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Technological Sovereignty and Strategic Dependencies: The case of the Photovoltaic Supply Chain[*]

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Abstract

This work sheds new light on the Photovoltaic Supply Chain (PVSC), providing fresh evidence on structural dependencies (SDs) and (asymmetrically distributed) technological capabilities. Bridging the perspectives of 'technological sovereignty' and 'strategic autonomy', we provide a number of contributions. First, we carry out a fine-grained mapping of the PVSC, combining trade and patent data. Second, we assess the long-term evolution of trade and technological hierarchies, documenting processes of polarization and growing SDs. Third, we zoom-in on critical PV areas (i.e. products and related technologies), providing a 'strategic intelligence' activity which may prove useful for tailoring trade, industrial and innovation policies. Fourth, we explore the relationship between technological specialization and productive capabilities, showing that, in the upstream segment, reinforcing the former may help mitigate SDs.

Keywords: Technological sovereignty, Strategic dependency, Photovoltaic industry, Trade, Patents.

JEL codes: C23, F18, O31, O38, Q42.

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1. Introduction

The disruption of Global Value Chains (GVCs) induced by the Covid-19 crisis and further exacerbated by the Russo-Ukrainian War has dramatically exposed the 'risks of globalization' (Baldwin and Freeman, 2021): shortages of essential goods (Winkler and Wuester, 2022), production chains undermined by the lack of critical raw materials (CRMs) and components (Celi et al., 2022), 'weaponized interdependence' (Farrel and Newman, 2019; Gjesvik, 2022) and 'technology wars' (Miller, 2021). These are the key features of a global economy that is increasingly divided between two 'competing blocs', i.e. the US and China (Rodrik and Walt, 2022).

In this context, decarbonisation and, more broadly, transition to renewables (e.g., solar, wind) become even more pressing goals. The urgency of achieving ambitious climate targets is compounded by the need to reduce dependence on economies that control fossil fuels in order to minimize their rents and related 'geopolitical leverage'.[1] Even in this case, however, asymmetries and conflicts are in order. The transition to renewables is constrained by the asymmetric distribution of raw materials, manufacturing capacity and technological capabilities (IEA, 2021). While China experienced an astonishing technological catching up, gaining dominant market shares in key markets, such as photovoltaic (PV) panels and lithium batteries (IEA, 2022a; Altenburg et al., 2022), the US and the EU are realizing that increasing dependence on a few suppliers of CRMs and intermediate goods can undermine growth prospects and distance their energy transition targets.

After nearly three decades of reliance on free trade as a 'metronome' of the global division of labor and relative productive/technological specialization, forgotten concepts such as absolute advantages (Dosi and Tranchero, 2021), idiosyncratic capabilities, selective industrial policy (Andreoni and Chang, 2019; Cucignatto and Garbellini, 2022), strategic autonomy/dependence (SD), and technological sovereignty (TS) (Edler et al., 2020, 2023; Cerra and Crespi, 2021; Crespi et al., 2021; Caravella et al., 2021; Bellanova et al., 2022; Da Ponte et al., 2022; Gehringer, 2023) have returned to the fore, even in Brussels (EC, 2019a, b; Couture and Toupin, 2019; EC, 2021, 2022). Epitomized by this 'resurrection' of Hamiltonian concepts (Celi et al., 2020), it has again become clear how countries' productive and technological capabilities play a fundamental role in ensuring their resilience and capacity to adapt to *poly* (several) and *perma* (lasting) *crises,* as well as vis-à-vis growing geopolitical tensions (Morin, 1999; Juncker, 2016; Tooze, 2022).

The literature focusing on TS and SD is thus flourishing. Its key aim is to provide theoretical rationale and empirical evidence to support industrial policies directed at strengthening economies in these domains, particularly in strategic areas such as those related to the digital and green transitions (Guarascio et al., 2023).

Concerning the latter, the PV supply chain (SC) is crucial for at least three reasons. First, solar energy is one of the key avenues for achieving climate goals, given the increasing performance of PV panels and their ductility, which makes them suitable for a myriad of civil and industrial settings.[2] Second, the manufacturing process of PV panels is among the most efficient, allowing the emissions produced during production to be "repaid" in a relatively short amount of time (IEA, 2022). Third, the PVSC has attracted a huge amount of investments during

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[1] At the European level, the growing ambitions concerning emissions reduction targets have been translated into a set of relevant policy actions, such as the *Green Deal*, the *RepowerEU* and the *Solar strategy*.

[2] At the global level, installed solar PV capacity is expected to become the largest in the world by 2027, with a cumulative capacity nearly tripling over the period (1.500 GW), surpassing natural gas by 2026 and coal by 2027 (IEA, 2023).

the last fifteen years,[3] resulting in growing market concentration, the reshuffling of productive/technological hierarchies and the increase of SDs (Kowalski and Legendre, 2023).

This explains the proliferation of industrial policy actions, such as those recently put forth by the US government and the European Commission, targeting this SC.[4] As far as PV-related industrial policy is concerned, a number of objectives are in order. First, increasing manufacturing capacity to meet the growing demand for PV panels and match the related climate targets. Second, consolidating technological capabilities to develop the necessary components, particularly the most technologically advanced, so as to avoid 'missing the train' of the new PV modules generations. Third, reducing the dependence on key suppliers (e.g., China) of CRMs and components (e.g., inverters). In the context of the energy transition, this means avoiding the switch from one dependency, i.e. fossil fuels and their suppliers, to another, i.e. CRMs and components needed to produce PV panels.

This work adds to the literature on TS (Crespi et al., 2021; Edler et al., 2023) and SDs (Gehringer, 2023) by focusing on the PVSC, on which it provides a number of empirical contributions. Therefore, the present paper complements previous, more theoretically oriented, analyses by developing an empirical framework that aims to apply concepts to the concrete case analysis (i.e. the PVSC), which can be potentially extended to other strategically relevant industries. In particular, building on Edler et al. (2023), the empirical framework adopted is aimed at developing a product-level 'strategic intelligence' analysis that could be potentially informative also for policy decision making.

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. This allows us to assess the long-term evolution of the SC, offering fresh evidence on changing hierarchies, SDs and the positioning of key players across each product segment. For each economy included in the analysis, we report the ranking of products facing 'critical dependencies', which is associated with information on the relevant suppliers. Third, product codes are merged with International Patent Classes (IPC) to assess the role of knowledge and technology in shaping hierarchies and SDs. We analyse the evolution of capabilities as well as the dynamics of technological specialization, relying on the Revealed Technological Advantage (RTA) indicator. The combined information on SDs and technological capabilities are jointly analysed in order to provide a thorough identification, for each economic area under scrutiny, of critical segments along the PVSC. Finally, a Dynamic Ordered Probit (DOP) model is estimated to test if and to what extent the accumulation of technological capabilities 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 production and technology capabilities in the PV industry.

The paper is structured as follows. Section 2 reviews the recent literature on TS and SD, with a specific focus on the PV industry. Section 3 illustrates the methodology and adopted databases, providing the mapping of the PV industry. The empirical evidence is presented in Section 4, while Section 5 concludes the paper by discussing the main implications in terms of industrial and innovation policy.

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[3] According to Jäger-Waldau et al., (2020) there are two main stylized facts regarding the recent evolution of the PVSC. First, the rise of China. Second, the relative retreat of the US and the EU as global players.

[4] The most relevant are the *Inflation Reduction Act* (IRA) on the US side (McKinsey, 2022), the *Green Deal Industrial Plan for the Net-Zero Age* and the *Solar Strategy* on the EU side (Kleimann et al., 2023).

2. Technological sovereignty, strategic dependencies and the PV industry

Global conflicts are increasingly played out over control of raw materials, technologies and strategic assets. This is testified by the proliferation of 'technological wars' (Miller, 2021) and geopolitical tensions concerning the access to CRMs (Guarascio et al., 2023). On the other hand, trade and technological dependencies are constraining economies' growth prospects, reducing their resilience vis-à-vis global shocks. This explains why, in a relatively short amount of time, the policy debate moved from extolling the benefits of globalization to rediscovering concepts with a 'Listian' flavour (Crespi and Guarascio, 2019; Dosi et al., 2021), such as TS and SDs (Edler et al., 2023).

According to Edler and colleagues, TS can be defined as "the ability of a state or a federation of states to provide the technologies it deems critical for its welfare, competitiveness, and ability to act, and to be able to develop these or source them from other economic areas without one-sided structural dependency". This concept builds on the acknowledgement that no country is able to rely only on its own capacities and market size to maintain sovereignty in a globalized and interconnected world. This implies that sovereignty does not require technological autonomy *tout court* but, conversely, it suggests the need for a country to develop or preserve, with respect to key technologies, its own autonomy or, alternatively, to have the lowest possible level of SDs with respect to international partners (Crespi et al., 2021). Reducing SDs and, even more so, achieving TS is all but an easy task, though. Global interdependencies are increasingly 'weaponized' (Drezner et al., 2021), fuelling core-periphery divides and polarization dynamics (Celi et al., 2018). On the other hand, productive and technological capabilities, crucial in mitigating SDs, are inherently local, cumulative, and correlated to the strength of pivotal institutions such as public R&D bodies, universities, organizations facilitating technology transfer (e.g., the German Fraunhofer Institute). In other words, such capabilities are difficult to create and accumulate, as this may require a considerable amount of time as well as the availability of complementary assets and skills, without considering the frequent use of protectionist measures (e.g., selective export bans) aimed at preventing their diffusion.

In this context, the 'operationalization' of TS and SDs implies the assessment of economies' relative autonomy (dependency) vis-à-vis key partners as a fundamental feature of their resilience (weakness) with respect to global shocks and conflicts. As a result, SDs need to be framed adopting a systemic perspective which goes beyond technology. Focusing on relevant supply chains (SCs), TS and SDs have to be analysed considering, jointly, technology, CRMs, capital, intermediate and final goods (EC, 2021, 2022).[5] Empirically, this means, first of all, identifying and mapping relevant SCs at the highest possible level of detail. Secondly, defining reliable indicators capable of quantifying the degree of productive and technological autonomy/dependence. Finally, the analysis must be conducted over a reasonably long period of time, in order to capture structural changes and relevant shifts in hierarchical relationships (Edler et al., 2023).

As argued, the debate on TS and SDs is strictly connected with the need to accelerate the energy transition. Achieving increasingly ambitious climate targets requires accessing to asymmetrically distributed CRMs, products, and technologies. By the same token, accelerating the shift to renewables, in addition to making the

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[5] The more systematic and fine-grained this process is, the greater the possibility of identifying the specific domains that really matter to efficiently allocate resources to develop the necessary technological and productive capabilities and to foster market processes that are conducive to increasing the level of sovereignty.

economy environmentally sustainable, can help weaken one of the key levers of weaponized interdependence: fossil fuels (Celi et al., 2022).

In this respect, solar energy and, more specifically, PV panels play a fundamental role. According to the EU *Green Deal*'s upgraded climate targets – emission reductions of 55% by 2030, the PV industry was expected to provide a massive contribution, with the installation of new capacity between 325 and 375 GW_{DC} by 2030, depending on the scenario considered. This would have required a 3- to 5-fold growth of the European PV market as compared to its 2019 size (Jäger-Waldau et al., 2020).

When the war-induced energy crisis stepped in, the EU planned efforts to increase PV installation became even more ambitious. Included in the *REPowerEU*, the *Solar Strategy*[6] sets out new targets: 400 GW_{DC} by 2025 and nearly 750 GW_{DC} by 2030 in terms of electricity generation additional capacities.[7] This means (more) than doubling EU capacity by 2025 compared to the current availability (170GW_{DC} in 2020), as well as to the *Green Deal*'s already challenging 2030 targets.

Are these targets reasonable given the EU productive and technological capabilities? Or, on the other hand, would the EU end up facing new and stronger SDs? Will the transition be fast and sustainable or, in turn, slow and characterized by relevant economic and social costs? The answer to these questions is to a significant extent related to the EU's ability to rapidly strengthen its production (and technological) capacity along the PVSC. Indeed, such concerns are clearly acknowledged by the EC, as testified by the recent *Net-Zero Industry Act*.[8] The latter aims at scaling up EU manufacturing capacity of clean technologies in order to meet at least 40% of total demand through domestic production by 2030.

However, as key players are in competition, their industrial and trade policy strategies can further complicate the picture, making the situation more difficult for those with weaker capabilities and/or fewer resources to invest. This is the case of the US *Inflation Reduction Act* (IRA), which is intended to sustain digital and green investments as a way to achieve climate targets and reduce SDs. In this respect, the large amount of subsidies that the IRA allocates to promote (national and foreign) investments in the US PVSC may transform the country into one of the areas where producing solar panels is more attractive.[9] Clearly enough, such an initiative can create distortions in the global market, fuelling new asymmetries. In fact, despite the EU's remarkable activism in this domain (e.g., the recently launched Green Deal Industrial Plan), whether its industrial and energy policies will be enough to counterbalance US efforts remains an open question (Jansen et al., 2023; Kleimann et al., 2023). Ironically, the US's attempt to resize China's power in the PVSC by stimulating domestic investments and FDIs may result in an EU-US redistribution that is unfavorable to the

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[6] European Commission (2022), Eu Solar Energy Strategy, *Staff Working Document 148*. https://energy.ec.europa.eu/system/files/2022-05/COM_2022_221_2_EN_ACT_part1_v7.pdf.

[7] These EU *Solar Strategy* targets are set in alternating current terms (320 GW_{AC} by 2025 and 592 GW_{AC} by 2030). Renewable power is produced by PV *modules* transforming sunlight in *Direct Current* (DC), then converted by the *inverters* to *Alternating Current* (AC) to feed into the grid and finally converted back to DC for final consumption. All these processes are energy dissipating; therefore, the Commission is considering an increase in the use of DC technologies within the electricity system.

[8] European Commission (2023). Proposal for a Net Zero Industry Act, *COM(2023) 161 final*. https://eur-lex.europa.eu/resource.html?uri=cellar:6448c360-c4dd-11ed-a05c-01aa75ed71a1.0001.02/DOC_1&format=PDF

[9] Mckinsey (2022). Building a competitive solar-PV supply chain in Europe, Report. Available at: https://www.mckinsey.com/industries/electric-power-and-natural-gas/our-insights/building-a-competitive-solar-pv-supply-chain-in-europe.

former and unlikely to seriously counter Chinese growth, as the latter is propelled by incomparable public investments, economies of scale, growth of the domestic market and vertical integration strategies (see below).

Overall, the PV industry represents a textbook example of hierarchical reshuffling and growing SDs. In the late 1990s, European companies managed to catch up with the leaders of the time, i.e. the US and Japan, gaining a leading position in the SC. However, China's market entry quickly changed the picture. Between 2007 and 2017, the EU global share of PV modules production fell from 30% to 3% and a large number of EU-based solar companies went bankrupt or were taken over (Buigues and Cohen, 2023).[10] At the same time, Chinese solar panel manufacturers massively expanded their production capacity, at the expense of all other producers. In less than ten years (2003-2013), China's share in the PV industry rose from less than 1% to around 60% (Jäger-Waldau, 2013; Shubbak, 2019). In 2021, China's share reached 75% in Modules production (IEA, 2022b).[11] Regarding wafers, China seems to have little competition, while a more nuanced picture characterizes cells and modules, for which Southeast Asia has considerable manufacturing capacity (i.e. Vietnam, Malaysia and Thailand). Concerning polysilicon, Germany remains the major supplier for the c-Si PV modules[12] industry, while the US and Japan have a good productive capacity but focus on semiconductor-grade products.

Such a production reshuffling has been eased by the exploitation of substantial economies of scale and incremental innovations allowing to reduce production costs all along the SC. For example, the average price of modules dropped by 80% between 2010 and 2020 (IEA, 2022a). As a consequence, most of the literature focused on price competitiveness and its implications (Hajdukovic, 2020; Garlet et al., 2020), while less attention has been given to long-term structural dynamics including changing hierarchies, positioning of countries as regards technological and productive capabilities, access to CRMs, as well as heterogeneities in terms of industrial and innovation policy.

In fact, excess supply and falling prices were not the only explanation for China's success. On the demand-side, the strong push provided by the green subsidies put forth by the EU and other countries to reduce carbon emissions played a relevant role. Huang et al. (2016) have documented the positive correlation between EU subsidies and the import of Chinese panels that, in 2011, were already above €20 billion (Buigues and Cohen, 2023; Yang et al., 2023). Moreover, Chinese industrial policy – based on a complex mix of public investments, R&D programs and credit support for PV producers - represents another important piece of the explanation (Zhang and He, 2013; Zhang et al., 2013; Huang et al., 2016; Costantini et al., 2018). In the aftermath of the Global Financial Crisis, such policies allowed key Chinese players to survive the recession, overcome overcapacity problems and gain a substantial competitive advantage vis-à-vis their Western counterparts (Ball et al., 2017; Shubbak, 2019). Process innovations are also important, though. In 2018, the introduction of the diamond wire saw enabled a significant reduction of silicon consumption in the ingot-cutting process, positively affecting the efficiency of production. According to IEA (2022a), 'the average polysilicon use per watt of finished cell decreased by almost 60% between 2010 and 2021'. Likewise, the switch to monocrystalline

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

[11] For further details, see the Photovoltaic Power System Programme's Report *Trend in Photovoltaic Application 2022*, published by IEA and available at: https://iea-pvps.org/wp-content/uploads/2023/02/PVPS_Trend_Report_2022.pdf.

[12] Accounting for more than the 95% of global production (IEA, 2022).

wafer manufacture is boosting production of high-efficiency cells, further reducing the per-watt cost of solar PV modules.

To understand its structural reshuffling, the fragmentation and complexity of the PVSC should be properly considered. The change in hierarchies and competitive positions is not limited to the final stage of production, e.g., the massive increase in Chinese solar modules exported all over the world. Chinese manufacturers managed to increase their global share in virtually all the key segments of the SC, reaching 79% in terms of Polysilicon production, 97% in Wafers and 81% in Solar Cells by 2021 (IEA, 2022b). Relying on vigorous public support, Chinese companies put forth vertical integration strategies, particularly towards the upstream segment, which proved effective in exploiting economies of scale and scope, as well as in strengthening their technological capabilities (Zhang and Gallagher, 2016). A paradigmatic case is that of Trina Solar, which has recently announced an ambitious industrial strategy to penetrate the SC, moving up to the wafer, silicon and CRMs segments.

Concerning the technological catching-up, Binz et al. (2017) argue that the PV geography changed in less than twenty years. Once undisputed leaders such as the US, Japan and Germany are heeled and, in some cases, caught up by 'latecomers' such as China, South Korea and Taiwan. All three are no longer latecomers, thanks to the combination of public investment, industrial policies, FDIs and technological spillover (Yuan et al., 2022). China, by virtue of a long-term plan aimed at gaining a leading role in the solar sector, including in technology, is experiencing a sustained strengthening of its position even in areas where it started off with a major disadvantage (e.g., machinery).

Another essential component of the SC are raw materials (IEA, 2021; Kowalski and Legendre, 2023). For most CRMs mining capacity is asymmetrically distributed and the environmental costs of extraction make the opening of new mining fields problematic, particularly where environmental standard are stringent, as in the EU. Overall, the EU displays relevant SDs with respect to a large number of CRMs (for an analysis, see Guarascio et al., 2023). Concerning PV modules, however, Rabe (2017) argues that SDs could be less intense as compared, for example, to the 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 – and discussing the risk the EU might face in this area as well, Rabe (2017) provides a rather optimistic prediction as diversification seems to be relatively manageable (e.g., alternative European and Japanese sources) and a moderate demand growth of thin film solar cells is expected.[13]

This review shows that the structural evolution of the PVSC represents a relevant case to study TS and SDs and their role in explaining economies' relative positioning and prospects concerning the energy transition. In particular, a number of stylized facts can be summarized. First, the global demand for PV modules increased substantially in the last twenty years, driven by the generalized attempt to accelerate the transition to renewable energies, large public subsidies, process innovation and falling prices. Second, a structural

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[13] In this respect, the recent ban imposed by the Chinese government on the export of gallium and germanium, both used in the production of thin cells, casts some doubt on Rabe et al. (2017)'s optimistic predictions concerning CRM-related SDs. For details on the Chinese ban, see Liu and Bradshaw (2023) in the *Financial Times*: https://www.ft.com/content/6dca353c-70d8-4d38-a368-b342a6450d95 (last access: 8 September 2023).

reshuffling took place, with China gaining a prominent place in the SC while the US and the EU scaling down their role. Third, a process of technological catching up has seen, again, China and a few other Asian economies, reduce (and in some case close) the gap vis-à-vis their western counterparts. Such dynamics, however, are heterogenous across SC' segments, and need to be investigated by carrying out granular explorations. Moreover, the evolution of productive capabilities and that of technological capabilities do not necessarily go hand in hand, and differences in this regard need to be properly assessed in order to identify exactly where SD issues are more compelling.

With regard to these aspects, the previous literature still appears to be undeveloped and the analysis presented in the next sections aims at providing a contribution in this direction by developing a product-level 'strategic intelligence' empirical framework based on a detailed mapping of the PVSC and an in-depth investigation of SDs and technological capabilities.

3. Mapping the PV supply chain: data and methodology

To analyse the long-term evolution of the PV value chain, two unique data sources are merged. The analysis of SDs is based on trade data, stemming from the United Nations Comtrade database. The latter provides granular product-level information, allowing for the tracing of all segments of the SC. Moreover, Comtrade data provide information on all the economies participating in the SC covering a rather long time span, making it possible to capture structural change and hierarchical reshufflings.[14]

Technological capabilities are measured relying on data from the OECD Patent database. The identification of the relevant patent IPC codes corresponding to the associated 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 SC: upstream, midstream and downstream. Therefore, 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, Korea, Japan and the US – representing around 70-80% of the global market.[15]

3.1. Mapping the PV value chain

The trade dimension

The extant literature has mostly focused on specific components of the SC, e.g., wafers, cells and inverters (Garlet et al., 2020). However, its significant degree of fragmentation - i.e. a larger number of relevant products

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[14] International trade statistics are characterised by a significant number of discrepancies and several attempts have been made to reconciliate trade data internationally (Shaar, 2019; Arjona et al., 2023) – i.e. the Global Trade Analysis Project (GTAP) or the BACI-CEPII database, just to mention a few (Gehlhar,1996; Gaulier and Zignago, 2010). Regarding Comtrade, the main data issues concerns outliers, missing values, and bilateral asymmetries (Chen et al., 2022). Some scholars argue that the BACI database is more suitable than Comtrade for studying SDs and even more appropriate would be the FIGARO-Eurostat database (Arjona et al., 2023). Nevertheless, none of these data are flawless, with the main problems being the use of biased measures of reporter quality, the subjective choice of acceptable quality thresholds and not accounting for the role of data availability as a dimension of reporter quality (Shaar, 2019). No less relevant is the fact that UN Comtrade is still the most widely-used data source, due to its broad coverage of commodity categories and reporters (Chen et al., 2022). It is particularly relevant when it comes to a thorough mapping of a specific industrial chain (Guo et al., 2023).

[15] Note that the analysis on PV-related patents is limited to 2019 due to missing observations.

and components in addition to those that are usually examined - and internationalization demands a more thorough mapping, as complementarities matter and competitive advantages can be fully exploited only by including "remote" corners of the chain. To the best of our knowledge, no contribution has yet provided a complete, long-term and updated mapping of the PVSC. Likewise, there are no available analyses bringing together the production and the technology side at a high-level of disaggregation (Yuan et al., 2022).

Our mapping focuses on the wafer-based crystalline silicon (cSi) PV technology. The latter accounts for over 95% of global module production, while cadmium telluride (CdTe) thin-film PV technology makes up the remaining part (IEA, 2022b). Moreover, the cSi modules are well placed to dominate future PV power generation, due to their high efficiency, low cost, long service time and relative abundance of materials (Benda and Cerna, 2020). By the same token, not only does the second generation - i.e. thin film solar cells - currently represents a very small share (4.6%) of the global PV market, but this share is not expected to grow substantially in the long run either. It is estimated to be between 1% and 23% for 2050 based on three different scenarios (Carrara et al., 2020).

To trace the PVSC components, we rely on the 6-digit product-level *Harmonised System* (HS) classification, which allows us to assess trade dynamics regarding feedstocks, machineries and components.[16] From a strictly methodological viewpoint, two elements are worth underlining. First, the selected set of HS codes went through a cleaning process following Korniyenko (2017), which is dropping the few product codes[17] 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 understand the deep functioning of the SC. Concerning this issue, further research advancing the approach herein proposed would be desirable.

The mapping is based (and validated) relying on a large set of contributions (Algieri et al., 2011; Rabe, 2017; Latunussa et al., 2016; Carrara et al., 2020;; Hajdukovic, 2020; Gahrens et al., 2021; Wang et al., 2021; IEA, 2022a). The starting point is the HS code referring to *Solar Cells and Modules* (HS 854140). In line with Gahrens et al. (2021), we add the HS codes related to machineries and, more specifically, those used for the production of wafer, cells, modules and related parts. In addition, we include the HS codes referring to three different types of electric generators; inverters and their parts.[18] In so doing, we provide a more comprehensive representation of the SC, allowing for the analysis of the evolution of the PV industry along the up, mid and downstream segments. Furthermore, we follow Wang et al. (2021) including *High-purity Silicon* (HS 280461) and *Wafers* (HS 381800), which are crucial components of the upstream segment (IEA, 2022a).

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[16] The UN Comtrade database provides even more disaggregated level product-level data, i.e. the Combined Nomenclature classification (8-digit) and the Harmonised Tariff Schedule (10-digit) (Algieri et al., 2011). Nonetheless, this would not allow us to cover all the relevant countries, given that these datasets do not provide internationally uniform data.

[17] H0, H1 and H2.

[18] These additional nine HS codes refer to *Machines for the manufacture of Wafers* (HS 848610), *Machines for the manufacture of Semiconductors* (HS 848620), *Parts of Machines* (HS 848690), *Parts of Cells and Modules* (HS 854190), *DC Generators with output less than 750W* (HS 850131), *DC Generators with output equal or more than 750W* (HS 850132), *AC Generators* (HS 850161), *Inverters* (HS 850440) and *Part of Inverters* (HS 850490). The HS code 848620 refers to the machines required for the production of cells and modules.

Finally, HS codes related to feedstock are included focusing on the cSi based PV panel composition, considering, in particular, the share of each relevant material in the total weight of the PV panel (Latunussa et al., 2016)[19]: *Low-purity Silicon* (HS 280469), *Hydrochloric acid* (HS 280610), *Back sheet* (HS 392062), *Solar glass* (HS 700719), *Silver paste* (HS 710692) and *Aluminium paste* (HS 760310), *Organic surface agents* (HS 340219) and *Aluminium structure* (HS 761090). Overall, we end up with 20 HS codes covering the whole PVSC.

The technological dimension

Once the production side was traced, we relied on patent data to identify the corresponding technologies. We consider patents belonging to the IP5[20] patent families, i.e., patents protected by at least two IP offices worldwide, one of which is part of the Five IP offices (IP5), namely the European Patent Office (EPO), the Japanese Patent Office (JPO), the United States Patent and Trademark Office (USPTO), the Korean Intellectual Property Office (KIPO) and the People's Republic of China National Intellectual Property Administration (CNIPA). In order to maximize the coherence with respect to the mapping based on trade data, we focus on the period 2007-2019 relying on three-year moving averages.[21]

As for the trade/production side, the technological mapping is based on a thorough literature review. Some studies make use of the Cooperative Patent Classification (CPC) to map PV patents. The CPC dedicates an entire section (Y02E) to environmental related patents (Angelucci et al., 2018), identifying solar PV technologies through the Y0E 10/70 class (Kangas et al., 2021). Unfortunately, the OECD patent database exploited in this exercise only provide the International Patent Classification (IPC)[22] codes used to distinguish different technologies. Among the contributions relying on the IPC classification, Wu and Mathews (2012) analyse solar-related patents filed in Taiwan, Korea and China between 1984 and 2008, detecting 12 6-digit IPC[23] subclasses linked to these technologies by distinguishing between three different technological trajectories (generations), i.e. 1G, 2G and 3G, which differ in terms of the material used for PV cells production (Conibeer, 2007; Rozanski et al., 2013).[24]

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[19] The weight considered within our PV supply chain amounts to almost 94% of the total weight and includes all the most relevant product and raw materials.

[20] In its 2016.01 version, the IPC divided the universe of patentable technologies into 8 main sections (A-H) under which are detailed levels of 130 classes (3-digit level), 639 subclasses (4-digit level), 7434 groups (5-digit level), and 65,152 subgroups (6-digit level). 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 IPC codes which is the most granular level of analysis possible given the availability of data.

[21] Note that data on 2020 and 2021 have been dropped due to missing observations.

[22] https://www.wipo.int/classifications/ipc/en/

[23] 1G: E04D13 (Roof covering aspects of energy collecting devices); H01L21 (Processes or apparatus adapted for the manufacture or treatment of semiconductor or solid state devices or of parts thereof); H01L31 (Semiconductor devices sensitive to infra-red radiation, light, electromagnetic radiation of shorter wavelength or corpuscular radiation and adapted either for the conversion of the energy of such radiation into electrical energy or for the control of electrical energy by such radiation); H02N6 (Generators in which light radiation is directly converted into electrical energy); C30B15 (Single-crystal growth by pulling from a melt, e.g. Czochralski method); C30B28 (Production of homogeneous polycrystalline material with defined structure); C30B29 (Single crystals or homogeneous polycrystalline material with defined structure characterized by the material or by their shape).
2G: C23C14 (Coating by vacuum evaporation, by sputtering or by ion implantation of the coating forming material); C23C16 (Chemical coating by decomposition of gaseous compounds, without leaving reaction products of surface material in the coating, i.e. chemical vapor deposition (CVD) processes).
3G: H01G9/02 (Organic semiconducting electrolytes); H01L51

[24] The first PV cell generation (1G) is a silicon wafer, which adopts a crystalline silicon wafer to absorb sunlight. The second generation (2G) is thin-film cells, in which semiconductor materials are used to absorb light. The third PV cell generation (3G) adopts some emerging materials combined in tandem structures to increase conversion efficiency. Crystalline silicon PV technology currently accounts for 95% of the global market because of its high conversion efficiency and its extensive manufacturing base.

Focusing on 3G PV inventions, Lizin et al. (2013)[25] documents that the top 5 most frequently used IPC codes originate from the 7-digit "H01L-031" class.[26] More recently, Martínez-Sánchez et al. (2022) show that about 77% of 3G solar energy inventions are concentrated in the 4-digit groups F03G and F24S, i.e., "Steam engine plants, steam accumulators, engine plants not otherwise provided for, engines using special working fluids or cycle". Trappey et al. (2019) apply a machine learning approach to examine 2.280 patents filed between 2008 and 2018 and retrieved from the Derwent Innovation search platform. Three distinct phases are considered: (i) energy generation, (ii) supply and (iii) storage systems for solar power. The analysis shows that the leading IPC classes are H02S (converting infrared radiation, visible light or ultraviolet light to generate electrical power), H02J (circuit devices or systems for power supply or distribution, and electrical energy storage systems), H01L (semiconductor devices or electric solid devices), F24J (heat generation devices). Exploiting the same statistical source, Sampiro et al. (2019) find that, out of 22,682 PV solar patents deposited between 2004 and 2013, the highest concentration of PV-related documents (77.95%) is related to the H01L[27] code, followed by the subgroups H02N (subclass: H02N-006/00) (8.24%) and E04D (subclass: E04D-013/18) (4.82%).

Adopting an approach similar to that followed in this paper, Kalthaus (2019) used various combinations of keywords to associate 4-digit IPC codes with the different stages of the PVSC, distinguishing between components - Photovoltaic cells, Modules and encapsulation and Balance of System - and PV technological generations (1G, 2G and 3G). In the same vein, Shubbak (2019) assigned IPC classes to six different PVSC components, i.e. Panels, Solar cells, Electronics, Energy storage, Portable powered devices, Testing and monitoring technology. Finally, relying on a broader definition of the PVSC (Zhang and Gallanger, 2016), Binz at al. (2017) associate IPC codes with three different segments of the PV production chain: up, mid and downstream. As a result, the number of PV-related IPC codes increases due to the wider definition of the SC.

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[25] More specifically, they focus on organic photovoltaic solar (OPV) cells, which are an alternative technology to silicon based solar cells from which they differ due to their potential of high-speed processability at low temperatures in ambient atmosphere, which allows for the production of large area solar cells on flexible, lightweight substrates using existing, easy techniques.

[26] Semiconductor devices sensitive to infra-red radiation, light, electromagnetic radiation of shorter wavelength, or corpuscular radiation and specially adapted either for the conversion of the energy of such radiation into electrical energy or for the control of electrical energy by such radiation.

[27] Subgroups: H01L-031/042, H01L-031/18, H01L-031/04, H01L-031/052, H01L-031/048, H01L-031/00, H01L-031/05, H01L-031/0224

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

HS Code	Commodity description	GSC stage	IPC code	IPC notes
280461	*Silicon, containing by weight not <99.99% of silicon*	UP	C23C	*CVD (chemical-vapor-deposition) method*
280469	*Silicon, containing by weight <99.99% of silicon*	UP	C01B	*Silicon; Compounds thereof*
280610	*Hydrogen chloride (hydrochloric acid)*	UP	C30B	*Production of homogeneous polycrystalline material with defined structure*
848610	*Machines & apparatus for the manufacture of boules/wafers*	UP	B28D	*Working stone or stone-like materials by sawing*
848620	***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***
848690	*Parts & accessories of machines & apparatus within HS codes 848610 & 848620*	UP	G01R	*Arrangements for testing electric properties*
381800	*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*
340219	*Organic surface-active agents...*	MID	H01L	*Special surface textures*
392062	*Plates, sheets, film, foil & strip, of poly(ethylene terephthalate)...*	MID	H01L	*Protective back sheets*
700719	*Toughened (tempered) safety glass, n.e.s. in 70.07*	MID	H01L	*Double glass encapsulation*
710692	*Silver (incl. silver plated with gold/platinum), in semi-manufactured forms*	MID	C03C	*Glass frit mixtures having non-frit additions, containing free metals*
760310	*Powders of non-lamellar structure, of aluminium*	MID	H01B	*Conductive material dispersed in non-conductive organic material, comprising metals or alloys*
761090	*Aluminium Structures & parts of structures...*	MID	H02S	*Structural details of PV modules other than those related to light conversion, Frame structures*
854140	***Photosensitive semiconductor devices, incl. photovoltaic cells whether/not assembled in modules***	MID	**H01L**	***PV modules or arrays of single PV cells***
854190	*Parts of the devices of 85.41*	MID	H01L	*Electrodes*
850131	*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*
850132	*DC generators (excl. generating sets), of an output >750W but not >75 kW*	DOWN	H02S	*Electrical components, comprising DC/AC inverter means associated with the PV module itself*
850161	*AC generators (alternators), of an output not >75kVA*	DOWN	H02S	*Electrical components, comprising DC/AC inverter means associated with the PV module itself*
850440	***Static converters***	**DOWN**	**H02M**	***Details of apparatus for conversion***
850490	*Parts of the machines of 85.04*	DOWN	H02J	*Arrangements for parallelly feeding a single network by two or more generators, converters or transformers*

Given the data at hand, our selection of patents combines Binz at al. (2017) and Shubbak (2019)'s IPC identification strategies, providing a final, comprehensive list of 4-digit codes. In particular, starting from the list proposed by Binz at al. (2017), we select those codes matching with the keywords used by Kalthaus (2019).

We further check the robustness of our selection by verifying the correspondence with the PV-related IPC codes identified by Shubbak (2019). The resulting selection comprehends 9 4-digit IPC subclasses including 214,458 IP5 patents filled during the period 2007-2019. About 87% of these applications originate from China, the EU, Korea, Japan and the US, lending further support to the country selection operated relying on trade data.

Finally, the matching between trade/product-level and patent data is completed by identifying two additional codes by means of a textual analysis. More specifically, for the HS codes with respect to which the literature does not provide a corresponding IPC class, we relied on relevant keywords to associate the appropriate patent code.[28] The final outcome of our mapping of the cSi PVSC is presented in Table 1 and results in the combination of 20 6-digit HS with 11 4-digit IPC codes.

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

As disruptions in GVCs are becoming commonplace, the empirical literature on SDs is flourishing (see, among others, Bonneau and Nakaa, 2020; Baldwin and Freeman, 2022; Arjona et al., 2023). In this work, we measure SDs building on Gehringer (2023), who has recently proposed an indicator, based on trade-data, to assess the global positioning of the EU. According to this author, 'reliance on foreign supply rises to the level of *strategic dependency* when three conditions are satisfied: 1) a country or region is a net importer of a good; 2) the country or region receives more than 50% of its total imports of the good from a single partner; and 3) the partner in question possesses at least 30% of the global trade share for the good. Thus, under strategic dependency, the exporter is a dominant player in the global market, and it is difficult for the importing country or region in question to readily obtain the product elsewhere. We rely on this definition, proposing a synthetic indicator of import dependency, IDEP, which combines the three dimensions in the following way.

First, for each country i (China, the EU, Japan, Korea, and the US), segment v (up, mid and downstream), product k (k ∈ HS 6-digit {1,..,20}) and year t (2007-2021)[29], we compute the Net Balance (NB) as:

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

This first component (1) is then standardized to vary between 0 and 1 providing information on the relative surplus/deficit of the considered countries along the PVSC, taking into account their size. The second component aims at capturing, for each country/segment/product, the import share stemming from the main supplier j (j≠i) (IMP-MS):

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

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[28] Regarding *Silver paste* (HS 710692), 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 was associated with the IPC class H02S referring to 'structural details of PV modules other than those related to light conversion.'

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

Therefore, the second 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 PVSC.[30] 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:

$$EXPSH_{j,v,k,t} = \frac{EXP_{j,v,k,t}}{TOT\ EXP_{v,k,t}} \quad (3)$$

The three components are then combined to obtain a synthetic indicator providing, for each country and year considered, a proxy of SD, at the segment/product level. To avoid misrepresenting countries' relative positioning by giving too much weight to the second and third component,[31] we rely on the following formula:

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

The IDEP is thus the measure we build upon to assess SDs along the PV supply chain for the 5 main players taken into consideration over the period 2007-2021.[32]

In parallel, to measure countries' technological positioning, we consider two main indicators. The first is the patent share over total patents by country i (China, Japan, 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). The second one is the Revealed Technology Advantage (RTA) indicator, which allows us to capture the evolution of countries' technological specialization. This indicator has been largely used in the literature to explore technological hierarchies and specialization in various domains (Meyer, 2006; Frietsch and Schmoch, 2010), including the PVSC (Fan et al., 2017). Formally, the $RTA_{c,w,t}$ indicates whether country c is specialized in technology w in year t or not. More specifically, the RTA is computed on patent applications filed in each country in each year and compares the relative frequency of patenting in a given technology (IPC class) w in country c with the relative frequency of patents in the same technology w at word level. Our aggregate is represented by the sum of patents filed by the group of countries considered for the analysis, which together are responsible for almost 95% of patents. Therefore, RTA is formulated as follows:

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

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[30] As we aim at building a synthetic indicator usable for multiple empirical objectives, we decided not to impose a predefined threshold to identify SD (for example, '50% of total imports of a [specific] good from a single partner', as in Gehringer, 2023).

[31] For example, avoiding the risk of considering highly vulnerable/dependent countries that, despite having a negligible deficit with respect to a specific product, rely on few (or a single) supplier which, in turn, holds a significant global market share. Even though such trade relationships may seem risky, the small size of the deficit tends to suggest relative autonomy and strong production capabilities.

[32] Note that sensitivity analyses relying on slightly different formulation of the IDEP - including a weighted average according to which the three components (NB, IMP-MS and EXPSH) are weighted, respectively, by 0.5, 0.25 and 0.25 - have been carried out and empirical results are not affected. Results are provided in the Appendix.

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 $RTA_{c,w,t}=1$ represents a threshold of specialization: when $RTA_{c,w,t} > 1$, the country is said to be specialized in technology w while the opposite holds when $RTA_{c,w,t} < 1$.

4. Empirical analysis

Two are the main stylized facts characterising the recent history of the solar industry: massive growth[33] and increasing fragmentation of the SC (Zhang and Gallagher, 2016; Yuan, 2022). In what follows, we rely on our mapping procedure, unique database and indicators to assess: i) SDs across the PVSC, carrying out an 'intelligence activity' aimed at identifying key segments/products with respect to which countries are most vulnerable; ii) persistency/mobility of countries' relative positioning; iii) the role of knowledge and technology, analysing the evolution of hierarchies and the relationship between technological capabilities and SDs; iv) role of technological capabilities and specialisation in shaping SDs.

4.1. Assessing trade dependence along the PV supply chain

Our investigation of the PVSC starts with an analysis of the evolution of countries' competitive positioning, focusing on export shares both total as well as distinguished by SC segment (down, mid and upstream). Figure A1 (Appendix) reports the distribution of the PV-related total export shares over the considered time period. Overall, the five economies included in our sample represent around 70-80% of the global market, lending support to the robustness of the country selection. Some key patterns are documented: the "rise of China" (from 15% in 2007 to almost 25% of export share in 2021), the relative stability of the EU and Korea, and the relative step back of the US (mild) and Japan (substantial).

The PVSC is distinguished between up, mid and downstream in Figure 1. China's performance is fundamentally driven by its consolidation in the down and, even more so, in the midstream of the VC. In these segments, virtually all other countries lose positions vis-à-vis China, 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 shares, in this segment China shows a less astonishing performance as compared to other segments. On the contrary, the EU reports a substantial increase in export share moving from around 13% to close to 23%. This may reflect a 'complementarity' between the growing dominance of China in the mid and downstream, and the consolidation of the EU as supplier of key upstream goods (e.g., machineries).

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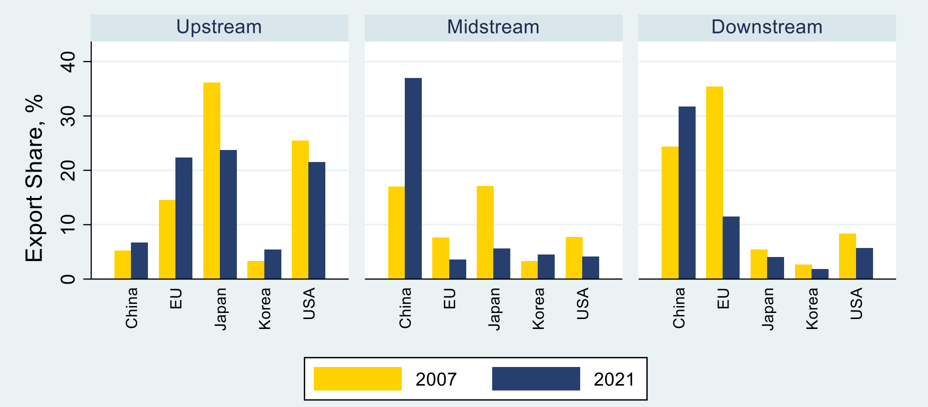
[33] Between 2005 and 2019, international trade – imports plus exports – in some of the most important PV supply chain components almost tripled, from around 110 billion (USD) to more than 300 billion, with an annual growth rate of around 7% compared to 4% for manufactured goods in general (Gahrens et al., 2021).

Figure 1. PV supply chain by segment (up, mid and downstream), export shares (2007 vs 2021)



Source: Authors' elaborations based on the UN Comtrade database

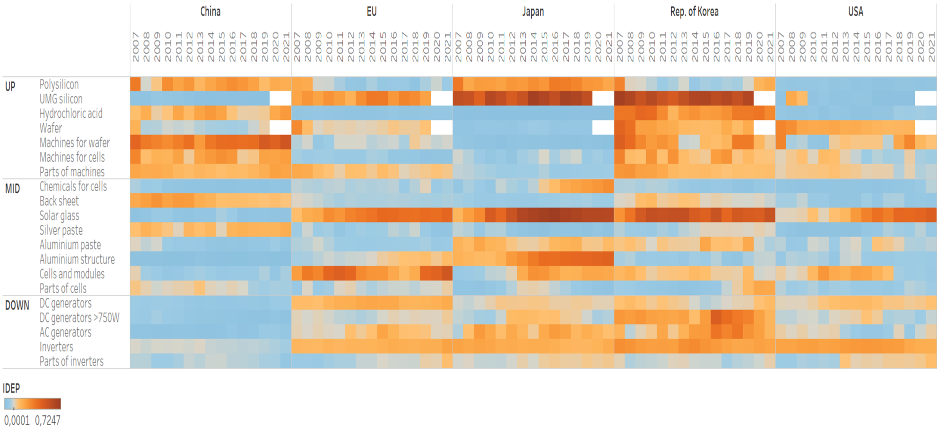
We now move more closely to the assessment of SDs by exploring the different components of the IDEP indicator (4). Figure 2 shows the evolution of the NB (1) in the various segments of the supply chain between 2007 and 2021 (left axis). To provide a more comprehensive picture, bilateral import shares are also included (right axis). The EU and the US display rather similar dynamics, mirroring the substantial consolidation of China, particularly in the mid and downstream segments. Both report a deficit (the EU enters negative territory in 2014 concerning the downstream) in those segments with China being their main supplier

Figure 2. 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.

However, while the Chinese import share keeps increasing in the EU case, a 'decoupling' dynamic seems to emerge with respect to the US. This process might be partly related to the anti-dumping policies introduced by the US International Trade Commission (ITC) since 2012. In about a decade (2011-2021), in fact, the Chinese share of US imports fell from 35% to 8% in the midstream and from 40% to 25% in the downstream, which is still the most exposed segment as far as the United States is concerned.[34] As a result, the EU's position may be considered relatively worse than the US one regarding SDs vis-à-vis China. In the midstream, the EU trade deficit reaches record levels, with a peak of 30 billion per year, paired with Chinese supplies which then came to exceed 60% of total EU imports and are currently projected towards 80% (in the downstream, the China' share of EU imports gets close to 60% in 2021). On the other hand, China shows a growing deficit in the upstream (confirming the evidence provided in Figure 1) but, at the same time, a rather good degree of diversification as its three main suppliers (the EU, Japan and the US) hold fairly similar import shares. Therefore, the Chinese SDs in the upstream, albeit being quantitatively consistent, are to a certain extent counterbalanced by a relative diversification in terms of suppliers. Japan stands out as the less dependent actor along the entire PVSC, with an impressive net export performance in the upstream and a fair hold in the segments where Chinese manufacturing dominance is felt most strongly. Finally, Korea, which shows a relatively small amount of trade in comparative terms, seems to be import dependent in the up and downstream segments (where China is, by far, the dominant supplier) while displaying a surplus in the midstream. We now inspect the evolution of the IDEP for each country and segment/product over the considered time period (2007-2021). Figure 3 provides a heatmap turning to dark red as SDs become more intense.[35]

Figure 3. Import Dependency Index (IDEP), by country, segment and product (2007-2021)



Source: Authors' elaborations based on the UN Comtrade. 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.

This allows us to carry out the first step towards what Edler et al. (2023) refers to as an 'intelligence activity', aiming at identifing critical industries/segments/products (and related trends) that might become the

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[34] It should be noted that Chinese producers have managed to outsource production to other countries that are not affected by US anti-dumping policies, namely Taiwan (Nguyen and Kinnucan, 2019) but also Malaysia, Vietnam and Thailand.

[35] As a robustness check, the same Heatmap based on alternative computations of the IDEP – weighted averages used as weighting parameters of the three components, respectively, 0.5, 0.25 and 0.25 – is provided in the Appendix (Figure A2).

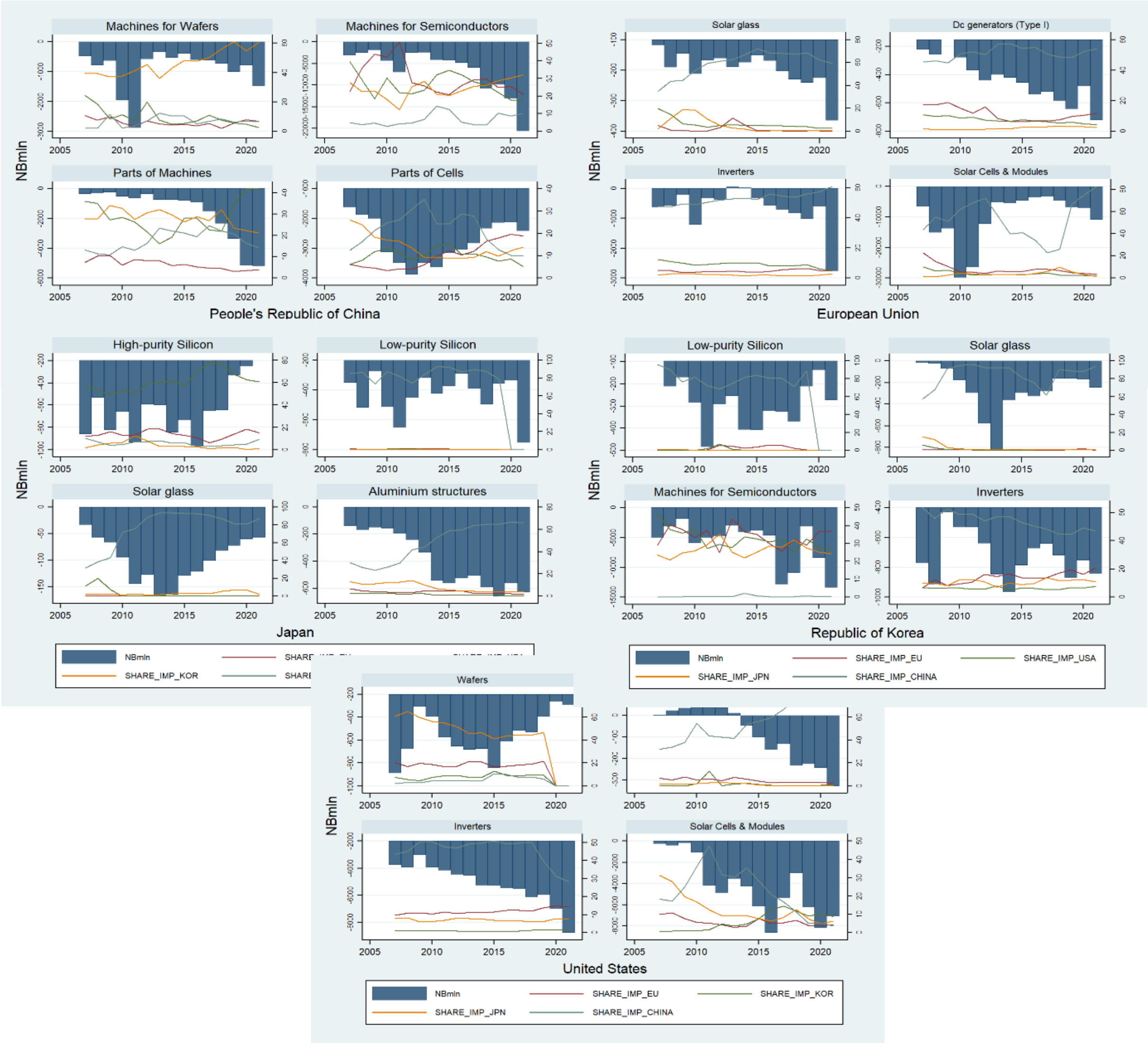
privileged target of specific industrial policy initiatives. Focusing on the upstream sector, China displays a certain degree of dependence with respect to *Polysilicon, Hydrocloric acid* and, more relevantly, *Machineries* (for wafer and cells). This is mirrored by the rather good position of the EU, which seems to maintain a stronghold in the PV-related 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 with respect to *Wafers* and *Machineries*. Korea, probably due to its relatively smaller size, reports a significantly more intense SD all across the upstream.

Moving to the midstream segment, the situation changes. China displays a strong position except for *Back sheet* and *Silver paste*, where a mild import dependency is detected. In turn, *Solar glass* seems to be an issue for all countries but China, as dark red tend to dominate almost everywhere over the considered time span. For the EU, the most serious 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 import dependency is documented with respect to *Aluminium paste* and *Chemicals for cells*. Remarkably enough, the US seems to have reduced its SDs, particularly regarding cells, modules and aluminium paste. As argued above, such dynamics could be partly related to the aggressive trade policy the US government has pursued during the last ten years, explicitly aimed at reducing SDs (Nguyen and Kinnucan, 2019). Even in the midstream, Korea displays a stronger SD as compared to the other countries with the only exception of *Aluminium structures* and *Part of cells*.

As it stands, the downstream segment of the PVSC seems to be "China's reign". It shows an extremely low IDEP level with respect to all critical products, which, in turn, are essential for the functioning of the whole SC (e.g., *Inverters*). On the other hand, the EU, Japan and 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.

SD is not only a matter of quantity, i.e. degree of import dependency, but also of quality or, more precisely, of the critical nature of goods/assets with respect to which a country has no productive autonomy (or is trapped in one-sided dependence). To address this crucial element, we now zoom-in on the products for which the stronger SDs are detected, also considering their relevance within the PV production chain. The analysis is carried out country-by-country 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%.

Figure 4. Strategic dependencies, by country and specific product (2007-2021)



Source: Authors' elaborations based on the UN Comtrade database.

Figure 4 reports the four products with respect to which our economies show the most intense SDs. The EU and the US show similarities in terms of SDs. As expected, their problems are to a large extent concentrated in the mid and downstream segments, where a relatively strong import dependence is detected concerning critical goods such as *Cells and modules* and *Inverters* (in addition to *Solar glass* and *DC generators* for the EU, *Solar glass* and *Wafers* for the US). In turn, significant differences emerge regarding the degree of diversification. While China is by far the main supplier of the EU with respect to all products for which a critical dependence is detected, the same is not true in the US case. With the exception of *Solar glass*, the US managed to reduce the relative share of Chinese import and significantly diversified its portfolio of suppliers.[36] China's situation is antipodal to that of the US and EU. Critical dependence is concentrated in the upstream, concerning *Machineries for wafers* and *Semiconductors* (in addition to *Parts of cells*). Similar to the US,

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

however, China shows quite a diversified portfolio of suppliers, with the exception of Japan, holding a 50% share of the total imports of machineries for wafers. On the other hand, Japan shows a relatively small deficit all across the products included in the list of the most critical SDs. Nonetheless, a certain degree of import 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, Korea's most serious SDs are dispersed along the entire SC and are characterized by a very limited degree of supplier diversification.

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

To provide a more thorough examination of changing hierarchies along the PVSC, we rely on Transition Probability Matrices (TPM), assessing whether or not economies characterized by a high level of SD are able to break out of that condition. Persistence (mobility) is examined focusing on the IDEP terciles, the latter proxing, respectively, low (1st tercile), medium (2nd tercile) and high SD (3d tercile). Events are modelled by a three-state Markov chain with transition probabilities. Each term of the (3X3) TPM is the conditional probability *p* of moving from state (tercile) j to state i. 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).

Table 2 reports the TPMs. As expected, the IDEP indicator is characterized by a strong degree of persistence. Irrespective of the considered segment of SC, 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 to improve 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. 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 of the SC.

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

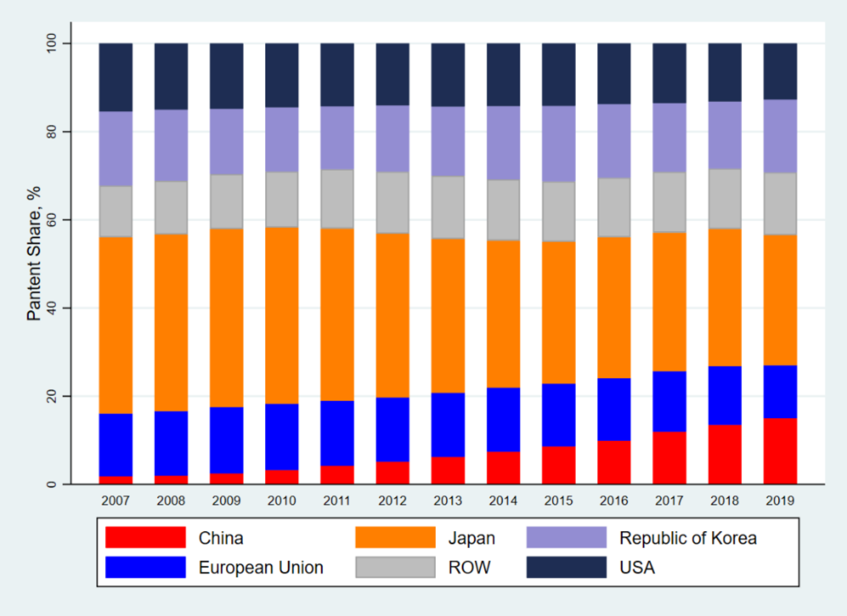
PVSC				**Upstream**			
	Low (1st tercile)	*Medium (2nd tercile)*	*High (3d tercile)*		*Low (1st tercile)*	*Medium (2nd tercile)*	*High (3d tercile)*
Low (1st tercile)	0,87	0,13	0,00	*Low (1st tercile)*	0,84	0,16	0,00
Medium (2nd tercile)	0,13	0,77	0,09	*Medium (2nd tercile)*	0,06	0,88	0,06
High (3d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

Therefore, while the path-dependent nature of SDs is confirmed, the possibility of changing its relative position seems to be more plausible in segments characterized by a relatively lower technological intensity (i.e., mid and downstream). A potential explanation may point to the lower complexity of the 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 and movements along the production chain. On the other, it confirms the urgency of implementing selective industrial policies capable of mitigating SDs that, given their path-dependent nature, may become very difficult to reverse.

4.3. The role of knowledge and technology

The evolution of technological capabilities along the PVSC is investigated by looking, first, at the dynamics of patent shares relying on the IPC classes included in the mapping reported in Table 1. Second, we focus on changes in relative technological specialization using the RTA index. Figure 5 displays, for the five economies included in our sample, a three-year moving average of PV-related patent shares referring to the period 2007-2019. Given their inherently cumulative nature, knowledge stocks (as proxied by patent shares) tend to show (relatively) stable distributions. When it comes to the PV industry, however, things have changed significantly over the last two decades.

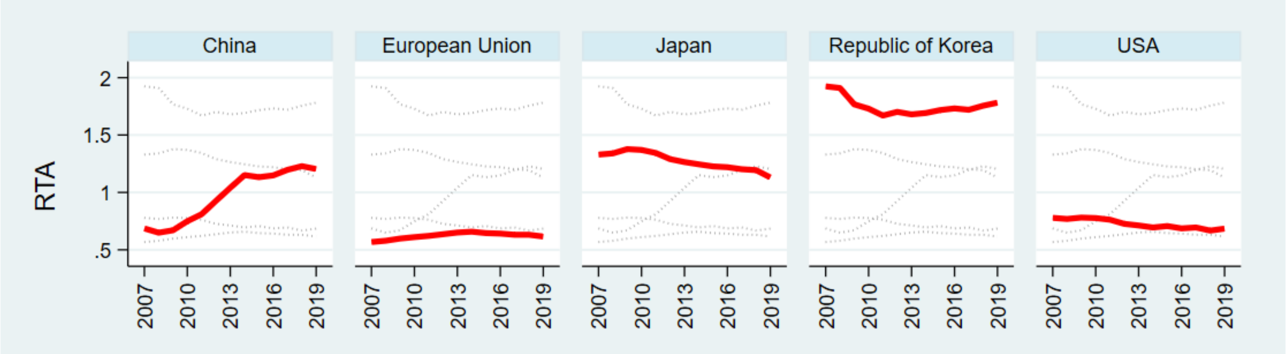
Figure 5. PV-related Patent share by country (three-year moving average, 2007-2019)



Source: Authors' elaborations based on the OECD Patent database, IP5 patent families.

First, in line with the evidence emerging from the analysis of trade data, a fast and substantial consolidation of China's position is observable. As for the remaining players, the hierarchy has not changed significantly. The EU moderately reduced its share, similarly to what happened in the US. At the top of the ranking, Japan retains its leadership and Korea does the same with reference to its relative patent share.

Figure 6. Revealed Technology Advantage (RTA) index, by country (2007-2019)



Source: Authors' elaborations based on the OECD Patent database, IP5 patent families.

To further inspect the relative positioning of countries, we now focus on specialization patterns (Figure 6). Japan and, especially, Korea turn out to be highly specialised in solar technologies. China, in turn, is consolidating its position also in terms of relative specialization, with the RTA 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 all along the considered time span. Therefore, the main patterns reported concerning trade dynamics and SDs seem to find confirmation as far as technological capabilities and relative specialization in solar technologies are concerned. Mirroring the analysis carried out with respect to the IDEP (Figure 3), the long-term evolution of countries' relative technological specialization is investigated by looking at different segments/products of the PVSC. For each country/product pair, the heatmap (Figure 7) turns dark blue as the specialization in corresponding technologies is relatively more intense; while the opposite holds when the colour is orange or, at the extreme, dark orange.[37]

Focusing on the upstream, Japan shows the highest level of specialization (apart from technologies related to *Generators*), followed by 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 relatively poor specialization (with the exception of *Machines for wafer* and *Parts of machines* in the EU case). That is, the relatively good positioning of both countries/geopolitical areas in the upstream segment concerning trade dynamics (see Figure 3) does not seem to be paralleled by an equally good performance in technological specialization. On the contrary, China is characterized by a process of growing specialization in those technological fields, i.e. those related to *Machineries for cells and wafers,* where it still displays a certain degree of import dependence (see Figure 4). This could mean that, in parallel with a diversification strategy aimed at reducing SDs in the upstream, China is performing a technological catching up which may help strengthen its productive capabilities in the same segment of the SC.

In the midstream, the hierarchical structure is fairly similar. Japan stands out as the most specialized (excluding technologies related to aluminium paste), followed by Korea, which, in turn, displays some weaknesses regarding *Silver paste* and, again, *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*.

Finally, the hierarchy changes as we move towards the downstream. China is taking over Japan as the most specialized economy in solar technologies. Japan and Korea, in turn, show a significantly lower level of specialization with the exception of, respectively, *Inverters* (Japan) and *Parts of inverters* (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. Such weakness matches the import dependence (vis-à-vis China) reported in Figure 4. Analogously, the US is de-specialized all along the downstream with the lowest levels of RTA registered with respect to *Inverters*.

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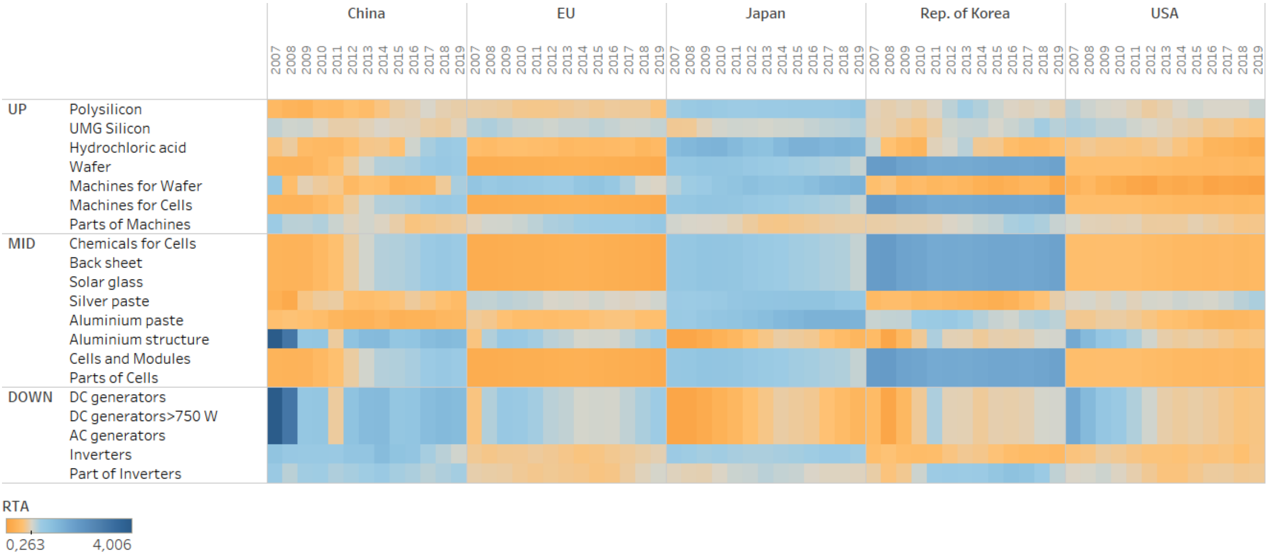
[37] Note that a more precise investigation of the linkage between technology (patent) classes and product codes could be possible as long as a more granular (text-based) analysis, based on more disaggregated patent-level information, is carried out. At present, data limitations do not allow this type of investigation.

Figure 7. RTA index, 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.

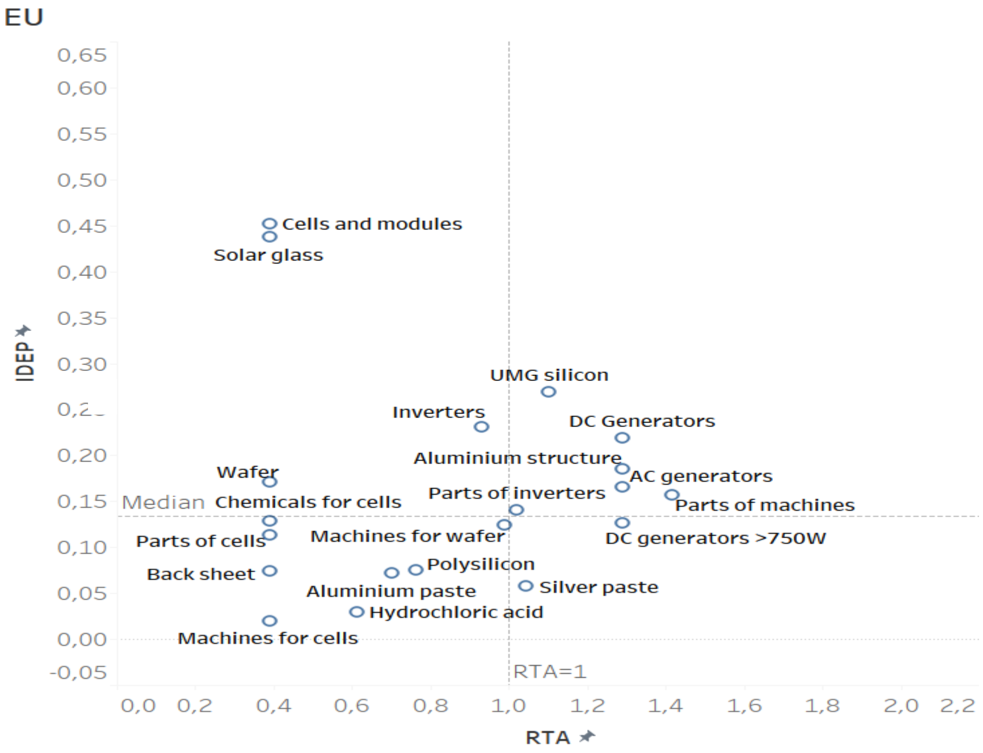
The joint analysis of indicators based on trade and patent data allows us to pursue a further step in our 'strategic intelligence' analysis by investigating the relationship between technological capabilities and specialization, on the one hand, and the degree of SDs along the PVSC, on the other. To this end we, first, descriptively combine the analysis of IDEP and RTA indicators. Figure 8 provides, for the EU, the US and China (2019), a 4-dial diagram characterizing products as follows: i) high IDEP-low RTA (i.e. critical situation needing action to strengthen both production and technological capabilities), top-left; ii) high IDEP-high RTA (i.e. reinforcing production capacity may be necessary but is potentially facilitated by technological specialization), top-right; iii) low IDEP-high RTA (i.e. economies are on the safe side as both productive and technological capabilities are available), bottom-right; iv) low IDEP-low RTA (i.e. although SDs are not detected, poor technological specialization may be exposed to risks related to unexpected changes concerning process and product innovations), bottom-left quadrant.

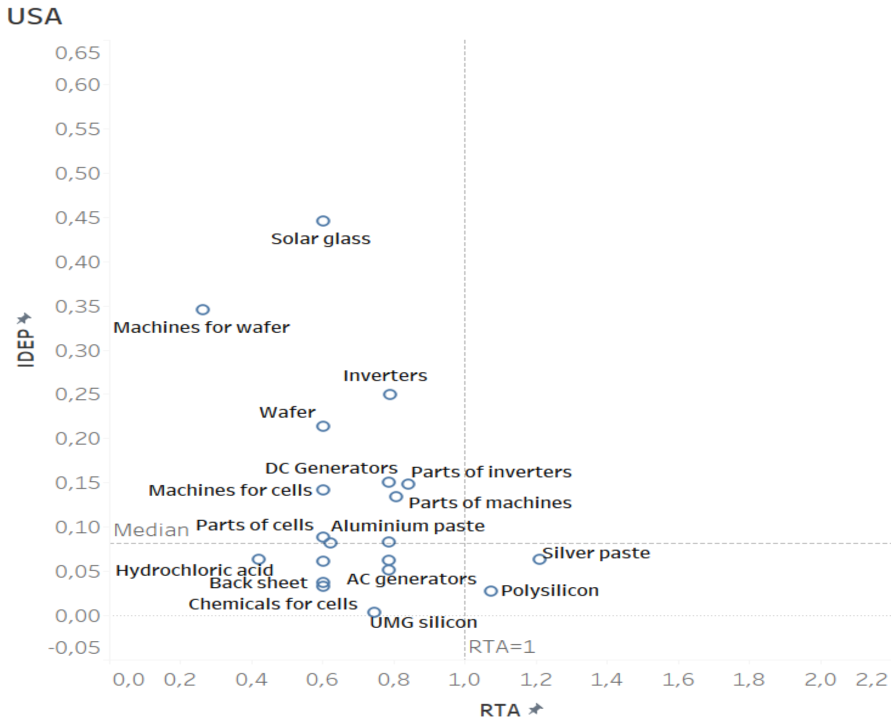
Focusing on the top-left quadrant, the EU faces a highly critical situation with respect to *Cells and modules*, *Solar glass* and *Inverters*. A similar situation is detected looking at the US, which, however, is relatively better positioned concerning *Cells* and worse off as regards *Wafers* and related machineries. These areas are those for which selective industrial and innovation policies seem to be more urgent. Moreover, the evidence provided in Figure 8 highlights, again, 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). The same outcome is found in EU countries, with again only two products (Polysilicon and DC generators) located in the "safer" part of the diagram.

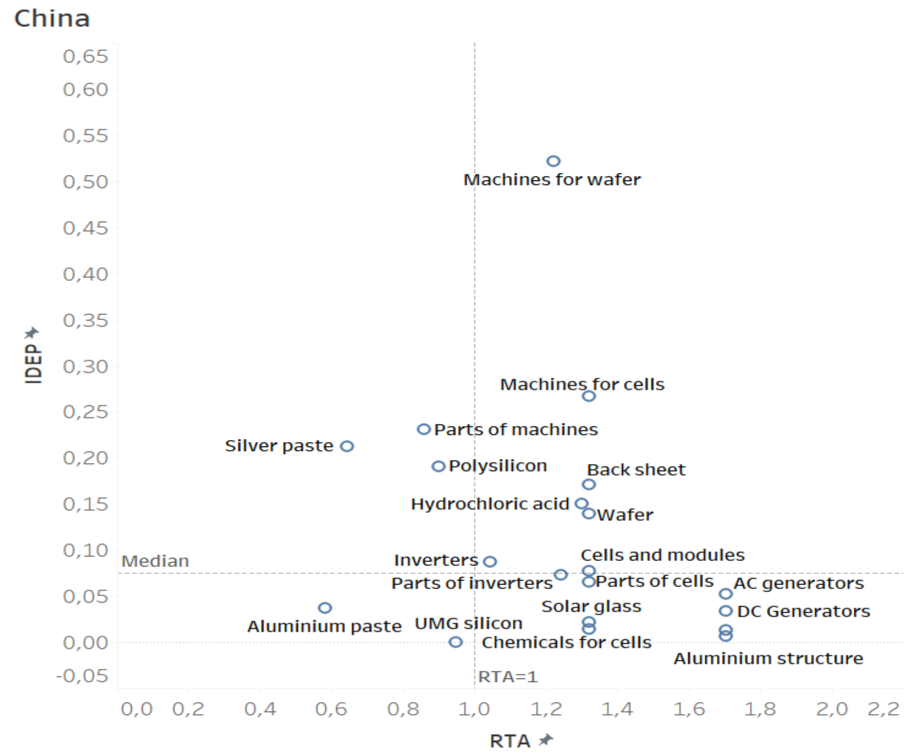
In contrast, for China most of the considered products belong to the bottom-right quadrant, while the critical goods for which China shows the most worrisome levels of SD (*Machines for wafers* and *Machine for cells*) are counterbalanced by high RTAs in the corresponding technologies. This is a sign of China's directed effort to close the gap and gain competitiveness also in these segments. Moreover, 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 Korea in the Appendix (Figure A3), evidencing that Japan has only two products facing a highly critical situation (high IDEP-low RTA), while Korea is badly positioned as regards *Inverters*, *Machineries for wafers* and *Hydrocloric acid*.

Figure 8. The four-dial representations of the IDEP-RTA relation (2019), Europe, 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.

4.4. Dynamic Ordered Probit Model

We now explore the probability of a country moving from a lower to a higher level of SD, applying a *discrete choice ordered model approach* and controlling for both persistence and innovation patterns. We rely on a Dynamic Ordered Probit model based on the estimator proposed by Wooldridge (2005). Though TPMs (Tab.2) provide summary evidence on the relative persistence of regional SD patterns with respect to key commodies of the PV chain, the following analysis allows for a better identification of the actual influence of path-dependency and the role of PV-related technological capabilities.

The dependent variable is represented by IDEP terciles ($SD_{i,k,t}$), i.e. an ordered variable assuming value 1, 2 or 3 in period t if a country i belongs, for a specific commodity k, respectively to the first, second or third tercile of the IDEP distribution. Specifically, $SD_{i,k,t}$ is regressed against its past realization ($SD_{i,k,t-1}$), its initial value (SD_{i,k,t_0}) and the technological capabilities proxied by patent shares ($PAT - SH_{i,k,t}$) and technological specialization ($RTA_{i,k,t}$). To deal, as much as possible, with endogeneity problems related to observable and unobservable individual heterogeneity u_i, we follow Wooldridge (2005). Accordingly, we specify the distribution of the unobserved component u_i conditional on SD_{i,k,t_0} and on the country-specific time average technological controls. Said otherwise, we apply the first 'realisation' of the the depended variable (SD_{i,k,t_0}) and the time-averaged covariates ($\bar{X}_i$) 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. Therefore, the main specification runs as follows:

$$SD_{i,k,t} = \alpha_{i,k,t} + \beta * SD_{i,k,t_0} + \gamma * SD_{i,k,t-1} + \delta * PAT - SH_{i,k,t} + \eta * RTA_{i,k,t} + \theta * \bar{X}_{i,k,t} + \varepsilon_{i,k,t} \quad (6)$$

Standard errors are clustered at the country-level to account for structural heterogeneities, particularly those related to different industrial policy strategies. The 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.

Table 3. Dynamic Ordered Probit – 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.

Plausibly, where products are more complex and innovation represents a key competitive ingredient (upstream), technological specialization is associated with stronger productive capabilities and, therefore, lower SDs. 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 despite their technological specialization. Although simple and providing no causal evidence, this model confirms that SDs are a major policy concern because, other things being equal, economies can easily continue to worsen their relative position once a 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 the country-specific positioning along the PV SC. 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 reinforced in parallel.

Table 4. Dynamic Ordered Probit – IDEP (terciles) vs patent shares and RTA

	CHINA	**EU**	**JAPAN**	**KOREA**	**US**
	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.

5. Conclusions and policy implications

This paper sheds new light on the solar industry, providing a detailed analysis of its supply chain concerning both SDs and technological capabilities. The analysis confirms the importance of looking at these two dimensions in all relevant segments of the SC in order to identify areas (i.e. PV segments, product and technological domains where such capabilities need to be urgently strengthened) which can be considered 'critical' according to the TS perspective (Crespi et al., 2021; Edler et al., 2023).

The contribution is manifold and 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 SC, highlighting processes of polarization and growing SDs. 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. Our intelligence allows us to identify the critical areas where industrial and innovation policies are more urgently needed. Finally, the DOP model shows that a relatively strong technological specialization may help reduce SDs, but only in the upstream segment.

More specifically, the empirical evidence - focusing on China, the EU, Japan, 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. From a technological viewpoint, the EU still has some specialization with respect to generators and machineries, but is running out of time as China is close to catching-up. The US situation is even worse, despite some diversification of the portfolio of suppliers, especially in the downstream.

On the other hand, China is rising as one of the new dominant players of the SC, at least concerning trade dynamics. Most countries report substantial bilateral SDs vis-à-vis the People's Republic, particularly concerning critical mid and downstream products (e.g., solar Cells and modules, Wafers, Inverters). In terms of technological specialization, China is still closing the gap. However, its fast scaling up in the upstream, as in the case of machineries-related technologies, casts doubt on the ability of its competitors and, in particular, of the EU - once one of the undisputed technological leaders in the PVSC (Buigues and Cohen, 2023) - to maintain their positions in that segment and, hence, to reduce their SD. Remarkably enough, Japan still maintains a leading position in the industry, given its rather good trade performance, combined with an impressive technological specialization, characterizing the entire SC, but especially in the up and midstream segments.

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). However, 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. 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 production capabilities needed for the green transformation of the economy.

As suggested by Edler et al. (2023), TS does not represent an end in itself, but a means to achieving the central objective of innovation policy – sustaining national competitiveness and building capacities for transformative policies. In this respect, the increasing attention on issues related to SDs requires adapting the existing framework of industrial and innovation policies to consistently account for these issues, which means also achieving higher levels of coordination with trade and foreign policies. Within this framework, the PV industry will be one of the most relevant candidates to apply and test the effectiveness of the 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.

Appendix

Figure A1. The evolution of export shares in the PV global market

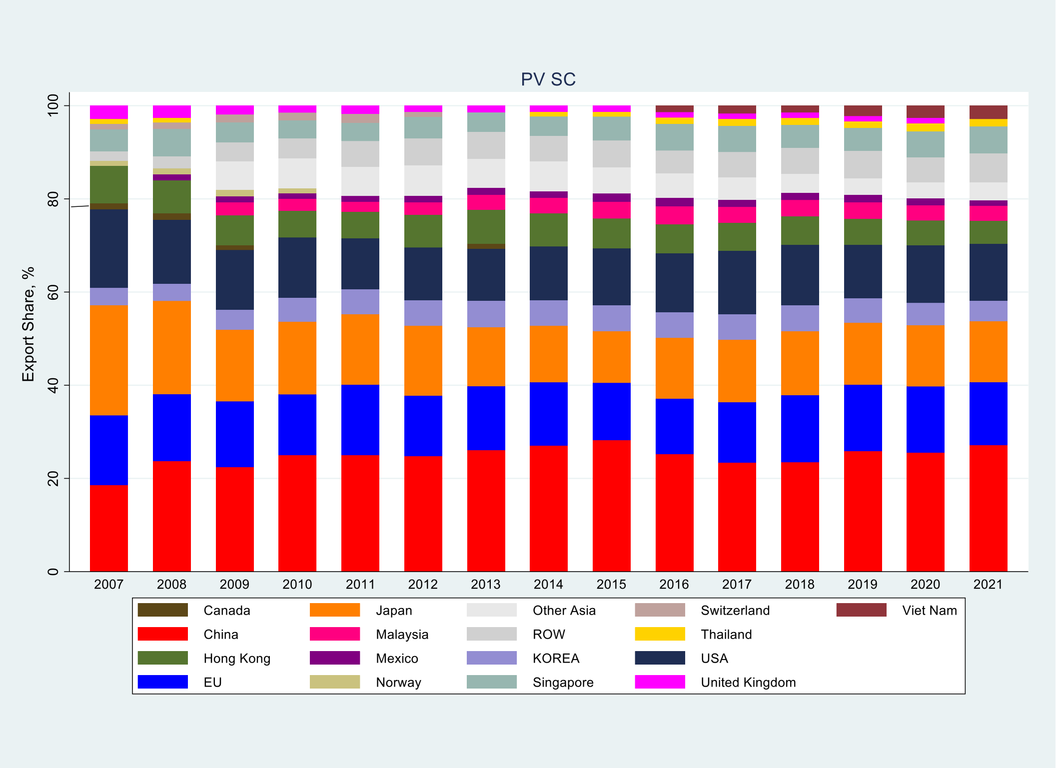


Figure A2. Import Dependency Index (IDEP) weighted, by country, segment and product (2007-2021)

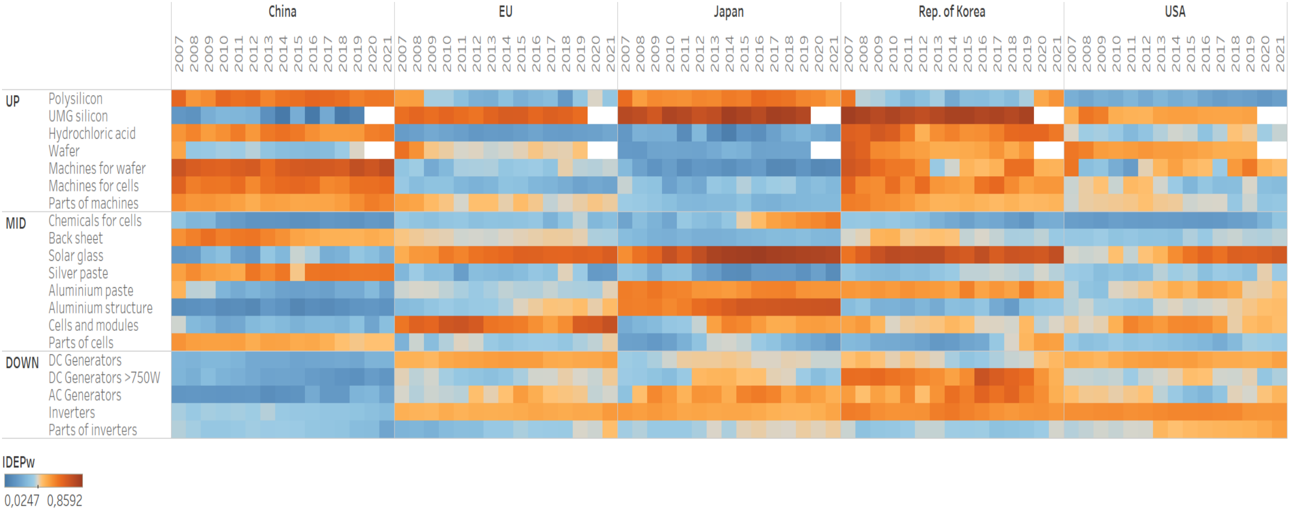
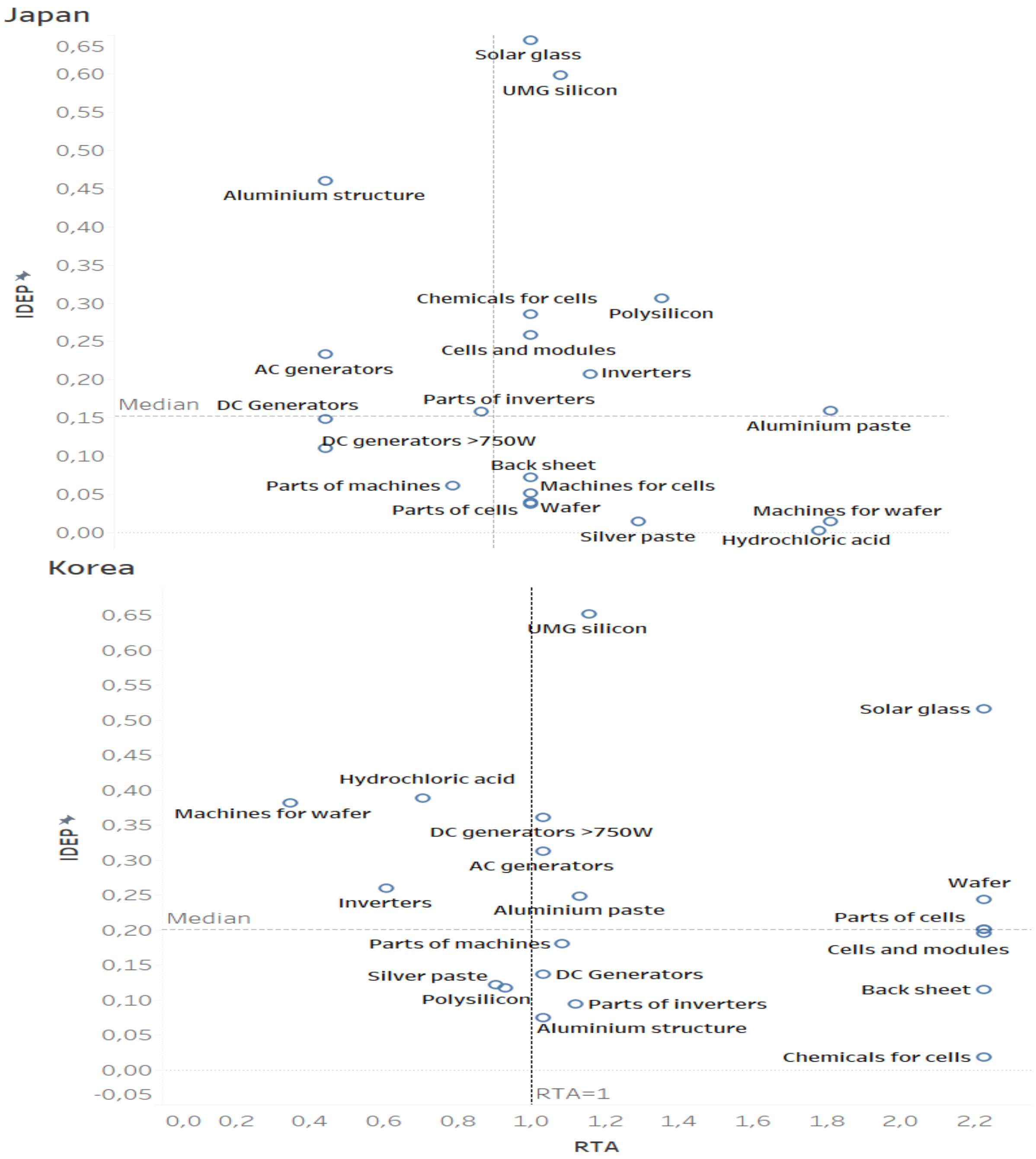


Figure A3. Thefour-dial representations of the IDEP-RTA relation (2019) – Japan and Korea



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