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Technological sovereignty and strategic dependencies: The case of the photovoltaic supply chain

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ABSTRACT

This study investigates the international Photovoltaic Supply Chain (PVSC) from the perspective of the recent literature on Strategic Dependencies and Technological Sovereignty. In so doing, the paper fills existing literature gaps by providing: i) a fine-grained long-term analysis of the PVSC, considering all its segments and integrating production and technology dimensions; ii) detailed evidence of the changing hierarchical relationships within the supply chain; iii) an analysis of the drivers of strategic dependencies in the PVSC in different economic areas. Focusing on China, the EU, Japan, South Korea, and the US over the 2007–2021 period, the empirical evidence highlights the existence of strong strategic dependencies in the EU, especially in the mid and downstream segments of the PVSC. A similar, and in some cases even worse, situation is found in the US, although some diversification of the portfolio of suppliers, especially in the downstream, has been emerging in more recent years. These results have relevant implications in terms of policy theory with specific reference to EU and US initiatives in the field of industrial policies for sustainable transition.

1. Introduction

In the current context of progressive Global Value Chain (GVC) disruptions, the transition to renewables becomes an ever more pressing goal despite the constraints brought about by the asymmetric distribution of Critical Raw Materials (CRMs), manufacturing capacity and technology (IEA, 2021, 2023). Contextually, with global conflicts increasingly being played out over the control of CRMs, technologies and strategic assets, the scientific literature on "Technological Sovereignty" (TS) and "Strategic Dependence" (SD) is gaining momentum with the aim of supporting industrial policy actions to strengthen economies in strategic sectors (Crespi et al., 2021; Edler et al., 2023). At the policy level, the debate moved from extolling the benefits of globalization to rediscovering concepts with a 'Listian' flavour (Crespi and Guarascio, 2019) such as TS and SD, whose "operalisation" implies the assessment of economies' relative autonomy (dependency) vis-à-vis key partners, considering, jointly, technology, CRMs, capital, and intermediate and final goods (EC, 2021; 2022; Arjona et al., 2023).

In this framework, the case of the PV industry is of particular relevance. Accelerating the shift to renewables, in addition to making the economy environmentally sustainable (Costantini et al., 2017), can help weaken one of the key levers of 'weaponized interdependence' (Drezner et al., 2021): fossil fuels. In this respect, solar energy plays a fundamental role. According to the EU Green Deal's upgraded climate objectives (55% emission reductions by 2030), the PV industry is expected to provide a massive contribution to the achievement of de-carbonization targets, with the installation of a new capacity between 325 and 375 GW_{DC} by 2030, depending on the scenario considered. This would require a 3- to 5-fold growth of the European PV market with respect to its 2019 size (Jäger-Waldau et al., 2020).

Overall, the PV industry represents a textbook example of global hierarchical reshuffling, marked by the rise of China and the parallel weakening of the US and the EU. In the late 1990s, European companies managed to catch up with the leaders of the time, i.e. the US and Japan,

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gaining a prominent position in the PVSC. However, China's market entry quickly changed the picture: between 2007 and 2017, the EU's global share fell from 30% to 3% and a large number of EU-based solar companies went bankrupt or were taken over (Buigues and Cohen, 2023).[1] At the same time, Chinese manufacturers massively expanded their production capacity, at the expense of all other producers (IEA, 2022b).

Excess supply and falling prices were not the only explanation for China's success, though. Huang et al. (2016) have shown how EU subsidies, with the aim to enlarge European PV installed capacity, translated into a sharp increase of imported PV cells from China. Moreover, China's industrial policy, based on a mix of public investments, R&D and financial support to PV producers, represents another important piece of the explanation (Zhang and He, 2013; Costantini et al., 2018). Process innovations matter too: for instance, in 2018, the wide introduction of the diamond wire saw enabled a significant reduction of silicon consumption in the ingot-cutting process, positively affecting the efficiency of solar panel production.

The change in competitive positions is not limited to the final stage of the PV production process (downstream segment of the supply chain). Relying on government support, Chinese companies have successfully experimented with vertical integration strategies, particularly toward the upstream segment, which have proven to be effective in strengthening their technological capabilities (Zhang and Gallagher, 2016). Concerning the technological catching-up, the PV manufacturing geography changed significantly in less than twenty years (Binz et al., 2017). Once undisputed leaders (the US, Japan and Germany) are now being pursued and, in some cases, are even caught up by 'latecomers' such as China, South Korea and Taiwan thanks to the combination of industrial policies, FDIs and technological spillovers (Yuan et al., 2022). Such a hierarchical reshuffling has been eased by the exploitation of substantial economies of scale and incremental innovations that resulted in the reduction of production costs all along the supply chain. For example, the average price of PV modules dropped by 80% between 2010 and 2020 (IEA, 2022a). As a consequence, most of the literature on this topic focused on price competitiveness and its implications (Hajdukovic, 2020; Garlet et al., 2020), while less attention has been devoted to long-term structural dynamics such as changing hierarchies, countries' positioning in terms of technological and productive capabilities, access to CRMs,[2] as well as heterogeneities in industrial and innovation policies.

Against this background, the present work intends to fill these literature gaps by analysing the evolution of the PVSC through the perspective of the new analytic categories of TS (Crespi et al., 2021; Edler et al., 2023) and SDs (Gehringer, 2023) and, relatedly, economies' prospects concerning extent and pace of the energy transition. In so doing, we develop an empirical approach that allows for the application of concepts such as 'strategic dependency' to concrete industry/SC cases (i.e. the PVSC), paving the way for further analyses on other key industries. In particular, building on Edler et al. (2023), we carry out a 'strategic intelligence' analysis which allows us to identify the key product/technology domains wherein industrial and innovation policy actions are greatly needed in order to reduce SDs.

The main contributions to the extant literature can be summarized as follows. Firstly, we provide a fine-grained long-term analysis of the PVSC, considering all its segments and integrating production and technology dimensions; secondly, detailed evidence of the changing hierarchical relationships within the supply chain is offered; iii) finally, we develop an analysis of path dependent dynamics and drivers of strategic dependencies in the PVSC in different economic areas. Focusing on China, the EU, Japan, South Korea, and the US over the 2007–2021 period, the empirical evidence highlights the existence of strong strategic dependencies in the EU, especially in the mid and downstream segments of the PVSC. A similar, and in some cases even worse, situation applies in the US, although some diversification of the portfolio of suppliers, especially in the downstream, is emerging in more recent years.

The remainder of the article is organized as follows. Section 2 briefly illustrates the background analytical framework, while Section 3 describes the data and the methodology and maps the PV industry. The empirical evidence is presented in Section 4. Finally, Section 5 concludes the article by discussing the main implications in terms of industrial and innovation policy.

2. Background analytical framework

Empirical contributions focusing on the PVSC have grown substantially in recent years, reflecting the driving role that this industry plays in the energy transition. However, the scientific effort in this subject has been basically aimed at relevant, yet fairly specific, issues related to the dynamics of the PVSC. Specifically, scholars focused on prices and market shares (Buigues and Cohen, 2023; Yang et al., 2023), the role of subsidies in promoting growth and reshaping the global PV market (Huang et al., 2016), process and product innovations (Zhang et al., 2013), distribution and access to CRMs (Rabe et al., 2017). Nonetheless, no contribution has so far provided a fine-grained long-term analysis of the PVSC, considering all its segments and integrating the productive and technological dimensions. Likewise, little evidence has been provided about the changing hierarchical relationships within the SCs or about the determinants of economies' relative positionings concerning CRMs, products and technologies. To fill these gaps, our analysis provides an original overview of the PVSC analysed from the perspectives of strategical dependency and technological capabilities. The study builds upon a rich theoretical framework whose starting point are the concepts of TS (Crespi et al., 2021) and SDs (Edler et al., 2023). Accordingly, in contexts where the ability to (quantitatively and qualitatively) satisfy demand and, even more so, pursue structural change and achieve 'grand missions' (e.g., de-carbonization) is constrained by the asymmetric distribution of key resources (i.e. CRMs, technologies, productive capabilities, competences), a certain degree of productive-technological autonomy becomes the essential precondition for growth and development (Mazzucato, 2018). Concerning the green transition and, particularly, the role of solar energy, this means identifying elements of strength (and weak spots) that may help (hamper) economies in achieving their industrial/energy policy goals while reducing (increasing) the risk that the same transition proves economically and socially unsustainable. Second, since building productive and technological capabilities is a long and costly process involving the accumulation of idiosyncratic knowledge and competences (Antonelli et al., 2013), heterogeneous competitive performance and path-dependencies are in order. As a result, economies' positioning along SC segments need to be investigated in order to understand under what circumstances mobility (e.g., moving from a state of high to one of low SD or from a situation of poor to one of strong technological specialization) is most likely or, on the other hand, it is plausible that economies maintain their strong (weak) position (Guarascio and Tamagni, 2019). Third, the role

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[1] Q-Cells, Solon, Conergy, Solarion, SMA Solar, Sunways, Solarwatt, and SolarWorld. As a result, most of the solar companies still present in the European market are subcontractors that buy their panels in Asia. They are therefore against further anti-dumping measures for Chinese manufacturers (Buigues and Cohen, 2023).

[2] For most PV-related CRMs, mining capacity is asymmetrically distributed and the environmental costs of extraction make the opening of new mining fields problematic, particularly where environmental standards are stringent, as in the EU. However, Rabe et al. (2017) argues that SDs could be less intense if compared, for example, to the case of lithium batteries SC (IEA, 2021; Naumanen et al., 2019). Focusing on tellurium, gallium and indium - which are widely used in the production of thin film solar cells, i.e. CdTe (cadmium telluride) and CIGS (copper indium gallium selenide) cells – Rabe et al. (2017) provides a rather optimistic prediction as diversification seems to be relatively manageable and a moderate demand growth of thin film solar cells is expected.

of technological capabilities as a driver of competitiveness is a well-established stylized fact (Fagerberg, 1996), as economies characterized by stronger capabilities are likely to show better performance, thus facing a lower risk of SDs (Dosi et al., 2015; Crespi et al., 2021). In the PVSC case, economies characterized by a relatively larger solar-related knowledge stock are less likely to be constrained by SDs. If anything, this is because these economies are more likely to have the skills and technological assets needed to create/strengthen production capacity in critical segments/product domains. Fourth, long-term patterns of technological specialization are another key predictor of countries' relative positioning along SCs, since strong specialization may reflect the economy's strategic orientation towards specific technological domains (and related policy objectives), as well as being a further proxy of solid technological capabilities (Archibugi and Pianta, 1992, 1994). As a consequence, we may expect that economies characterized by significant specialization in solar technologies tend to face relatively lower SDs and/or are able to reduce the same dependence in segments where it has previously increased.

The steps of our empirical analysis are closely related to the theoretical framework just outlined and allow us to address the research questions underlying each building block. The analytical steps characterizing our approach are reported in more detail in Fig. 1 and can be summarized as follows.

First, building on an in-depth literature review, we carry out a granular mapping of the PVSC, tracing all its relevant segments (up, mid and downstream). Second, we provide a novel SD indicator based on detailed product-level trade data, offering fresh evidence of changing hierarchies, SDs and the positioning of key players across each product segment. Third, product codes are merged with International Patent Classes (IPC) to assess the role of knowledge and technology in shaping hierarchies and SDs. Finally, path-dependencies are analysed using Transition Probability Matrices, while a Dynamic Ordered Probit model is estimated to test if and to what extent the accumulation of technological capabilities and specialization patterns may shape the degree of SD at the country-segment-product level. This evidence is then discussed in the light of the industrial policy initiatives aimed at strengthening productive and technological capabilities in the PV industry.

3. Mapping the PV supply chain: data and methodology

To analyse the evolution of the PVSC, two unique data sources are merged: trade data, stemming from the UN Comtrade database, and information on patents from the OECD Patent database. The identification of patent IPC codes corresponding to Comtrade product identifiers is based on previous literature (Binz et al., 2017; Shubbak, 2019; Kalthaus, 2019) and carried out by distinguishing different segments of the PVSC. The unit of analysis is the triad country-segment-product/patent IPC code, while the evolution of the SC is investigated over the period 2007–2021 focusing on five economies (China, the EU, South Korea, Japan and the US), which represent 70–80% of the global market.[3]

3.1. Mapping the PV value chain

3.1.1. The trade dimension

Previous literature has mostly focused on specific components of the PVSC, e.g., wafers, cells and inverters (Garlet et al., 2020). However, its significant degree of fragmentation and internationalization requires a more granular mapping, as complementarities and competitive advantages can be fully exploited only by including "remote" corners of the chain. Our mapping focuses on the wafer-based crystalline silicon (cSi) PV technology. The latter accounts for over 95% of module production, while cadmium telluride (CdTe) thin-film PV technology makes up the remaining part (IEA, 2022b).

We rely on the 6-digit product-level *Harmonised System* (HS) classification, allowing us to assess trade dynamics regarding feedstocks, machineries and components. From a strictly methodological viewpoint, two elements are worth underlining. First, the selected set of HS codes went through a 'cleaning' process following Korniyenko et al. (2017), which means dropping the few product codes[4] for which information is available only at the beginning of the period considered or associated exclusively with countries having a negligible role in global trade. Second, there are specific limitations related to Comtrade data. In particular, product descriptions may be too broad to exclusively include solar PV products. Therefore, results need to be interpreted with some caution (Gahrens et al., 2021). Furthermore, there is no information on re-exporting practices, which may however be relevant to understanding the deep functioning of the SC. Concerning this issue, further research advancing the approach herein proposed would be desirable.

A large set of contributions has been considered to validate our mapping strategy (Algieri et al., 2011; Rabe et al., 2017; Latunussa et al., 2016; Carrara et al., 2020; Hajdukovic, 2020; Gahrens et al., 2021; Wang et al., 2021). The starting point is the code referring to *Solar Cells and Modules* (854,140). In line with Gahrens et al. (2021), to the latter we add the codes referring to machineries. In addition, we include HS codes related to electric generators and inverters.[5] Furthermore, we follow Wang et al. (2021), adding *High-purity Silicon* (280,461) and *Wafers* (381,800), which are both crucial components of the upstream chain (IEA, 2022a).

Finally, we complete the mapping by including HS codes related to feedstock (Latunussa et al., 2016)[6]: *Low-purity Silicon* (280,469), *Hydrochloric acid* (280,610), *Back sheet* (392,062), *Solar glass* (700,719), *Silver paste* (710,692) and *Aluminium paste* (760,310), *Organic surface agents* (340,219) and *Aluminium structure* (761,090). Overall, we end up with 20 HS codes allowing us to cover the whole PVSC.

3.1.2. The technological dimension

Once the trade dimension is traced, we rely on patent data to identify the corresponding technologies. We consider the IP5[7] patent families, focusing on the period 2007–2019 and relying on three-year moving averages.[8] Adopting an approach similar to the one followed in this paper, Kalthaus (2019) uses various combinations of keywords to associate 4-digit IPC codes with the different stages of the PVSC, distinguishing between components and 'technological generations' (1G, 2G and 3G). In the same vein, Shubbak (2019) assigned IPC classes to six different components, i.e. panels, solar cells, electronics, energy storage, portable powered devices, and testing and monitoring technology. Finally, relying on a broader definition of the SC (Zhang and Gallagher, 2016), Binz et al. (2017) associate IPC codes with the same segments considered in our analysis: up, mid and downstream.

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[3] Note that the analysis on PV-related patents is limited to 2019 due to the lack of observations.

[4] H0, H1 and H2.

[5] These additional nine HS codes refer to *Machines for the manufacture of Wafers* (848,610), *Machines for the manufacture of Semiconductors* (848,620), *Parts of Machines* (848,690), *Parts of Cells and Modules* (854,190), *DC Generators with output less than 750W* (850,131), *DC Generators with output equal or more than 750W* (850,132), *AC Generators* (850,161), *Inverters* (850,440) and *Part of Inverters* (850,490).

[6] The weight considered within our PVSC amounts to almost 94% of the total weight and includes all the most relevant products and raw materials.

[7] Patents are counted based on the fractional criteria which is applied for both inventor(s)'country of residence and IPC codes. Specifically, if one application has more than one inventor (IPC code), the application is divided equally among all of them and subsequently among their country of residence (IPC codes), thus avoiding double counting. We employ 4-digit codes which is the most granular level of analysis possible given the availability of data.

[8] Note that data on 2020 and 2021 have been omitted due to the lack of observations.

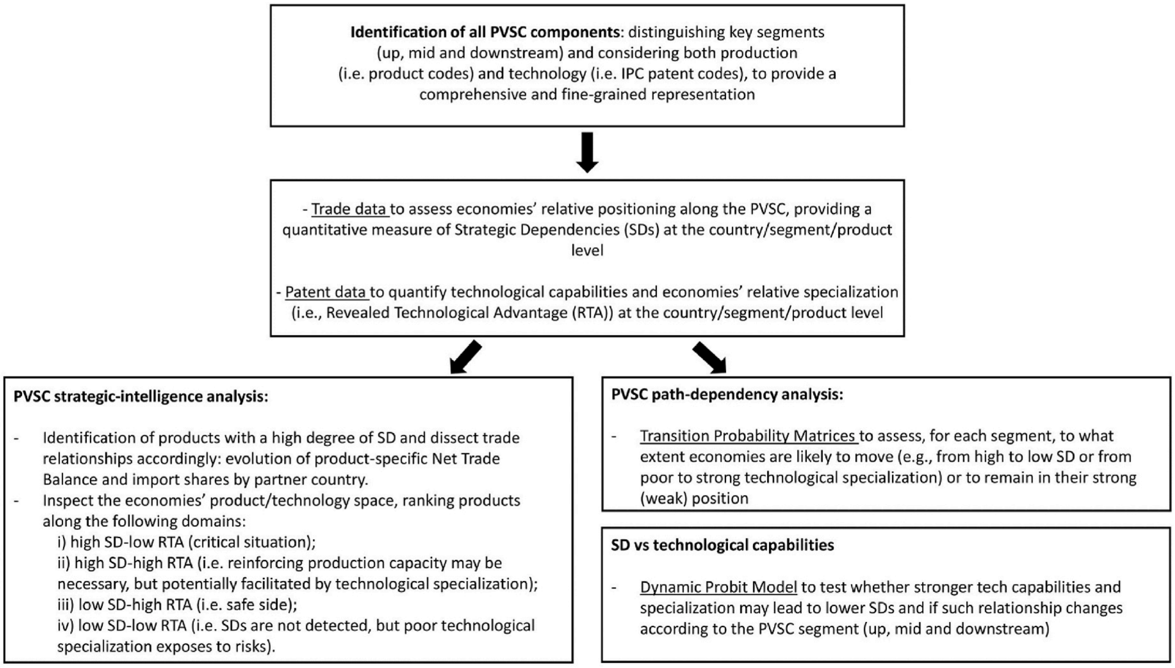

Fig. 1. TS and SDs along the PVSC: analytical steps.

Given the data at hand, our mapping combines Binz et al. (2017) and Shubbak (2019)'s identification strategies, providing the final, comprehensive list of 4-digit codes. The codes matching the keywords used by Kalthaus (2019) are further validated by checking their correspondence with the ones identified by Shubbak (2019). The resulting selection comprehends 9 IPC subclasses including 214,458 IP5 patents filled during the period 2007–2019. About 87% of these applications originate from China, the EU, South Korea, Japan and the US, lending further support to our country selection. The mapping is completed by including 2 additional codes by means of a textual analysis. More specifically, for the HS codes lacking a corresponding IPC class, we relied on relevant keywords to associate the appropriate code.[9] The final outcome is presented in Table 1, resulting in the combination of 20 6-digit HS with 11 4-digit IPC codes.

The main limitation of this part of the PVSC mapping concerns the level of detail of patent information. Going beyond 4-digit patents would have allowed for a more fine-grained analysis of the technologies underlying materials and components, as well as a more precise matching of the productive and technological sides. Providing greater detail on solar-related patents and establishing a methodology to capture all the individual technologies included in the PVSC should be a key task of future research on this subject.

3.2. Measuring strategic dependencies and technological capabilities along the PV supply chain

In this work, we measure SDs building on Gehringer (2023). We define import dependency - IDEP – as the combination of three dimensions. First, for each country *i* (China, the EU, Japan, South Korea, and the US), segment *v* (up, mid and downstream), product *k* (k ∈ HS 6-digit {1, …,20}) and year *t* (2007–2021)[10], we compute the Net Balance (NB) as:

$$NB_{i,v,k,t} = \frac{IMP_{i,v,k,t} - EXP_{i,v,k,t}}{IMP_{i,v,k,t} + EXP_{i,v,k,t}} \tag{1}$$

This first component (1) is standardized to vary between 0 and 1, providing information on the surplus/deficit of the considered countries, taking into account their size. The second component aims at capturing the import share stemming from the main supplier $j (j \neq i)$ (IMP-MS):

$$IMP - MS_{i,v,k,t} = \frac{IMP^{j}_{i,v,k,t}}{IMP_{i,v,k,t}} \tag{2}$$

This component (2) provides information on how relevant, in terms of import share, the main supplier *j* of country *i* is for each segment/product of the SC. The third component refers to the 'market power' of the main supplier *j*, capturing its global market share regarding the specific product *k*. Formally, the indicator reads as follows:

$$EXPSH_{j,v,k,t} = \frac{EXP_{j,v,k,t}}{TOT\ EXP_{v,k,t}} \tag{3}$$

The three components are combined to obtain an indicator providing a proxy of SD at the segment and product level. To avoid misrepresenting countries' relative positioning by giving too much weight to the second and third component, we rely on the following formula:

$$IDEP_{i,v,k,t} = NB_{i,v,k,t} * \frac{\left(IMP - MS_{i,v,k,t} + EXPSH_{j,v,k,t}\right)}{2} \tag{4}$$

To measure countries' technological positioning, we consider two main indicators. First, the patent share over total patents by country *i* (China, Japan, South Korea, the US and the EU), segment *v* (up, mid and downstream), IPC class *w* (w ∈ IPC 6-digit {1, …,11}) and year *t* (2007–2019). Second, the Revealed Technology Advantage (RTA)

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[9] Regarding *Silver paste* (710,692), for example, we used the keyword combination including 'silver paste', 'metallization' and 'silver solar', identifying the IPC class C03C as Correspondence. The same procedure was followed for *Aluminium structures,* which has been associated with the IPC class H02S referring to 'structural details of PV modules other than those related to light conversion'.

[10] Note that the analysis on PV-related patents is limited to 2019 due to the lack of observations.

Table 1
The PV supply chain: mapping production and technology.

HS Code	Commodity description	GSC stage	IPC code	IPC notes
280,461	*Silicon, containing by weight not < 99.99% of silicon*	UP	C23C	*CVD (chemical-vapor-deposition) method*
280,469	*Silicon, containing by weight < 99.99% of silicon*	UP	C01B	*Silicon; Compounds thereof*
280,610	*Hydrogen chloride (hydrochloric acid)*	UP	C30B	*Production of homogeneous polycrystalline material with defined structure*
848,610	*Machines & apparatus for the manufacture of boules/wafers*	UP	B28D	*Working stone or stone-like materials by sawing*
848,620	*Machines & apparatus for the manufacture of semiconductor devices/ of electronic integrated circuits*	UP	H01L	*Processes or apparatus specially adapted for the manufacture or treatment of these devices or of parts thereof*
848,690	*Parts & accessories of machines & apparatus within HS codes 848,610 & 848,620*	UP	G01R	*Arrangements for testing electric properties*
381,800	*Chemical elements doped for use in electronics, in the form of discs/wafers/ similar forms …*	UP	H01L	*Manufacture or treatment of semiconductor devices or of parts thereof*
340,219	*Organic surface-active agents …*	MID	H01L	*Special surface textures*
392,062	*Plates, sheets, film, foil & strip, of polyethylene (terephthalate) …*	MID	H01L	*Protective back sheets*
700,719	*Toughened (tempered) safety glass, n.e.s. in 70.07*	MID	H01L	*Double glass encapsulation*
710,692	*Silver (incl. silver plated with gold/platinum), in semi-manufactured forms*	MID	C03C	*Glass frit mixtures having non-frit additions, containing free metals*
760,310	*Powders of non-lamellar structure, of aluminium*	MID	H01B	*Conductive material dispersed in non-conductive organic material, comprising metals or alloys*
761,090	*Aluminium Structures & parts of structures …*	MID	H02S	*Structural details of PV modules other than those related to light conversion, Frame structures*
854,140	*Photosensitive semiconductor devices, incl. photovoltaic cells whether/not assembled in modules*	MID	H01L	*PV modules or arrays of single PV cells*
854,190	*Parts of the devices of 85.41*	MID	H01L	*Electrodes*
850,131	*DC generators (excl. generating sets), of an output not > 750W*	DOWN	H02S	*Electrical components, comprising DC/AC inverter means associated with the PV module itself*
850,132	*DC generators (excl. generating sets), of an output > 750W but not > 75kW*	DOWN	H02S	*Electrical components, comprising DC/AC inverter means associated with the PV module itself*
850,161	*AC generators (alternators), of an output not > 75kVA*	DOWN	H02S	*Electrical components, comprising DC/AC inverter means associated with the PV module itself*
850,440	*Static converters*	DOWN	H02M	*Details of apparatus for conversion*
850,490	*Parts of the machines of 85.04*	DOWN	H02J	*Arrangements for parallelly feeding a single network by two or more generators, converters or transformers*

Source: authors' elaboration

indicator, allowing us to capture the evolution of countries' technological specialization. The $RTA_{c,w,t}$ indicates whether country c is specialized in technology w in year t or not:

$$RTA_{c,w,t} = \frac{\frac{IP5_{c,w,t}}{\sum_{z=1}^{Z} IP5_{c,z,t}}}{\left(\frac{\sum_{z=1}^{Z} IP5_{ct}}{\sum_{z=1}^{Z}\sum_{c=1}^{5} IP5_{ct}}\right)} \tag{5}$$

where $IP5_{c,w,t}$ is the number of IP5 patent families of country c in technology w at year t; while Z is the total number of technological fields. Thus, it follows that $\mathrm{RTA}_{c,w,t} = 1$ represents a threshold of specialization: when $\mathrm{RTA}_{c,w,t} > 1$, the country is said to be specialized in technology w, while the opposite holds when $\mathrm{RTA}_{c,w,t} < 1$.

3.3. Assessing trade dependence along the PV supply chain

Our investigation starts with a snapshot of countries' competitive positioning (Figure A1, Appendix). Overall, the five economies included in our sample represent 70–80% of the global market. Some key patterns emerge: the "rise of China" (from a 15% in 2007 to an almost 25% export share in 2021), the relative stability of the EU and South Korea, and the step taken back by the US (mild) and Japan (substantial). The PVSC is distinguished between up, mid and downstream (Fig. 2). China's performance is driven by its consolidation in the down and, even more so, midstream. In these segments, virtually all the other countries lose their positions, with the EU experiencing a dramatic worsening of its relative position in the downstream. A slightly different pattern characterizes the upstream. Despite moderately increasing its export share, China shows a less astonishing performance as compared to other segments. On the contrary, the EU reports an increase in export share, moving from 13% to 23%. This may reflect a 'complementarity' between the growth of China in the mid and downstream, and the consolidation of the EU as a supplier of key upstream goods.

We now explore the different components of the IDEP. Fig. 3 shows the evolution of the NB (1) between 2007 and 2021 (left axis), including bilateral import shares (right axis). The EU and the US display similar dynamics, mirroring the consolidation of China, particularly in the mid and downstream. Both worsen their position vis-à-vis China, although

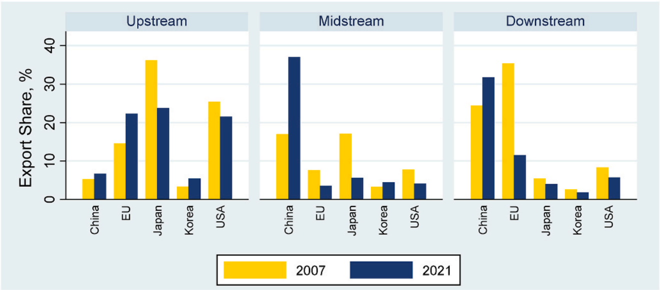

Fig. 2. PV supply chain by segment, export shares (2007 vs 2021).
Source: Authors' elaborations based on the UN Comtrade database

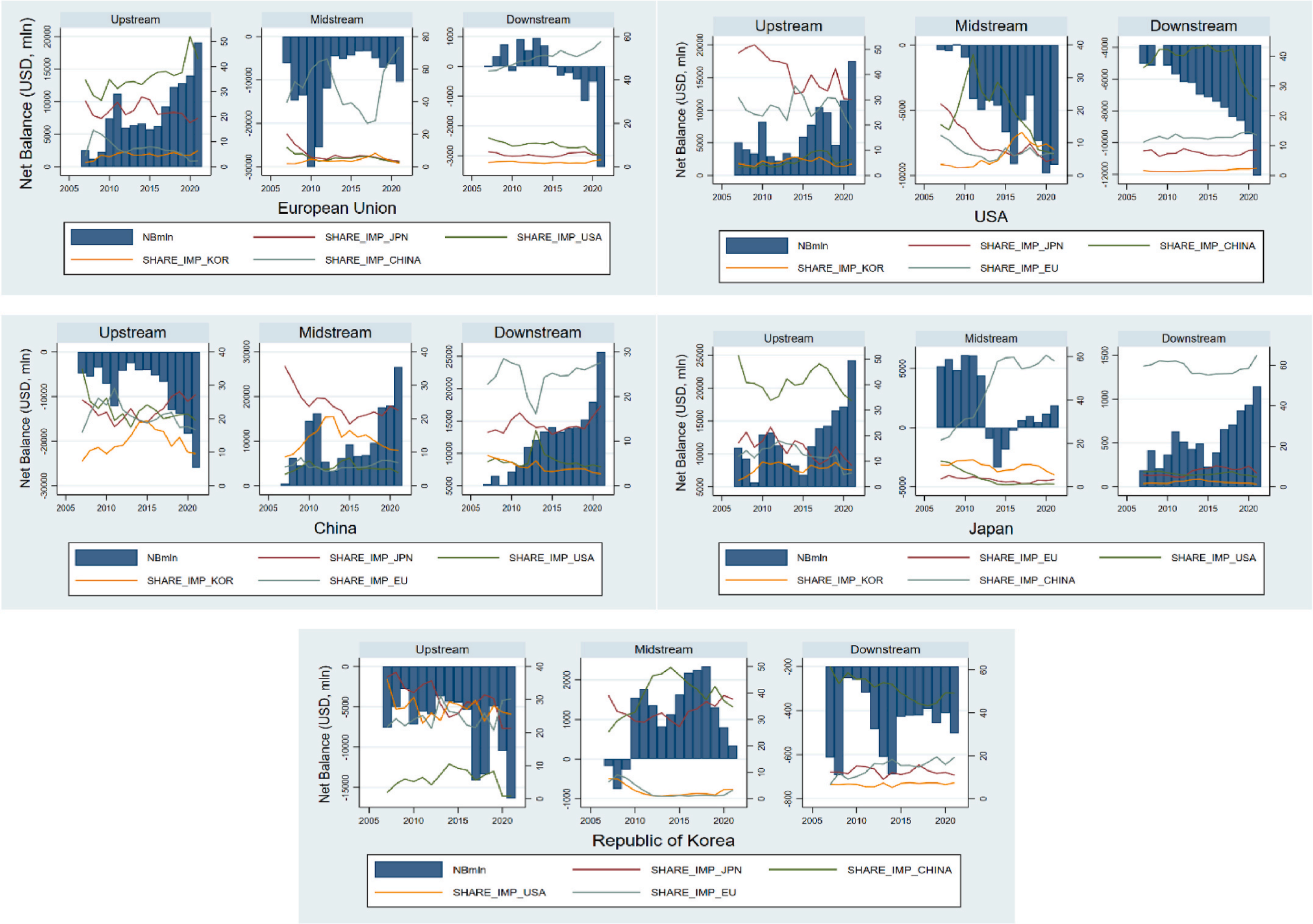

Fig. 3. Net balance and Import shares, by country and segment (2007–2021).
Source: Authors' elaborations based on the UN Comtrade database. Note: Net Balance is expressed in USD million.

some 'decoupling' is visible for the US. In the midstream, the EU trade deficit reaches record levels, with a peak of 30 billion euro per year, paired with Chinese supplies which came to exceed 60% of total imports. On the other hand, China shows a growing deficit in the upstream but, at the same time, a rather good degree of diversification. Japan stands out as the less dependent actor along the entire SC, while

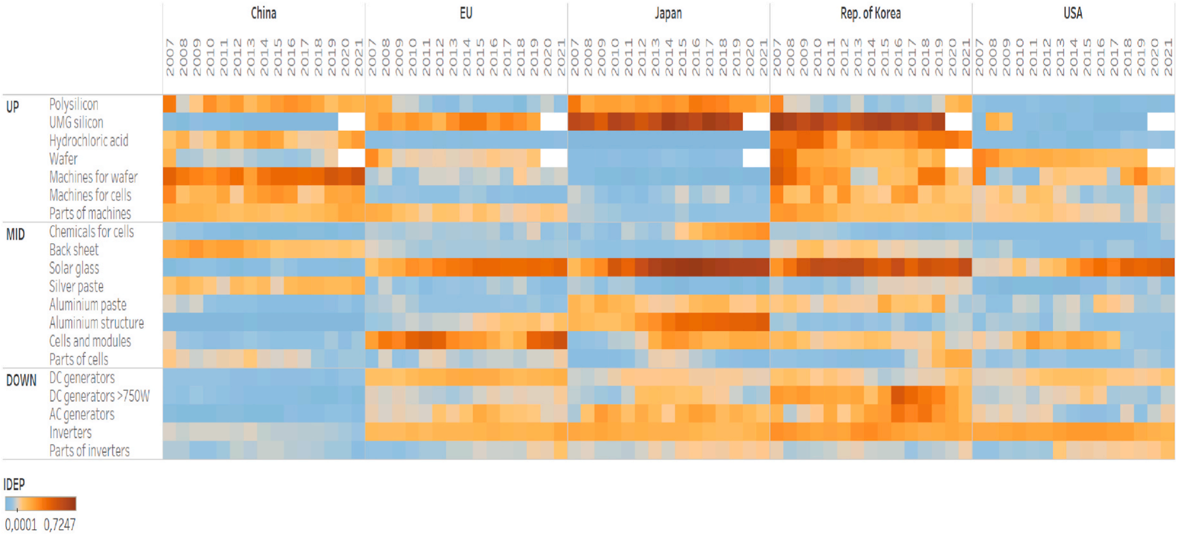

Fig. 4. IDEP by country, segment and product (2007–2021).
Source: Authors' elaborations based on Comtrade database. Note: the central value with respect to the colour distribution is identified in the median value of the IDEP. Note: data related to UMG silicon and wafer are not available for 2020–2021.

South Korea, which however shows a small amount of trade in comparative terms, is dependent in the up and downstream, displaying a surplus in the midstream.

Fig. 4 provides a heatmap that turns to dark red as SDs become more intense for each segment/product.[11] In the upstream, China displays a certain dependence concerning *Polysilicon*, *Hydrocloric acid* and, more relevantly, *Machineries*. This is mirrored by the good position of the EU, which seems to maintain a stronghold in the machineries market, Japan, which, however, turns out to be rather import depedendent on *Polysilicon* and *UMG silicon*, and the US. The latter seems fairly well positioned concerning *Polysilicon*, *UMG silicon* and *Hydrochloric acid* showing, in turn, a less rosy picture regarding *Wafers* and *Machineries*.

South Korea, probably due to its relatively smaller size, reports a significantly more intense SD all across the upstream. The situation changes in the midstream, though. China displays a strong position except for *Back sheet* and *Silver paste*. In turn, all countries but China report SDs regarding *Solar glass*. For the EU, the strongest SD regards *Cells and modules* (the most pivotal PV component). Japan's performance is rather similar to the EU's, although a certain degree of dependency emerges with respect to *Aluminium paste* and *Chemicals for cells*. Remarkably, the US seems to be reducing its SD, particularly regarding *Cells*, *Modules* and *Aluminium Paste*. Even in the midstream, South Korea displays a stronger SD with the only exception of *Aluminium structures* and *Part of cells*. As it stands, the downstream seems to be "China's reign". The latter shows an extremely low IDEP with respect to all critical products (e.g., *Inverters*). In turn, the EU, Japan and South Korea are strongly dependent with respect to both *Inverters* and *DC generators*. The US is also import dependent when it comes to *Inverters* but is relatively better positioned as regards the other products included in the downstream segment.

We now zoom-in on the products for which the stronger SDs are detected, also considering their relevance within the PVSC (Fig. 5). The analysis is performed following, as a first step, a simple data-driven criterion. For each country in the sample, we focus on those goods that fulfil one of the two conditions (Gehringer, 2023): i) a negative net balance of 2 billion (USD) or more, ii) the main supplier import share equal to or above 40%. For the US and the EU, the strongest SDs are concentrated in the mid and downstream: *Cells and modules* and *Inverters* (in addition to *Solar glass* and *DC generators* for the EU, *Solar glass* and *Wafers* for the US). Significant differences emerge regarding the degree of diversification, however. While China is by far the main supplier of the EU with respect to all products for which SDs are detected, the same is not true for the US. With the exception of *Solar glass*, the US managed to reduce its relative share of Chinese imports and significantly diversified its portfolio of suppliers.[12] China's situation is antipodal. SDs are concentrated in the upstream, concerning *Machineries for wafers* and *Semiconductors* (in addition to *Parts of cells*). Similar to the US, however, China shows quite a diversified portfolio of suppliers, with the exception of Japan, which holds a 50% share of the total Chinese imports of machineries for wafers. On the other hand, Japan shows a small deficit all across the products included in the list of its most critical SDs. Nonetheless, a certain dependence and a significant market power of a single supplier (i.e., China) can be observed with respect to *Solar glass* and *Aluminium structures*. Finally, South Korea's SDs are dispersed along the entire SC and are characterized by a very limited degree of supplier diversification.

This first set of evidence confirms the importance of analysing SDs distinguishing SC segments and focusing on critical products (Edler et al., 2023). By looking at the long-term evolution of the IDEP, we document the substantial hierarchical reshuffling characterizing the PVSC wherein the 'rise of China' is mirrored by growing SDs in the EU and the US. Segment-level heterogeneities matter, though. While facing concerning SDs in the mid and downstream, the EU and the US could attempt to reinforce their situation by building on the fairly good competitive position they hold in the upstream. Nonetheless, to understand the evolution of hierarchical relationships and SDs in the PVSC more precisely, it would be important to integrate information regarding the role of domestic production and demand, as well as information on PV corporations and the offshoring and re-exporting activities they conduct. These elements may in fact change the picture, further qualifying the structural evolution of the PVSC and the related positioning of key actors. Despite being currently limited by the lack of data, this kind of analysis is an important task for future research.

3.4. Persistence and mobility along the PV supply chain: Transition Probability Matrices

Transition Probability Matrices (TPM) help assess whether or not economies characterized by a high level of SD are able to break out of that condition. Persistence (mobility) is examined by focusing on the IDEP terciles proxying, respectively, low (1st tercile), medium (2nd tercile) and high SD (3d tercile). Events are modelled by a three-state Markov chain. Each term of the (3 × 3) TPM is the conditional probability p of moving from state (tercile) j to state i.[13] Based on the estimated probabilities, different situations are in order:

1. *Transient SD (economies are likely to reduce their relative SD)*: if the sum of the lead diagonal terms is less than 1, there is no evidence of persistence;
2. *Weak persistence (economies are likely to remain import dependent)*: if the sum of the main diagonal terms is more than 1 but some of these terms are lower than $1/n$ (in this case 0.3);
3. *Strong persistence (economies are highly likely to remain import dependent)*: if the sum of the main diagonal terms is more than 1 and all the main diagonal terms are larger than $1/n$ (in this case 0.3).

As expected, the IDEP indicator is characterized by a strong degree of persistence (Table 2). This confirms the hypothesis of a strong path-dependency of countries' structural positioning along SCs (Antonelli et al., 2013): as the strengthening of competitive positions is the result of costly, complex, and idiosyncratic processes, the exit from a condition of high SD is, unsurprisingly, a relatively rare phenomenon. In fact, the sum of the values on the main diagonal are always greater than 1 and all terms are larger than 0.3 (i.e. strong persistence). Mobility is relatively poor, as economies displaying a high (medium) degree of SD have a significantly low probability of improving their position: 10% and 1% probability to move from high to, respectively, medium and low SD; 13% probability to move from medium to low SD. Nevertheless, even concerning path-dependency analysis, the technological characteristics of the SC segments matter (Fagerberg, 1996). A relatively higher probability to move from higher to lower levels of SD is detected in the mid and downstream, while the opposite seems to emerge looking at the upstream.

The possibility of changing position seems to be more plausible in segments characterized by a relatively lower technological intensity (i.

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[11] Sensitivity analyses based on alternative formulations of the IDEP confirm the main results and are available upon request.

[12] It should be noted, however, that part of the US diversification may have involved countries importing intermediate and final goods from China (e.g., Malaysia, Thailand and Vietnam).

[13] Let's consider i and j the event of being below and above the median value of IDEP. The events could be approximated by a two-state Markov chain with transition probabilities: $P[X_t = i|X_{t-1} = j] = [p\ (1 - p)\ (1 - q)\ q\ ]$. The corresponding AR (1) process for the stochastic variable X_t is the following: $X_t = (1 - q) + \rho X_{t-1} + \upsilon_t$, where: $\rho = p + q - 1$. As a result, each term of the (2 × 2) TPM will be the conditional probability $p_{ij} = P(I_t = j|I_{t-1} = i)$, or the probability of moving from state j to state i.

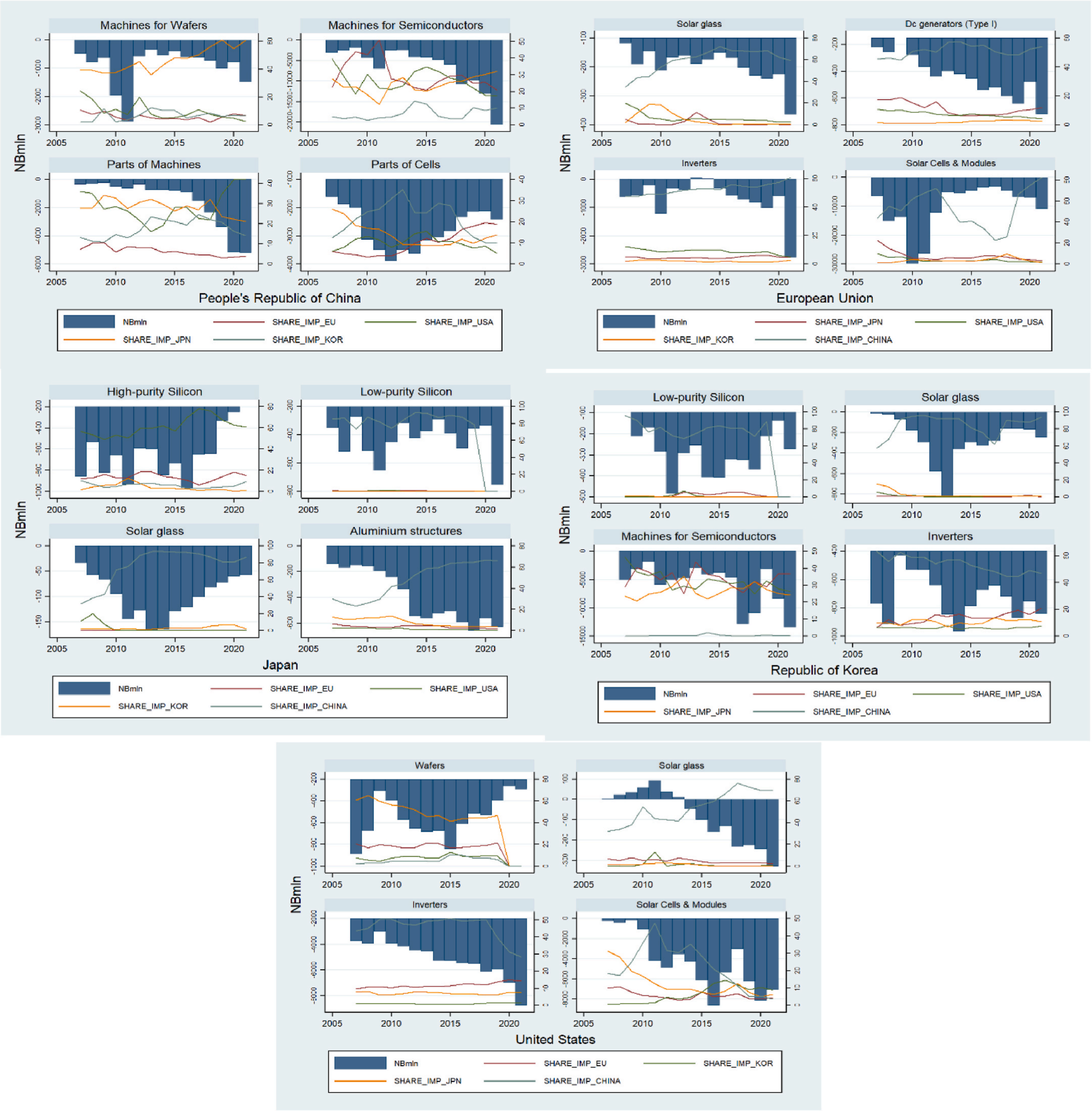

Fig. 5. Strategic dependencies, by country and specific product (2007–2021).
Source: Authors' elaborations based on the UN Comtrade database.

e., mid and downstream). This may be explained by the lower complexity of activities characterizing these segments which, in turn, could make it relatively easier to expand production capacity. As a result, it is necessary, on the one hand, to further investigate the role of technological capabilities in explaining hierarchies along the SC. On the other, it confirms the urgency of implementing policies capable of mitigating SDs, which, given their path-dependency, may become difficult to reverse.

3.5. The role of knowledge and technology

The evolution of technological capabilities is investigated by looking, first, at the dynamics of patent shares. Second, we focus on changes in technological specialization by relying on the RTA. Fig. 6 displays a three-year moving average of PV-related patent shares (2007–2019).

Knowledge stocks tend to show (relatively) stable distributions. Concerning the PV industry, however, things have changed significantly over the last two decades. The fast and substantial consolidation of China' position is observable. As for the remaining players, the hierarchy remained fairly stable. The EU moderately reduced its share,

Table 2
Transition Probability Matrix – IDEP terciles (whole sample).

PVSC				Upstream			
	Low (1st tercile)	Medium (2nd tercile)	High (3d tercile)		Low (1st tercile)	Medium (2nd tercile)	High (3d tercile)
Low (1st tercile)	0,87	0,13	0,00	*Low (1st tercile)*	0,84	0,16	0,00
Medium (2nd tercile)	0,13	0,77	0,09	*Medium (2nd tercile)*	0,06	0,88	0,06
High (3d tercile)	0,01	0,09	0,90	*High (3d tercile)*	0,00	0,08	0,92
Midstream				**Downstream**			
Low (1st tercile)	0,86	0,14	0,00	*Low (1st tercile)*	0,90	0,10	0,01
Medium (2nd tercile)	0,18	0,72	0,10	*Medium (2nd tercile)*	0,16	0,70	0,13
High (3d tercile)	0,01	0,08	0,91	*High (3d tercile)*	0,01	0,11	0,88

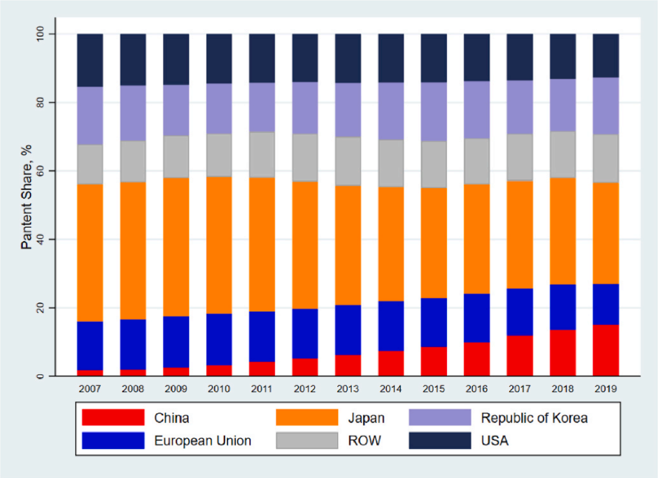

Fig. 6. PV-related patent share (three-year moving average, 2007–2019).
Source: Authors' elaborations based on the OECD Patent database, IP5 patent families.

similarly to the US. At the top, Japan retains its leadership and South Korea does the same concerning its relative patent share.

We now focus on specialization patterns (Fig. 7). Japan and, especially, South Korea are highly specialized in solar technologies. China, in turn, is consolidating its position: the RTA has been moving above 1 since 2012. On the contrary, both the US and the EU are experiencing a pattern of de-specialization, remaining well below 1 during the considered time span. This evidence lends support to the hypothesis that specialization patterns go hand in hand with the strengthening of productive capabilities (and competitive positions) in specific SC segments (Archibugi and Pianta, 1992, 1994). In the case of China, the consolidation of market shares (in the down, mid and, to a lower extent, upstream) is matched by a leap in terms of technological specialization taking place in a relatively limited amount of time.

The long-term evolution of countries' relative technological specialization is further investigated by looking at different segments/products. The heatmap (Fig. 8) turns dark blue as the specialization is relatively more intense, while the opposite holds when the colour is orange or, at the extreme, dark orange. In the upstream, Japan shows the highest level of specialization (apart from technologies related to *Generators*), followed by South Korea, which, however, reports relatively lower RTA levels concerning *Polysilicon*, *UMG silicon* and *Hydrochloric acid*-related technologies. The EU and, even more so, the US are characterized by a poor specialization (with the exception of *Machines for wafer* and *Parts of machines* in the EU case). This means that the relatively good positioning of both countries/regions in the upstream concerning trade dynamics (see Fig. 4) does not seem to be paralleled by an equally good performance regarding technological specialization. On the contrary, China is strengthening its specialization in those technological fields, i.e. *Machineries for cells and wafers*, where it displays a certain degree of import dependence (see Fig. 5). This could mean that, in parallel with a diversification strategy aimed at reducing SDs, China is performing a technological catching up which may help strengthen its productive capabilities in the same segment. In the midstream, the hierarchical structure is fairly similar. Japan stands out as the most specialized (excluding technologies related to *Aluminium Paste*), followed by South Korea, which, in turn, displays some weaknesses regarding *Silver paste* and *Aluminium*. Interestingly, the US and the EU show a mild degree of specialization with respect to technologies connected to *Silver paste* and *Aluminium structures,* while both are highly de-specialized across the rest of the segment. China seems to be experiencing a substantial catching-up regarding all technologies, except those related to *Silver* and *Aluminium paste*. The hierarchy changes as we move towards the downstream. China is taking over Japan as the most specialized economy in solar technologies. Japan and South Korea, in turn, show a significantly lower level of specialization with the exception of, respectively, *Inverters* (Japan) and *Parts of inverters* (South Korea).

The EU has a good level of specialization regarding *DC* and *AC generators,* while it is relatively weak when it comes to inverters-related technologies. Analogously, the US is de-specialized all along the

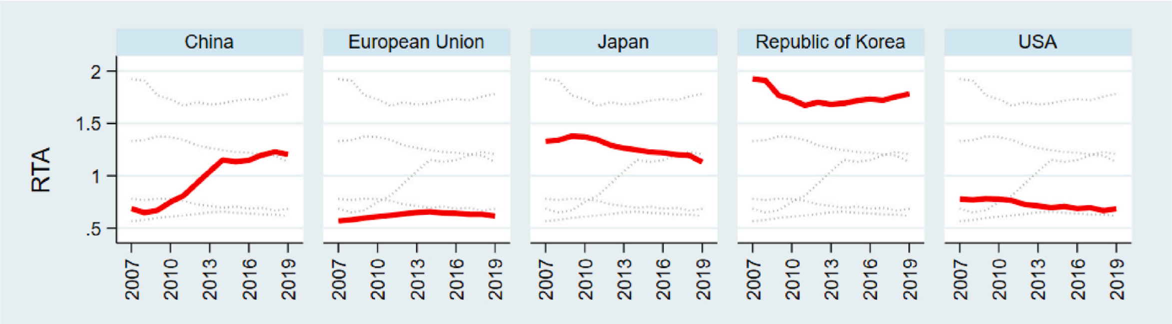

Fig. 7. RTA, by country (2007–2019).
Source: Authors' elaborations based on the OECD Patent database, IP5 patent families.

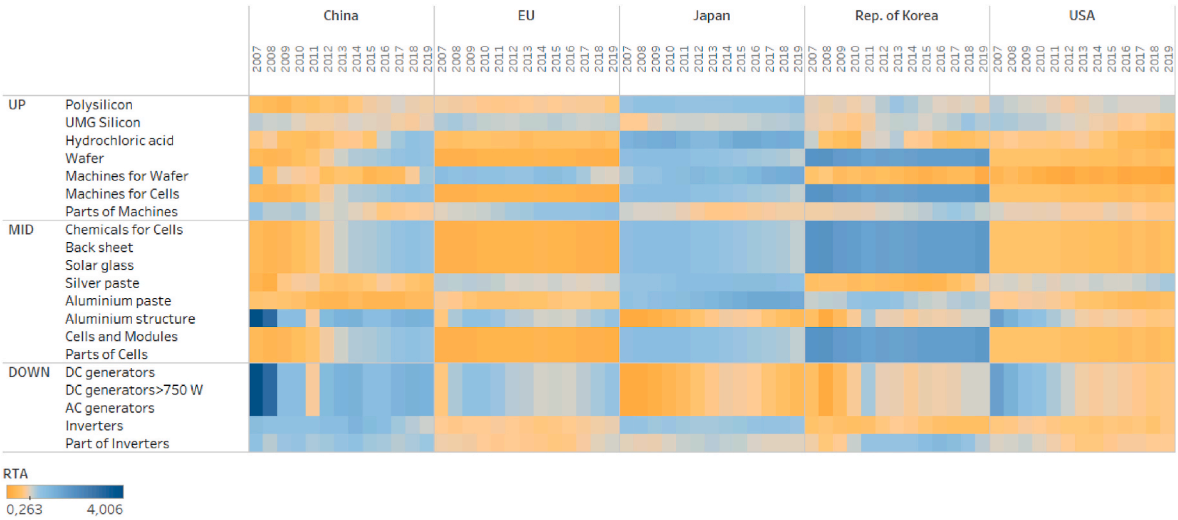

Fig. 8. RTA, by country, segment and product (2007–2019).
Source: Authors' elaborations based on the OECD Patent database, IP5 patent families. Note: the central value with respect to the colour distribution is identified in the unity.

downstream with the lowest levels of RTA registered with respect to *Inverters*. The joint analysis of trade and patent data allows us to take a further step in our 'strategic intelligence' analysis, investigating the relationship between technological capabilities and SDs. To this end we, first, descriptively combine IDEP and RTA. Fig. 9 provides, for the EU, the US and China, a 4-dial diagram characterizing products as follows: i) high IDEP-low RTA (i.e. critical situation needing action to strengthen production and technological capabilities), top-left; ii) high IDEP-high RTA (i.e. reinforcing production capacity may be necessary but potentially facilitated by technological specialization), top-right; iii) low IDEP-high RTA (i.e. safe side, as both productive and technological capabilities are available), bottom-right; iv) low IDEP-low RTA (i.e. SDs are not detected but poor technological specialization exposes to risks), bottom-left quadrant.

Focusing on the top-left quadrant, the EU faces a highly critical situation with respect to *Cells and modules*, *Solar glass* and *Inverters*. A similar situation is detected when looking at the US, which, however, is relatively better positioned concerning *Cells* and worse off as regards *Wafers* and related machineries. These areas are those for which industrial policies seem to be more urgent. Moreover, Fig. 9 highlights the relative vulnerability of the US: only 2 goods (*Silver paste* and *Polysilicon*) are situated in the bottom right of the diagram (i.e. low IDEP-high RTA). And the EU is no better off: only *Polysilicon* and *DC generators* are in the "safer" part of the diagram.

In contrast, China has most of the key products in the bottom-right quadrant. On the other hand, the goods for which China shows the strongest SDs (*Machines for wafers* and *Machine for cells*) are counterbalanced by high RTAs in the corresponding technologies, which is a signal of China's directed effort to close the gap also in these segments. Likewise, the only three goods in the top-left quadrant are barely critical (low technological complexity), showing a level of IDEP that is just above the median. The same information is reported for Japan and South Korea in the Appendix (Figure A2), evidencing that Japan has only two products facing a highly critical situation (high IDEP-low RTA), while South Korea is badly positioned concerning *Inverters*, *Machineries for wafers* and *Hydrocloric acid*.

3.6. Dynamic Ordered Probit model

Although TPMs (Table 2) provide sketchy evidence of the relative persistence of regional SD patterns with respect to key commodies of the PV chain, further analysis is required to test the key hypotheses put forth in Section 2.1. In this respect, we explore the probability of a country to move from a lower to a higher level of SD by applying a *discrete choice ordered model approach*. Given the structural nature of the phenomenon under scrutiny, we control for path-dependency (Antonelli et al., 2013), which is typically due to permanently unobserved heterogeneity across countries. We also focus on PV-related innovation patterns, such as technological capabilities (Fagerberg, 1996; Dosi et al., 2015) and specialization (Archibugi and Pianta, 1996), as being recognized as fundamental drivers in explaining competitiveness at the industry and GVC-level.

Therefore, the baseline specification for the model is:

$$y_i = \gamma y_{it-1} + \beta x_{it} + u_i + \varepsilon_{it} \tag{6}$$

where y_i and x_i represent, respectevely, the dependent variabile and the co-varariates. In our specific context, we rely on a Dynamic Ordered Probit model based on the estimator proposed by Wooldridge (2005) and applied by Peters (2009). This approach allows us to deal with potential endogeneity of the dependent variable (y_i) that could arise when its initial value correlates to the error term (c_i). This basically happens when the actual beginning of a given process does not coincide with its fist available observation, as in our case. Therefore, to avoid bias estimates for the autoregressive parameter which represents persistency, the model is augmented by the initial realization of the dependent variable (y_{i0}) and time-average covaraties $(\bar{x}_{i0})$, which are expected to be correlated to unobservable individual heterogeneity (u_i).

Formally, this relationship could be written as:

$$u_i = \alpha_0 + \alpha_1 y_{i0} + \alpha_1 \, \bar{x}_{i0} c_i \tag{7}$$

where

$$\bar{x}_i = T^{-1} \sum_{t=1}^{T} x_{it} \tag{8}$$

Under the assumption that the distribution of the error term c_i is $N(0, \sigma_c^2)$ with $c_i \perp (y_{i0;}\ \bar{x})$, we have:

$$u_i \big| y_{i0}, \bar{x}_i \approx \mathrm{N}\left(\alpha_0 + \alpha_1 y_{i0} + \alpha_2 \bar{x}_i,\ \sigma_c^2\right) \tag{9}$$

After renaming y_i with the acronym $SD_{i,k,t}$, that indicates to which tercile (1st, 2nd or 3rd) of the IDEP distribution a country i belongs during a period t for a specific commodity k, the dynamic ordered model can be written according to the following specifications:

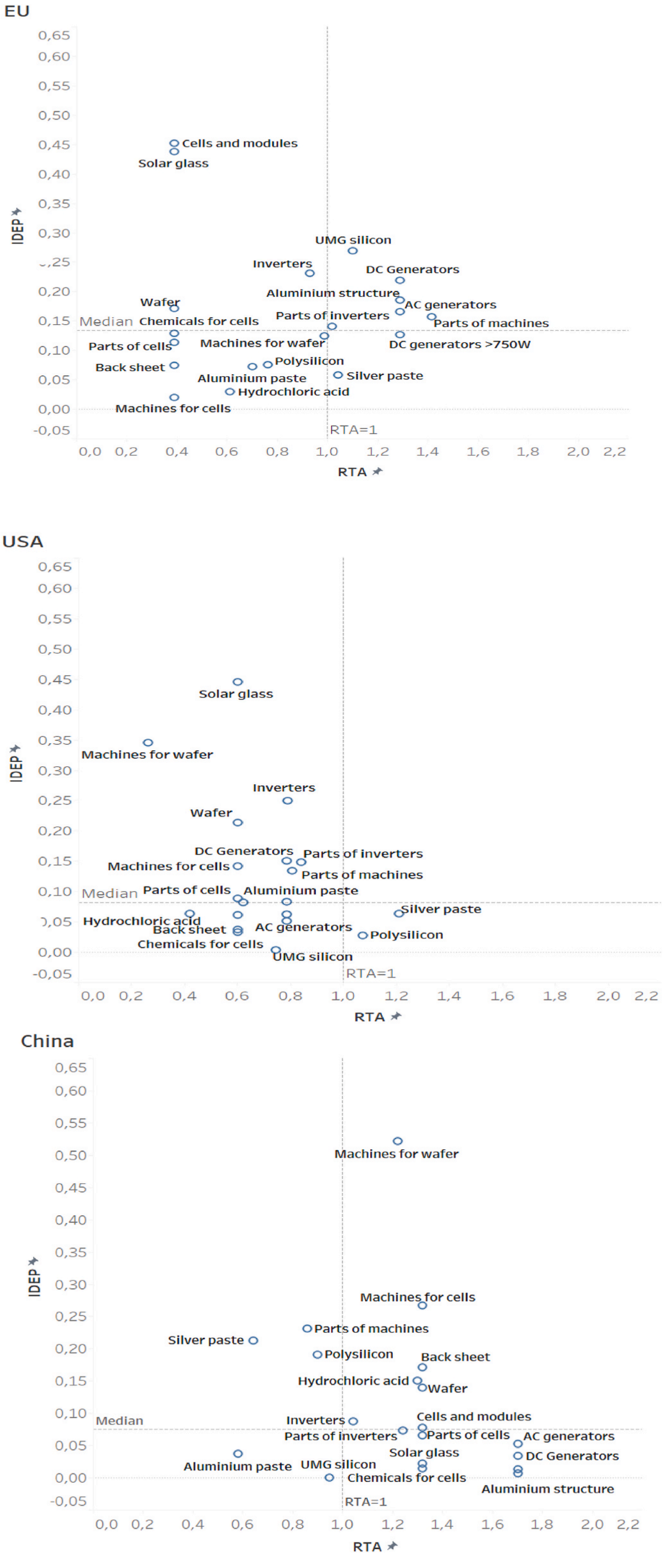

Fig. 9. IDEP-RTA (2019), the EU, the US and China.
Source: Authors' elaborations based on the UN Comtrade database and the OECD Patent database - IP5 patent families. Note: the four dials for each country are obtained using the median value for the IDEP index and the unity for the RTA index.

$$SD_{i,k,t} = \alpha_0 + \underbrace{\gamma SD_{i,k,t-1}}_{\boxed{\textit{Path-dependency}}} + \underbrace{\beta_1 PAT-SH_{i,k,t} + \beta_2 RTA_{i,k,t}}_{\boxed{\textit{Innovation capabilities}}} + \underbrace{\alpha_1 SD_{i,k,t_0} + \alpha_2 X_{i,k,t}}_{\boxed{\textit{Predictors of the individual effect}}} + c_{i,k,t} \quad (9)$$

$$\text{where } SD_{i,k,t} = \begin{cases} 1 \text{ if a country } i \text{ belongs, for commodity } k, \text{ to tercile } 1 \\ 2 \text{ if a country } i \text{ belongs, for commodity } k, \text{ to tercile } 2 \\ 3 \text{ if a country } i \text{ belongs, for commodity } k, \text{ to tercile } 3 \end{cases}$$

Specifically, $SD_{i,k,t}$ is regressed against its past realization ($SD_{i,k,t-1}$), technological capabilities proxied by patent shares ($PAT - SH_{i,k,t}$) and specialization ($RTA_{i,k,t}$). Finally, the initial value of the dependent variabile (SD_{i,k,t_0}) and the time-averaged covariates ($\overline{X}_i$) are included for predicting countries' individual effect. We also include dummy variables indicating the PV-SC positioning of commodity k (Upstream, Midstream and Downstream) and control for country and year-fixed effects. Standard errors are clustered at the country level to account for structural heterogeneities, particularly those related to different industrial policy strategies.

Results reported in Table 3 confirm the path-dependent nature of the SD indicator: economies showing a high (low) level of SD are likely to remain in this condition. At the broad SC level (first column), no significant relationship between SD and technological variables is detected. Things change when the distinction between SC segments is introduced, though. In the upstream, a strong technological specialization is negatively correlated with the SD indicator: for those products for which economies show a high RTA value, the probability of decreasing the level of SDs also seems to be higher. The same is not true in the mid and downstream, where no significant correlation between the RTA and the probability of increasing SD is detected.

Plausibly, where products are more complex and innovation represents a key competitive ingredient (upstream), technological specialization is associated with stronger productive capabilities and, hence, lower SDs (Archibugi and Pianta, 1994). As a result, selective innovation policies may be usefully complemented to interventions aimed at increasing productive capacity. In turn, in the mid and downstream, the problem seems to be the loss of productive capacity and the path-dependent nature of SDs. As economies resize their manufacturing capacity, this condition can get worse regardless of their technological specialization. Although simple and providing no causal evidence, this model confirms that SDs are a major policy concern because, other

Table 3
DOP – IDEP (terciles) vs patent shares and RTA.

	TOTAL PV	Upstream	Midstream	Downstream
	b/se	b/se	b/se	b/se
IDEP_tercile_T0	0.605***	1.021***	0.316**	1.299***
	(0.080)	(0.185)	(0.139)	(0.351)
IDEP_tercile_T-1	1.995***	1.662***	2.100***	2.111***
	(0.220)	(0.227)	(0.179)	(0.194)
RTA	0.046	**−1.205****	0.006	0.506
	(0.128)	**(0.579)**	(0.512)	(0.486)
PAT-SHARE	0.464	3.671	3.045	−4.751
	−1.196	−3.938	−4.093	−5.103
Upstream	0.420***			
	(0.134)			
Midstream	0.325***			
	(0.121)			
Downstream	*Baseline*			
Countries	*Yes*	*yes*	*yes*	*yes*
Years	*Yes*	*yes*	*yes*	*yes*
cut1	4.275***	4.910***	3.642***	4.248***
	(0.237)	(0.453)	(0.339)	(0.370)
cut2	6.643***	6.870***	5.868***	8.075***
	(0.397)	(0.620)	(0.364)	(0.544)
Obs	*1.200*	*420*	*480*	*300*
Adj. R-Square	0.5798	0.5959	0.5458	0.7106

Note: the time average of patent share and RTA are included.

things being equal, economies can easily continue to worsen their relative position once dependence has been developed.

The relationship between SD and technological specialization is further investigated by having RTA and PAT-SHARE interact with country dummies, testing whether technological capabilities play a differentiated role, given the structural heterogeneities and country-specific positioning along the PVSC (Fagerberg, 1996). According to our estimates (Table 4), only China seems to benefit from technological specialization: the coefficient associated with the RTA interaction term is negative and statically significant, while no significant results are obtained with respect to the other countries included in the sample. This result is relevant as it confirms the strong complementarity between productive and technological capabilities: in order to benefit from the latter in terms of lower SDs, the former need to be in parallel reinforced.

Table 4
DOP – IDEP (terciles) vs patent shares and RTA.

	CHINA	EU	JAPAN	KOREA	USA
	b/se	b/se	b/se	b/se	b/se
IDEP_tercile_T0	0.601***	0.616***	0.627***	0.588***	0.628***
	(0.078)	(0.080)	(0.082)	(0.072)	(0.096)
IDEP_tercile_T-1	1.986***	2.004***	1.999***	1.995***	2.002***
	(0.219)	(0.220)	(0.221)	(0.219)	(0.223)
RTA	0.322	0.069	0.035	−0.112	0.062
	(0.329)	(0.090)	(0.082)	(0.223)	(0.080)
Country dummy	**0.369****	−0.223	**0.635*****	−0.024	**−0.279****
	(0.187)	(0.143)	**(0.070)**	(0.130)	**(0.136)**
Country dummy#RTA	**−0.672****	0.497	0.038	0.145	1.159
	(0.278)	(0.731)	(0.598)	(0.355)	−2.434
PAT-SHARE	0.117	0.080	0.933	0.732	0.369
	(-1.829)	(-1.312)	(-1.797)	(-1.336)	(-1.618)
Country dummy#PAT-SHARE	0.376	−1.132	−2.491	1.560	−4.020
	(-2.061)	(-3.099)	(-2.423)	(-3.575)	(-13.281)
Upstream	0.466***	0.429***	0.381***	0.446***	0.416***
	(0.119)	(0.118)	(0.126)	(0.118)	(0.130)
Midstream	0.314**	0.357**	0.357***	0.307**	0.347***
	(0.135)	(0.140)	(0.129)	(0.132)	(0.111)
Downstream	*Baseline*	*baseline*	*baseline*	*baseline*	*baseline*
Years	*Yes*	*yes*	*yes*	*yes*	*yes*
cut1	4.317***	4.370***	4.193***	4.193***	4.423***
	(0.253)	(0.296)	(0.220)	(0.220)	(0.312)
cut2	6.695***	6.734***	6.566***	6.566***	6.787***
	(0.398)	(0.413)	(0.395)	(0.395)	(0.426)
Obs	1.200	1.200	1.200	1.200	1.200
Adj. R-Square	0.5810	0.5781	0.5791	0.5800	0.5783

Note: the time average of patent share and RTA are included.

4. Conclusions and policy implications

This paper sheds new light on the solar industry, providing a detailed analysis of its supply chain concerning both strategic dependencies and technological capabilities. Its main contribution can be summarized as follows. First, we provide a fine-grained mapping of the PVSC combining both production/trade and technology. Second, we assess the long-term evolution of trade and technological hierarchies within the supply-chain, highlighting processes of polarization and growing SDs. More specifically, the empirical evidence - focusing on China, the EU, Japan, South Korea, and the US analysed over the 2007–2021 period - highlights strong SDs in the EU, especially in the mid and downstream segments of the PVSC. At the same time, a certain degree of 'industrial resilience' – and a possible source of leverage within the SC – is detected in the upstream segment, particularly regarding PV-related machineries. On the other hand, China is rising as one of the new dominant players of the SC, at least concerning trade dynamics.

Third, we zoom-in on highly critical areas (i.e. products and related technologies), carrying out a 'strategic intelligence activity' (Edler et al., 2023) which may prove useful to tailor trade, industrial and innovation policies. Fourth, we document, by means of TPMs, the strong path-dependency of the hierarchies characterizing the PVSC, as well as the heterogenous degree of 'mobility' across segments. Fifth, we explore the relationship between technological specialization and productive capabilities to see whether and to what extent reinforcing the former may help mitigate SDs. In this respect, the estimated econometric model shows that a relatively strong technological specialization may help reduce SDs, but only in the upstream segment.

Our results have relevant implications both in terms of policy theory and practice. The evidence suggests that once the importance of issues related to TS and SDs is recognized, these aspects should be included in the conceptualization, design and implementation of policy objectives and instruments. This is particularly relevant in a context wherein the renewed relevance of once neglected concepts, such as mission-oriented (Mazzucato, 2018; Wittmann et al., 2021) and transformative policies (Steward, 2012; Haddad et al., 2022), is bringing selective/strategic industrial policies back to the forefront of the policy agenda. In this direction, paradigmatic examples include the EU Solar Strategy and the Green Deal Industrial plan, as both initiatives aim at strengthening the EU's productive and technological capabilities in strategic sectors, adopting a vertical and selective approach to industrial policy.

In particular, our results have important implications for European policies aiming at achieving a sustainable transition and the full decarbonization of the economy, as the evidenced EU SDs in the solar industry are also the result of radically different industrial policies with respect to key international players (Buigues and Cohen, 2023). In principle, environmental targets can be achieved by adopting a "buy from abroad" strategy both in terms of the development of environmental technologies and the production of green goods and services. However, this option obviously entails relevant consequences from the perspective of technological and productive SDs. In this regard, our analysis suggests that the EU climate strategy should fully integrate the objective of fostering the European technological and productive capabilities needed for the green transformation of the economy. Hence, the PV industry is one of the most relevant candidates to apply and test the effectiveness of a new policy approach in which climate objectives, technological sovereignty and strategic autonomy objectives go hand in hand to maximize sustainability, security and growth opportunities for the green transformation of the economy.

CRediT authorship contribution statement

Serenella Caravella: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Francesco Crespi:** Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Giacomo Cucignatto:** Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. **Dario Guarascio:** Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing.

Declaration of competing interest

We hereby declare that, concerning the submission of the revised version of our original article entitled 'Technological Sovereignty and Strategic Dependencies in the Photovoltaic Supply Chain', we have no conflict of interest to declare. Likewise, we confirm that this article is original and has not been submitted elsewhere.

Data availability

Data will be made available on request.

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Appendix

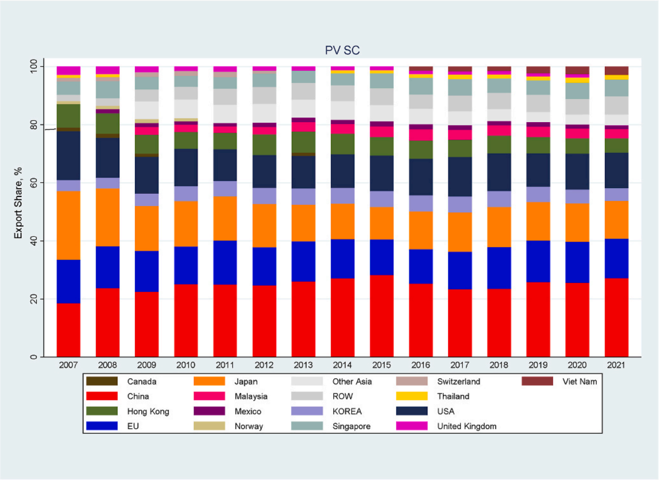

Figure A1. Export shares in the PV global market.

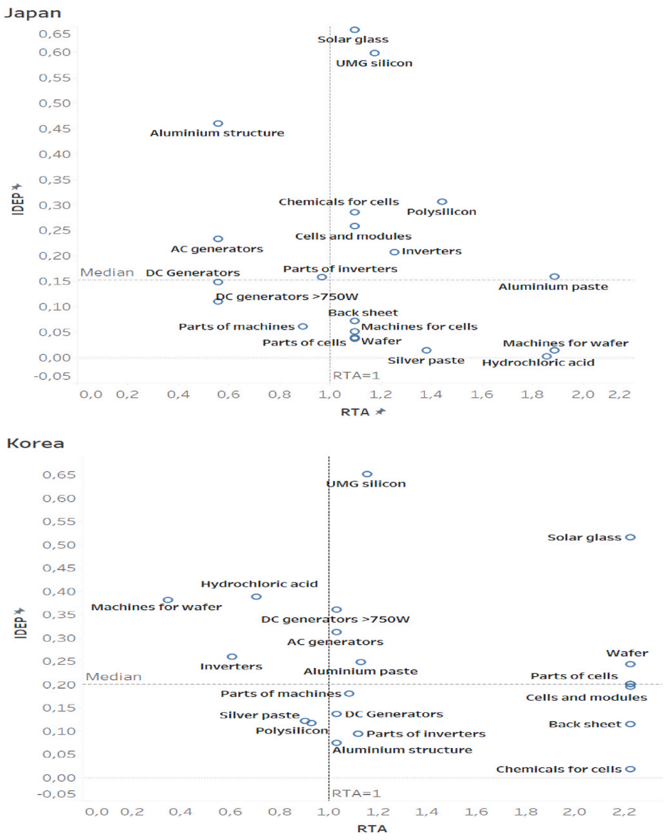

Figure A2. IDEP-RTA (2019) – Japan and South Korea.

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