/shares acquisitions/mergers. Although at the cost of independence. In any case, supply diversification should not cause deployment delays. Once installed, PV modules are a reliable source of electricity, immune to external supply disruptions contrary to fossil fuels. Even though circularity will not de-risk supply over the next decades, extended PV module lifetimes should be targeted, as well as recycling or wafer recovery, depending on which parts of the supply chain are available locally.

Diversification can have different forms (e.g., reshoring, friendshoring, external investment) and objectives (e.g., small manufacturing capacities for domestic use in case of a crisis, or large capacities of the newest technologies for global competitiveness). Navigating the different pathways to diversification remains a largely unexplored research area. Assessing the gap with frontrunners is central to transparently discuss how realistic a diversification is. Most probably, not every critical supply chain can or should be diversified. Investments for local production are time-sensitive, as inaction might further increase the knowledge gap with frontrunners, and bear a risk, as there is no guarantee for technological or economic competitiveness. This is particularly true for highly specialized process steps. For some critical supply chains, it might make more sense to concentrate financial resources on building strategic advantage for innovative product segments (e.g., next generation technology, automation) rather than trying to catch up with difficult to reproduce standard techs.

Beyond the technological and economic challenges, the institutional constraints to diversification should also be addressed. Trade mechanisms intended to protect some industries can generate harmful effects on others. For instance, EU import duties on Chinese solar glass drives up costs for local PV module manufacturers, thus adding to their competitiveness handicap. In general, countries appear more inclined to financially support some industrial sectors than others. For those industries which tend to be left behind, reshoring is especially difficult. Finally, a resilience strategy in the EU can only be successful if there is a strong coordination between member states to implement supply disruptions response mechanisms for key technologies. The first months of the pandemic showed how crises can trigger inward-looking policies. Governments competed with one another to procure personal protective equipment and national borders closed. Nation-first reflexes in the EU will however fail at securing access to critical raw materials and building industry capacities on par with the US, China, or India.

5. Conclusion

We have characterized the impact of supply diversification on the risk exposure of major PV markets. Takeaways from the case study are as follows.

EU: A module export ban from China is fatal to PV deployment in a business-as-usual configuration. The EU is not exposed to export restrictions on PV components but strongly impacted by involuntary supply shortages at any stage in China (> 80 % fragility ratio). This is explained by the high degree of vertical integration in China. Under reshoring, the supply of quartz and SiMe does not call for concern: at worst, a supply disruption from Norway would impact up to 20 % of EU PV deployment. Under friendshoring, the EU becomes a wafer, cell, module exporter to the US and Asia ex-China.

US: Our dataset indicates that US cell and module sourcing are already diversified. However, a wafer export ban from China would impair cell and module production in Thailand, Rep. of Korea, Malaysia, Viet Nam, Cambodia, and, down the line, put 60 % of US PV deployment at risk. US PV is not significantly exposed to foreign bilateral conflicts: at worst, a trade disruption from China to Viet Nam would impact up to 20 % of US PV deployment. Similarly, the supply of quartz and SiMe under reshoring does not call for concern: supply disruptions in Canada, Brazil, or the US, would impact up to 20 % of US PV deployment. Under friendshoring, the US increases module supply from the EU and China, and becomes largely averse to export restrictions, more so than under reshoring.

China: PV deployment is largely immune to external supply disruptions in all scenarios considered. Interestingly, results from the friendshoring modelling for China mimics the outcomes of the business-as-usual scenario: the global disruption potential *DP* is minimal when China keeps relying on domestic production to cover its own demand while exporting its surplus production to other countries. This means that domestic reliance is indeed a low-risk approach for this country, but also that there is no apparent downside to global friendshoring for China. As with any concentrated market, domestic reliance calls for safeguards against local crises, such as production redundancies, and stocks.

India: A module export ban from China seriously impedes Indian PV deployment (70 % fragility ratio) in a business-as-usual configuration. Under friendshoring, India becomes a wafer supplier for Asia ex-China, and procures more modules from Viet Nam to reduce Chinese dependency. As a result, Indian PV exposure to export restrictions would be reduced (< 40 % fragility ratio), potentially even lower than under reshoring.

The rest of the world was not the focus of our model. Still, it appears that an “each country for itself” strategy in the EU, US, and India might increase supply chain risks for other countries.

As with any risk analysis, the results are not meant to have high predictive accuracy. The way companies can recover from supply disruptions was out of the scope of this paper. The model could be refined, for instance, by integrating economic data and finding trade-offs between reshoring/friendshoring costs and supply risk. It could also be used to improve national stockpiling strategies (optimization of β).

Showing the impacts of supply disruptions is another way to highlight dependencies. Although the case study confirms PV supply risks previously identified in the literature, the novel network model approach also uncovers interesting findings:

- Export restrictions can have a boomerang effect due to the highly interconnected nature of supply chains, i.e., in the end hurting the restricting country further downstream. For instance, if China bans SiMe exports, Malaysia gets insufficient SiMe input for poly-Si production. As China currently covers a minimal share of its poly-Si demand from Malaysia, the SiMe export ban could therefore backfire – although in this case to a marginal extent.
- Diversification spreads risk exposure but can also generate new risks. For instance, if India starts producing poly-Si instead of importing vertically produced modules, its PV deployment would become exposed to SiMe export restrictions from China. To solve this conundrum, India could accompany reshoring by SiMe supply diversification.
- The EU could become an important PV supplier through friendshoring to reduce the risk exposure of other countries and represents a low-risk sourcing option for Asia.

From a methodological perspective, the fragility ratio has been introduced as a metric for supply risk exposure. The fragility ratio quantifies the potential downstream shortage resulting from a supply disruption, highlighting indirect dependencies along the supply chain. It can complement typical measures of market concentrations which do not account for suppliers' interlinkages. The use of the UN voting data to identify “like-minded” countries and simulate friendshoring provides first encouraging results and should further be examined. However, this metric for friendshoring is only useful if policymakers intend friendshoring as a supplier ranking strategy, and not a way to exclude specific countries a priori. The proposed methodology also contributes to the ongoing research efforts to construct supply chain scenarios: our model illustrates how a differential evolution algorithm can be used to find optimal trade relations between countries based on non-pricing criteria such as supply concentration. Finally, our results encourage more detailed studies on diversification. Most likely, not every critical supply chain can be diversified. Supply chain specific analyses of the costs and benefits of diversification are needed. Further methodological development is also needed to account for a region's ability to supply a product in terms of e.g., electricity prices, infrastructure, and labor skills.

CRediT authorship contribution statement

Estelle Gervais: Writing – original draft, Methodology, Investigation, Conceptualization. **Benjamin Sprecher:** Writing – review & editing, Methodology, Conceptualization. **Sebastian Nold:** Writing – review & editing, Supervision, Conceptualization. **Peter Brailovsky:** Writing – review & editing, Conceptualization. **René Kleijn:** Writing – review & editing, Supervision, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.resconrec.2024.107948.

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