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Towards transformative leapfrogging

Xiao-Shan Yap[a,b,*], Bernhard Truffer[a,b,c], Deyu Li[c,d], Gaston Heimeriks[a]

[a] Copernicus Institute of Sustainable Development, Utrecht University, The Netherlands
[b] Department of Environmental Social Sciences, Eawag, Swiss Federal Institute of Aquatic Science and Technology, Switzerland
[c] Department of Human Geography and Spatial Planning, Utrecht University, The Netherlands
[d] Centre for Environment, Energy and Natural Resource Governance, Department of Land Economy, University of Cambridge, United Kingdom

A R T I C L E I N F O

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A B S T R A C T

Latecomer countries are increasingly confronted with the simultaneous challenge of achieving industry competitiveness and sustainability transitions. We revisit the long-standing debate on how latecomers may break free from the trajectories of the developed countries and leapfrog into more sustainable directions. Connecting insights from the fields of catching-up, socio-technical transitions, and economic geography, we propose a heuristic typology of four development pathways for latecomers. While the catching-up literature has focused on knowledge development as a main strategy, we posit that to address grand challenges, it is imperative for latecomers to implement valuation-focused strategies, which include shaping technology legitimacy, markets, and finance flows at the systemic level. We showcase the shifting trajectory of the Chinese solar photovoltaic industry from technology catching-up to forging ahead in pre-existing global value chains, and eventually towards transformative leapfrogging aimed at reconfiguring the entire socio-technical system of the electricity sector. We conclude with a research agenda for latecomer development.

1. Introduction

Transition studies began about a decade ago to seriously engage with sustainability transition challenges in the context of latecomer countries or regions (Coenen et al., 2012; for exception see Berkhout et al., 2009). Meanwhile, actual developments in green technology innovation, manufacturing, and deployment have spanned across the globe putting countries like China or India into pole positions of the corresponding value chains (Fu and Zhang, 2011; Lema and Lema, 2012; Meckling and Hughes, 2017; Surana et al., 2020; Sandor et al., 2021). Recently, the question of how grand challenges may provide 'green windows of opportunity' for latecomers to shift global leadership in cleantech sectors has attracted increasing interest among studies on latecomer catch-up (Yap and Truffer, 2019; Binz et al., 2020; Lema et al., 2020; Zhou et al., 2020; Gosens et al., 2021). These green windows of opportunity are perceived to emerge from a new long-term techno-economic development cycle (Perez, 2013; Mathews, 2013; Kaplinsky, 2022) or even the emerging traits of 'deep' sustainability transitions (Schot and Kanger, 2018), driven by the information and communication technologies (ICT) revolution and pressing environmental issues. However, given the primary focus on industrial competitiveness in extant catching-up studies (Amsden, 1989; Lee and Lim, 2001; Lee and Malerba, 2017), it remains unclear through which processes and mechanisms latecomers may achieve sustainability transitions at the same time.

In this article, we connect insights from the catching-up and leapfrogging research with nascent theorizing within sustainability

* Corresponding author at: Copernicus Institute of Sustainable Development, Utrecht University, the Netherlands
E-mail addresses: x.s.yap@uu.nl, xiaoshan.yap@eawag.ch (X.-S. Yap).

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transitions literature to explain how latecomers may shape new, more sustainable development trajectories to avoid replicating the pre-existing trajectories of old, industrialized countries. There has been a long-standing scholarly debate about whether latecomers could escape or bypass the polluting footsteps of the developed countries (Perkins, 2003; Angel and Rock, 2009; Berkhout et al., 2009; Berkhout et al., 2010). In fact, the notion of catching-up and leapfrogging has been criticized over the years. In many cases, latecomer countries either could not find alternative or more environmentally sustainable trajectories (Tukker, 2005; Rock et al., 2009; Schroeder, 2010) or do not find competitive positions in global industries due to the lack of technology transfer or upgrading, and hence remain trapped at middle-income levels (Gallagher, 2006; Rasiah, 2010; Binz et al., 2012; Lema and Lema, 2012; Schot and Steinmueller, 2018; Wieczorek, 2018; Yap and Truffer, 2019). Furthermore, several catch-up studies have recently discussed the urgency for fast-growing economies such as China to abort the catching-up mentality to escape the middle-income trap (Liu et al., 2017; Chen et al., 2021; Lee, 2021; Wu, 2022). We argue that, especially when considering the urgency for achieving sustainable development goals, the theorizing of leapfrogging must move beyond the current focus on global industrial or technological leadership in specific global value chains (GVCs) (Watson and Sauter, 2011) and start to embrace the transformation of entire sectoral systems.

The transformation of sectoral systems such as electricity, food, transport, sanitation, and health care to solve grand challenges requires the input from actors in broader industrial and institutional contexts (Bergek et al., 2015; Stephan et al., 2017; Malhotra et al., 2021). The traditional view of catching-up and leapfrogging based on knowledge accumulation in individual industrial sectors like automobiles and semiconductors (Lall, 1992; Kim, 1997; Lee and Lim, 2001; Mathews and Cho, 2007; Figueiredo, 2008; Yap and Rasiah, 2017a) is therefore not adequate. Additionally, serious engagements with local sustainability transitions are critical to solve grand challenges due to the contested nature of contextual problem identification and solving (Coenen et al., 2015a; Wanzenbock and Frenken, 2020), which in turn may support latecomer countries or regions to shape next-generation development trajectories. This is different from the conventional wisdom of leapfrogging in the existing catching-up literature, which aims to fit into pre-existing GVCs through, for instance, an export-oriented strategy and gradually upgrade along the predefined trajectories of those GVCs to achieve industrial leadership (Humphrey and Schmitz, 2002; Pietrobelli and Rabellotti, 2011; Lee and Malerba, 2017).

In the established literature on leapfrogging, value-related success conditions are mostly considered as exogenously provided by the global markets, which prescribe product characteristics and feasible innovation trajectories. Latecomers primarily act as cheap suppliers in existing GVCs of products for established socio-technical systems that have been invented elsewhere (Pietrobelli and Rabellotti, 2011; Lee and Malerba, 2017). Global markets therefore represent the external selection environment, which can hardly be shaped by latecomers. However, we argue that, to address grand challenges, latecomers will have to 'endogenize' the selection environment by proactively driving valuation processes in their local contexts (Yap and Truffer, 2019).

In the recent *geography of transitions* literature, scholars have been advocating a broader set of value concerns on innovation success (Jeannerat and Kebir 2016; Binz and Truffer, 2017; Hansen and Coenen, 2015). According to these studies, innovation success depends not only on the best available technological knowledge but increasingly on the ability to construct new workable 'socio-technical configurations', i.e., aligned technological and institutional structures that provide specific services reliably (Rip and Kemp, 1998). As a consequence, latecomers have to start simultaneously working on legitimation, guidance of search, resource mobilization, and market formation with the aim to create new socio-technical configurations to transform entire sectoral systems (Bergek et al. 2008; Hekkert et al., 2007; Binz and Truffer, 2017). The key resources for innovation success are therefore those that enable the alignment of new technologies with prevalent value concerns in society.

At the level of innovation policy, the focus on industry competitiveness and leadership coincides strongly with what scholars have identified as the 'second wave' of innovation policy, which prioritizes economic goals assuming that other societal needs would be solved through a trickle-down effect (Schot and Steinmüller, 2018). However, addressing grand challenges and achieving sustainable development require a new 'third' wave of innovation policy, which responds to a broader set of societal goals (Schot and Steinmueller, 2018). The success of innovations in this new wave will not only depend on the ability to manage top-notch technical knowledge but also to engage in multiple forms of 'valuation' of new products and services (Jeannerat and Kebir, 2016). In this context, the directionality of innovation development must be dealt with more explicitly (Weber and Rohracher, 2012; Yap and Truffer, 2019; Yang et al., 2021).

Drawing from the above insights, we elaborate on a heuristic typology that encompasses four major latecomer development pathways. We emphasize the shift from conventional leapfrogging aimed at '*forging ahead*' of the incumbent companies in globally pre-existing industry trajectories (Lee and Malerba, 2017) towards *transformative leapfrogging* that simultaneously aims at long-term industry leadership and sustainability transitions. This approach therefore extends the original framework of leapfrogging by Lee and Lim (2001) and elaborates on how latecomers may leapfrog by creating new socio-technical configurations to achieve sustainable development. We derive core mechanisms of the framework from an in-depth case study of the Chinese solar photovoltaic (PV) industry. We observe an emblematic shift in the development goals of the Chinese PV industry from a knowledge-focused strategy towards a valuation-focused strategy. More specifically, the Chinese PV industry began with pursuing a path-following catching-up strategy, which led to them forging-ahead in the pre-existing GVC. However, instead of higher-value products and services, this early strategy led to massive overcapacity, relentless price cuts and high waste production. The domestic industry ended up tumbling and facing major shakeouts. Valuation-focused strategies focusing on socio-technical reconfiguration only became prominent in the last decade, which enabled Chinese companies to envisage more radical innovations in electricity system provision and shape new trajectories for solar PV system integration. The early trajectory of the Chinese PV case therefore serves as a cautionary tale for future latecomers, while the latter part presents potential learnings for *transformative leapfrogging*.

The rest of the paper proceeds as follows: Section 2 discusses the recent conceptual developments of leapfrogging in the fields of catching-up, sustainability transitions, as well as geography of transitions to derive our heuristic typology. Section 3 elaborates on the research method used in the empirical case. Drawing from expert interviews and a patent analysis, Section 4 retraces the historical development of the Chinese solar PV industry to demonstrate how the strategies of actors and the focuses of policies have both moved towards an integrative approach encompassing knowledge and valuation developments. Section 5 discusses how this integrative approach has led to a new focus on the socio-technical reconfigurations of the electricity system towards accommodating for renewables, which might prepare for a *transformative leapfrogging* that simultaneously addresses industrial development and sustainability transitions. Section 6 concludes by elaborating on a future research agenda for leapfrogging in view of grand challenges.

2. Theorizing latecomer development pathways

2.1. Latecomer sustainability challenges and limits of existing approaches

Studies concerning latecomer catching-up have become increasingly prevalent since the 1990s, in particular following the successful cases of South Korea, and then Taiwan and Singapore (Amsden, 1989; Mathews, 1997; Lee and Lim, 2001; Mathews and Cho, 2007). Scholars in this field adopt different theories and methods for analyzing the catching-up processes. However, the arguments of these studies have mostly centered on the availability of an appropriate knowledge base in the respective countries or regions. A majority of these studies asked how institutions can improve the national absorptive capacity for knowledge accumulation, for instance by building on the national innovation systems framework (Lundvall, 1992; Hu and Mathews, 2005; Dodgson et al., 2008; Pietrobelli and Rabellotti, 2011). Other research over the years focused on how latecomers acquire external knowledge by drawing on the resource-based view in the management literature (Mathews, 2002, 2006); the role of broader institutional systems for knowledge generation (Mathews and Cho, 2007); firm-level knowledge accumulation (Lall, 1992; Figueiredo, 2008; Yap and Rasiah, 2017a); organizational strategies to leapfrog in terms of technological capabilities (Kim, 1997; Lee and Lim, 2001; Yap and Rasiah, 2017b); and knowledge insourcing via linkages with GVCs (Mathews, 2002; 2006; Vind, 2008; Fu et al., 2011; De Marchi et al., 2018).

Among these different approaches, external linkages at the international level and with multinational corporations (MNCs) are seen as the most promising sources of knowledge as these knowledge stocks mostly did not pre-exist in latecomer countries or regions. These latecomers are most attracted to sourcing the external knowledge to increase and broaden their technological capabilities with the aim to develop new indigenous industries or to attract foreign direct investments. Therefore, the notion of leveraging on GVCs is strongly anchored, focusing on how latecomers may strategically insert themselves into pre-existing GVCs (often through reverse engineering global incumbent technologies) and then gradually move up the GVC ladders (Kim, 1997; Mathews, 2006; Figueiredo, 2008; Vind, 2008; Pietrobelli and Rabellotti, 2005; 2011; Gereffi, 2014; Lauridsen, 2018). More often than not, latecomers begin by becoming contract manufacturers to the MNCs (i.e., original equipment manufacturers) due to lower cost of production. They may later become original design manufacturers and eventually original brand manufacturers (Hobday, 1995; Gereffi, 1999; Gereffi et al., 2005; Pietrobelli and Rabellotti, 2011), for instance through product, process, functional, or inter-sectoral upgrading (Humphrey and Schmitz, 2002; Ponte and Ewert, 2009; Rasiah et al., 2015; Staritz and Whitfield, 2019).

A more radical form of development was proposed under the label of leapfrogging, through which latecomers skip certain technological steps and jump to more advanced developments through institutional or organizational strategies (Lee and Lim, 2001). Two types of leapfrogging were proposed: path-skipping and path-creating leapfrogging (Lee and Lim, 2001). However, the focus thus far has remained on the level of technological capabilities as the key determinant for success. This results in a tendency to emphasize leapfrogging as forging ahead of global incumbents in pre-existing technological trajectories, leading to successive shifts in global industrial leadership – conceptualized as 'catch-up cycles' in Lee and Malerba (2017).

Latecomer countries thus often invest considerable amounts of their resources into building a knowledge economy with the hope to mimic the success stories of the East Asian development in the 1990s. These successes, however, have not been easily replicated by the rest of the 'later' comers, such as countries and regions in Southeast Asia and Latin America that have remained in the middle-income trap for decades. A knowledge-focused strategy seems even more limited when in view of grand challenges with rising sustainability requirements. More specifically, industrial economists argued that the green techno-economic paradigm will unfold new longer-term economical and societal trends (Perez, 2013; Mathews, 2013; Kaplinsky, 2022) and that each historical paradigm shift has provided new windows of opportunity for latecomer leapfrogging (Perez and Soete, 1988; Perez, 2013). Given that latecomers now face the simultaneous challenge of driving economic development while tackling environmental sustainability issues, a new leapfrogging concept building on strategies broader than knowledge development will be critical to define the next wave of global green development.

More recent studies concerning latecomer catching-up in the cleantech sectors have increasingly pointed to new elements that play equally decisive role, such as market creation, resource mobilization, entrepreneurial experimentation, and directionality in shaping the sectoral selection environments (Yap and Truffer, 2019; Binz et al., 2020). Scholars furthermore paid increasing attention to the role of policy- and demand-related windows of opportunity and how latecomers may appropriate such windows (Lee and Malerba, 2017; Yap and Truffer, 2019; Binz et al., 2020; Lema et al., 2020; Gosens et al., 2021).

2.2. A socio-technical reconfiguration perspective

To explicate how latecomers may shape new development trajectories while achieving sustainability transitions, we draw on recent debates and insights from the fields of economic geography and geography of transitions. Economic geography focuses on how countries and regions can diversify into new technologies and industries, and how they develop new growth pathways by emphasizing the key role of knowledge production (Neffke et al., 2011; Rigby, 2015; Trippl et al., 2017; Martin, 2010). Research in this field consistently showed that the creation of new regional industrial development paths depends on the availability of prior related knowledge stocks or industrial structures in the region (Boschma, 2017). In correspondence with the catch-up literature, these studies focus primarily on conditions of knowledge generation as the main factor driving the diversification of regional technology portfolios. Aspiring regions that lack or have only limited competitive knowledge stocks available are then essentially left with importing the critical knowledge from elsewhere, or they may bet on specific natural context conditions or simply trust in serendipity (Trippl et al., 2017).

The related diversification approach has been criticized for its excessive focus on local related technological or industrial capabilities as the drivers of regional diversification (Hassink et al., 2014; Castaldi et al., 2015; Coenen et al., 2015b; Steen, 2016; Boschma et al., 2017; Hassink et al., 2019; Trippl et al., 2017; Mackinnon et al., 2019). New industries occasionally emerge in places that have no particular advantage in related knowledge. Unrelated diversification becomes particularly relevant for radical changes, which may help tackle grand challenges (Boschma et al., 2017; Coenen et al., 2015a). Drawing on these insights, Boschma et al. (2017) proposed a ‘general theory of diversification’ that borrows insights from the recent socio-technical transitions literature. The latter suggests that latecomers should seek conditions for success beyond related knowledge by adopting a socio-technical innovation perspective because radical transformations are typically driven by a co-evolution of technologies and institutional contexts (Smith et al., 2010).

Scholars of geography of transitions have therefore argued that besides focusing on knowledge-related conditions for innovation success, capabilities for driving ‘valuation’ processes must be considered (Binz and Truffer, 2017). Valuation refers to those processes in technology development that lead different stakeholders to appreciate (or oppose) the new option as being more (or less) attractive compared to established alternatives (Jeannerat and Kebir, 2016). Valuation therefore will be important in the creation of new markets through specifying attractive features of the innovation for specific segments of customers. But beyond that, it also encompasses those activities that mobilize support or opposition for the product or technology, because it aligns (or conflicts) with specific value positions, e.g., equitable treatment of workers, preventing environmental impacts, respecting cultural taboos (Jeannerat and Kebir, 2016). Finally, valuation also refers to the capability of innovating actors to mobilize financial and other resources in their local contexts or from abroad. The overall attitude of different stakeholders will lead to the mobilization (or withdrawal) of resources, like government

		Main drivers for change	
		Knowledge-focused (GVC reconfiguration)	Valuation-focused (Socio-technical system reconfiguration)
Radicality of change	Path-following	***Technology catching-up*** Becoming leading manufacturers of PV panels, batteries, semiconductors, etc. ***Replication or transplantation***	***Greening of domestic sectors*** Sourcing global latest technologies to provide greener public services, e.g., wastewater treatment, electricity system. ***Replication or transplantation***
	Path-creating	***Forging ahead in pre-existing GVCs*** Becoming the home of lead companies in electric cars, digital devices, etc. ***Exaptation***	***Transformative leapfrogging*** Developing new sectoral regimes, e.g., smart grids and decentralized power production, new small-scale sanitation solutions, new satellite-based solutions. ***Saltation***

Fig. 1. A typology of latecomer development pathways in view of grand challenges.
Source: Authors

funding or venture capital, which are essential for the new technology or industry to develop (Geddes and Schmidt, 2020). Valuation is key for entrepreneurial activities in the form of marketing, corporate communications, or lobbying. The success of valuation efforts can, however, not be controlled by single companies but will result from the systemic interplay between different actors such as companies, users, advocacy groups, and governments (Yap and Truffer, 2019).

Regarding policy implications, transition theorizing emphasizes the importance of analyzing innovation and institutionalization processes in experimental settings, where new technologies, new business models, use patterns and new institutional frameworks are tried out and tested, and thus generate new socio-technical configurations (Hoogma et al., 2002; Schot and Geels, 2008; Berkhout et al., 2010; Schot and Steinmueller, 2018). The policy aim is to balance societal goals that are broader than industrial catching-up to include sustainability transitions that improve environmental conditions and societal living standards. Once a specific region has been able to build stable socio-technical configurations in local testbed markets and demonstrate the functionality of these new systems, preconditions for leapfrogging towards more sustainable solutions may be given.

2.3. A typology of latecomer development pathways

Drawing on the different theoretical strands above, we present a heuristic typology in Fig. 1 that provides a more nuanced view on different catching-up and leapfrogging strategies. More specifically, we distinguish *transformative leapfrogging* that aims at system transformation (by co-shaping values and knowledge) from the conventional 'forging-ahead' type of leapfrogging embedded in a catch-up cycle paradigm, as indicated by the horizontal axis in Fig. 1. For both paradigms, latecomer strategies can be further distinguished along two dimensions: path-following and path-creating trajectories (i.e., the vertical axis).

Latecomers in the catch-up cycle paradigm aim to reconfigure their positions in pre-existing GVCs. In a *path-following* trajectory, latecomers generally fit themselves into extant global production networks, climbing up the GVC ladder through technology transfer and upgrading, or skipping ahead to the frontier of the GVC (also known as the stage-skipping scenario in Lee and Lim 2001). Typical examples of *technology catching-up* include the early phase of Chinese firms, which aimed for fitting themselves into the GVC of PV panel manufacturing (Binz and Anadon, 2018), or Malaysia's export-oriented strategy in solar PV manufacturing. Other examples may be catching-up in the production of batteries or semiconductor chips.

In the catch-up cycle paradigm, latecomers may also leapfrog by forging ahead through a *path-creating* trajectory (Lee and Lim, 2001) that shapes the frontier of a competitive 'technological regime' (Malerba and Orsenigo, 1994; Malerba and Orsenigo, 1996; Breschi et al., 2000). Following Lee and Malerba (2017), this form of leapfrogging generally only applies to 'qualified latecomers' that have already accumulated prerequisite technological capabilities, and which are supported by effective policies that help obtain leadership in particular industry sectors. As such, *forging ahead in pre-existing GVCs* involves jumps in new but related industry paths (Boschma, 2017) that are guided by shared rules or principles of a technological regime, e.g., the general principle of chip miniaturization and the concomitant sectoral replica of a Silicon Valley in Hsinchu, Taiwan that introduces many new digital devices. Other examples may include becoming the home of lead companies in the electric car industry drawing on related capabilities or context conditions. The introductions of these new products or services are often 'modular' in terms of system integration, which means plug-and-play into existing socio-technical systems that do not involve fundamental socio-technical reconfigurations such as jumping from landline phones to mobile telephony (James, 2009). In view of grand challenges, path-creation of this sort may therefore be seen as a less radical form of leapfrogging.

Addressing grand challenges needs to go beyond the predefined paths and requires the adoption of a system transformation ambition, in which latecomers aim for reconfiguring the entire 'socio-technical system' of service provision and not only the core technologies of a sector. One alternative that has been explored is how latecomers may respond to increasing sustainability pressure by 'greening of domestic sectors' (Ho, 2005). This strategy relies mostly on importing solutions from elsewhere and build up indigenous service value chains. Therefore, the valuation processes in this regard tend to still mimic 'globally existing socio-technical regimes' (Fünfschilling and Binz, 2018). An example of such *greening of domestic sectors* is the case of the Chinese urban water management sector that follows the dominant trajectory of large-scale centralized wastewater treatment plants prevalent in the West by aligning societal visions and expectations, new policies and regulations, as well as networks and alliances (Yap and Truffer, 2019). Another example would be a country setting up strong incentives for domestic use of electric vehicles to curb national CO_2 emissions. Even though they might profit from job creation effects when providing local charging stations and specific services, they will likely be confronted with high import costs when implementing this transition.

Transformative leapfrogging is possible when a country or region becomes a testing site for alternative socio-technical configurations while serving to experiment and scale radical alternatives for its indigenous industry. System integration of this sort often requires an overhaul of existing institutional structures. A classic example of this type of leapfrogging is the case of Mpesa in Kenya in delivering cellphone-based payment services, which became a dominant payment mode years before they were introduced in the advanced countries (Mbiti and Weil, 2015; Mbogo, 2010). In cleantech sectors, examples may include building smart grids for decentralized power production or diffusing small-scale sanitation solutions in infrastructure-poor regions, which may then be exported or adopted elsewhere. With the prevalence of digitalization, ICT, and satellite-based data in the green techno-economic paradigm, latecomers may also envision innovating indigenous environmental management services using satellite data, which enables new service industries while bypassing the build-up of conventional infrastructures (Yap and Truffer, 2022). *Transformative leapfrogging* therefore requires a more experimental approach allowing a wide range of valuation efforts, leading to new products or services.

To illustrate the different degrees of *radicality of change*, we may refer the four development pathways in Fig. 1 with the distinction of *new-to-the-world* and *new-to-the-region* trajectories identified by Boschma et al. (2017). *Technology catching-up* and *greening of domestic sectors* are two path-following strategies of the *replication* or *transplantation* type. *Forging ahead in pre-existing GVCs* describes an *exaptation* trajectory, i.e., the development of new solutions or path-creation that build on existing knowledge and making new jumps into alternatives within a same portfolio of industry paths that share the rules of extant GVCs. Finally, *transformative leapfrogging* requires a *saltation* approach, i.e., a strategy which aims at developing new socio-technical configurations that are 'new to the world'. In terms of technological innovations, this entails making radical jumps beyond a single portfolio of industry paths or that are 'inter-sectoral' to introduce new products or services lacking dominant designs. Beyond the technology focus, we posit that the path creation strategy depicted in this quadrant requires broader valuation strategies and has a higher potential to fulfill the simultaneous ambitions of industry development and sustainability transitions.

Building on the above premises, we outline the main structural differences and expected mechanisms of latecomer knowledge-focused and valuation-focused development strategies, respectively (see Table 1). It is important to note that the two approaches are not mutually exclusive. Building a certain amount of learning capabilities, knowledge, and general absorptive capacity (Lundvall, 1992) will be *necessary* for both conventional and transformative leapfrogging. However, it will be *insufficient* to tackle grand societal challenges. More importantly, latecomers have to conjointly pursue knowledge and valuation development strategies to actively construct new socio-technical configurations, instead of first creating the knowledge base and then bothering about setting up new markets for the diffusion of the green technologies, which also reinforces the *'grow first, clean up later'* mentality. In terms of innovation policy implications, earlier works on Strategic Niche Management (Hoogma et al., 2002) or technological innovation systems (Hekkert et al., 2007; Bergek et al., 2008) may be instructive, which emphasize the need for a balanced development of critical resources. It also aligns with the recent call in innovation policy studies to switch from a focus on research and development (R&D) or knowledge-based approach to a focus on whole system reconfigurations to achieve transformative change (Schot and Steinmueller, 2018). Mission-oriented innovation policy may play a major role in shaping the directionality of these green developments (Mazzucato, 2016; Yap and Truffer, 2019).

Applying these insights to latecomer leapfrogging in the age of grand challenges suggests the simultaneous applications of knowledge- and valuation-oriented resource building. In particular, it addresses the relevance of shaping technology legitimacy in public discourses, as well as leveraging material and symbolic resources from different actors in the country or region. This may eventually allow latecomers to escape globally pre-defined industry trajectories and embark on development pathways that are potentially more sustainable.

3. Research method

Our concept building adopts an abductive reasoning approach (Bell et al., 2019; Bryman, 2016). The typology on latecomer development pathways in Figure 1 and the mechanisms outlined in Table 1 were first derived deductively based on extant theorizing. To identify and specify key mechanisms of the valuation-focused strategy, we followed an inductive approach based on process tracing within an exemplary case study (Yin, 2016). Fig. 1 and Table 1 were subsequently revised to ensure our conceptual framework matches the empirical data, and vice versa (Yin, 2011). This process was repeated in an iterative form before arriving at the final conceptualization. In terms of case selection, solar PV represents one of the key industries for sustainable transitions in the electricity sector (IEA, 2020). Gaining global leadership as an emerging economy has been repeatedly presented as a poster case of a new kind of green catching-up (Fu and Zhang, 2011; Zhang and Gallagher, 2016; Shubbak, 2019).

The following empirical analysis draws on 19 semi-structured interviews with key informants of different stakeholder groups in the Chinese solar PV industry, including academia who are also active policy experts, intermediaries (e.g., associations, alliances, consultancies and expert committee members), domestic solar PV manufacturers, domestic and foreign technological companies, as well as key component suppliers. The interviewees include the most representative industry association and consultants with a rather

Table 1
Comparing knowledge- and valuation-focused strategies for latecomers.

	Knowledge-focused	Valuation-focused
Drivers of change	Competitive position in GVCs	Shaping new socio-technical configurations
Primary policy realms	Science, education and industry policy	Science, environmental and industry policy, deployment policy, i.e., transformative innovation policy coupled with mission orientation
Core resources	Related or imported knowledge; indigenous innovations as key; technological accumulations as core competence; tapping on global market conditions	Capability of system building and experimenting; leveraging local and institutional conditions
Entrepreneurial strategies	Reverse engineering; collaboration with MNCs; firm-level strategic management	Entrepreneurial experimentation, institutional entrepreneurship
Technology focus	Existing value chains; feeding into mainstream products	Creating new socio-technical systems; developing alternative, non-mainstream trajectories
Market availability	Exogenously given; mainly supporting existing value positions of stakeholders	To be shaped endogenously; formation of new market segments; often opposing existing value positions of stakeholders
Actor steering domains	Focuses on interdependent relationships (e.g., coopetition) among producers and buyers across the value chain	Whole system reconfiguration; closely aligned strategies among policy makers, companies and users in sectoral transformation
Leapfrogging aim	Moving up the value chain; forging ahead in pre-existing GVCs	Transformative leapfrogging by implementing new-to-the-world socio-technical configurations to create more sustainable development trajectories

Source: Authors.

neutral stand, and an exemplary failed PV company known as a core indigenous pioneer in the 1990s. The interviews were conducted in 2018 in Beijing, Shanghai, Anhui, Zhejiang, Jiangsu, and Shaanxi.

The interviewed companies were selected on the basis that they are leaders of particular activities concerning solar PV production or system integration (e.g., installation and maintenance, balance-of-systems based on information and communication technologies (ICT), energy efficiency and storage technologies). To identify leapfrogging potentials, the priority of interviews was given to incumbent companies that proactively seek new business models and start-ups that experiment new technologies (see Appendix 1). A theoretically informed but open-ended interview guideline was prepared beforehand. All interviews in the study were fully recorded, transcribed verbatim, and thoroughly checked. The interview findings were triangulated with government and company reports, as well as secondary data sources (Yin, 2011; 2014). To assess developments of the knowledge base over time, we complement our findings on the valuation dimension with reconstruction of patent indicators (see Appendix 2 on data compilation and Section 4.4).

4. Towards transformative leapfrogging: a sequence of disrupted development phases

The development of the Chinese PV industry has been analyzed by many studies in the past years, mostly reporting on its rapid takeover of market shares in manufacturing PV modules in the 2000s and its subsequent obtainment of world leadership since 2010 (Grau et al., 2012; Dewald and Fromhold-Eisebith 2015; Quitzow, 2015; Zhang and White, 2016; Nahm 2017a, 2017b; Binz and Anadon, 2018; Jackson et al., 2021). However, it remains unclear whether the development of the solar PV industry has facilitated the integration of solar energy in the electricity mix in China and contributed to the system transformation of the domestic electricity sector.

In this section, we present a three-phase development story of the Chinese PV industry, featuring its trajectory *across* the alternative pathways in Fig. 1: (i) technology catching-up till 2008, (ii) forging ahead in pre-existing GVC between 2009 and 2013, and (iii) transformative leapfrogging since 2013. Our study particularly focuses on Phase III, in which fundamental shifts took place both in terms of government policies and innovation focus among many Chinese PV companies toward shaping new social-technical configurations.

4.1. *Technology catching-up (late 1990s – 2008)*

Until 2008, the development of the Chinese PV industry had followed the *technology catching-up* pathway in Fig. 1. Although solar PV energy was already considered an important renewable energy source in the Renewable Energy Law effective since 2006, and in several government plans such as the 11th Five-Year Plan (2006–2010) for National Economic and Social Development and the Medium and Long-Term Development Plans for Renewable Energy Development published in 2007, the Chinese government was not convinced to channel large financial resources to support the domestic market for PV (Quitzow, 2015). Except for some small-scale PV demonstration projects to provide electricity access in remote areas, only four commercial PV power plants were approved by the National Development and Reform Commission (NDRC) between 2007 and 2008 with the fixed price of four CNY (0.4 Euros) per kilowatt hour (Grau et al., 2012).

Although there were science and technology policies supporting research, development and demonstration (RD&D) in PV technology during this period (Anadon, 2012; Huang et al., 2012; Zhi et al., 2013), Chinese entrepreneurs, especially those internationally well-connected returnees, played a crucial role in forming the infant stage of the industry (Zhang and White, 2016; Binz and Anadon, 2018). Due to the lack of a strong domestic PV-related knowledge base, these entrepreneurs mainly adopted a 'transplantation' strategy to build up the industry by drawing on different resources (i.e., knowledge, finances, markets, and technology legitimacy) through international networks (Binz and Anadon, 2018). Furthermore, Chinese PV companies utilized central government R&D funding to build technological capabilities that could not be gained from foreign partners, e.g., establishing engineering and design skills required to commercialize new technologies and scale up to mass production (Nahm, 2017a).

Since the early 2000s, the production capacity and export volume of the Chinese solar PV industry started to grow rapidly as more domestic companies entered the industry following the increasing demands in the booming European and the United States (US) markets. China became the world's largest producer of solar modules in 2007. The position of the Chinese solar PV manufacturers in the global PV value chain during this phase was mainly to produce PV modules for foreign markets (Dewald and Fromhold-Eisebith, 2015). Moreover, the Chinese PV companies were heavily reliant on the supply of advanced machineries from German companies and polysilicon materials from foreign companies in the US, European Union (EU), and South Korea (Quitzow, 2015). This overall led to a halt of the booming industry when the global financial crisis in 2008 weakened the demand of PV products in many markets overseas. Many Chinese PV firms encountered losses, suffered, and crumbled over substantial financial debts.

4.2. *Forging ahead in pre-existing GVCs (2009 – 2012)*

The development of the Chinese PV industry during this period moved from *technology catching-up* to *forging ahead in pre-existing GVCs*. Several deployment policies were introduced in this period to salvage the domestic PV industry due to the weakened demand in foreign markets as a result of the global financial crisis. Overall, the Chinese PV industry went into a consolidation period following the crisis in which larger Chinese PV companies sought to scale up manufacturing capacity and expanded along a broader set of pre-existing PV value chains through upstream and downstream integration (Zhang and Gallagher, 2016).

The deployment policies implemented in China during this period included two rounds of public tenders for PV power plants by the National Energy Administration in 2009 and 2010, the Solar Roofs Program and the Golden Sun Demonstration Program in 2009, and the introduction of the national feed-in-tariff (FIT) in 2011 (Grau et al. 2012; Shubbak, 2019). These deployment policies facilitated the initial formation of domestic markets. In only four years, China became the world's largest PV market in 2013 (IEA, 2020). However, the domestic PV market was not well-functioning due to problems such as incumbent inertia (i.e., traditional grid and energy suppliers), curtailment problems due to inefficient grid connections, non-operational PV plants, uncompetitive prices of renewable energy supply, late incentive payments from the government, etc. (AC/PE3; AC/PE4; TC3; TC5). As a result, the export-orientation remained a core targeted strategy for many Chinese solar PV companies.

Besides the continued public RD&D, more industrial policies were deployed. For example, solar PV industry was listed as one of the strategic emerging industries in 2010 (Shubbak, 2019). In order to facilitate the vertical expansion to upper stream of polysilicon production, anti-dumping and anti-subsidy investigations on imported solar graded polysilicon from the US, South Korea, and the EU were initiated in 2012 (Lewis, 2021). Besides the central government, local governments in China also played an important role in helping Chinese PV firms scale up their manufacturing capacity by offering tax incentives, cheap lands, loans with low interest rates, etc. (Nahm, 2017b).

The rapid expansion of manufacturing capacities and the ill-functioning domestic market jointly contributed to the significant overcapacity in the Chinese PV industry during this period. Top companies reduced the selling prices of their PV modules substantially to win bidding projects. It had become controversial whether that would be a sustainable trajectory (TC7). After the introduction of the US and EU's anti-dumping and anti-subsidy tariffs on Chinese solar PV modules in 2011 and 2012, the Chinese PV industry plunged into an aggravated crisis. Many companies went bankrupt, including successful large PV companies such as Suntech and LDK Solar (TC11).

Despite the attempted deployment policies in this period, the associated aim for jumping into broader pre-existing GVCs based on a technology or knowledge-focused strategy led to neither a successful industry development nor a transition of the domestic electricity system. This period, therefore, demonstrates the 'functional upgrading' strategy (Humphrey and Schmitz, 2002) of the Chinese PV industry along broader but pre-existing GVCs. This strategy allowed the Chinese PV industry—more specifically those firms that survived—to grow larger in terms of scale and achieve leadership in terms of market share with low-priced products. Although these Chinese firms managed to upgrade, their strategy and the poorly implemented deployment policies did not lead to high-value industry paths nor did it support environmental leapfrogging.

4.3. Transformative leapfrogging (2013 onwards)

Since around 2013, after the conventional knowledge-focused strategy had almost led into an economic crash of the then rising Chinese PV industry, a drastic shift in the overall innovation approach took place both among companies and policy makers. This led to the development of a much broader range of business models and innovation strategies. Drawing from the interview insights, we will in the following elaborate on (i) the fundamental change in domestic policies that shaped a strong directionality; (ii) the concomitant innovation strategies among firms in finding new alternatives for the electricity system instead of following the global mainstreams; and (iii) how this eventually led to a widening innovation system boundary with a strong orientation towards socio-technical reconfiguration. We will then complement these findings with a background patent analysis on how the knowledge dimension of the Chinese PV industry evolved concomitantly with the strategic shift.

4.3.1. Shifts in deployment policy for shaping strong directionality

In 2013, several policies and regulations were implemented to facilitate a well-functioning domestic market for solar PV in China following the guidance from the State Council. These policies and regulations were formulated by different ministries of the central government, and covered almost all aspects regarding the PV industry (Shubbak, 2019). Among them, the FIT scheme was revised in 2013 to adopt different FITs for different regions. More importantly, the revised FIT scheme also set the mechanism for future revisions based on learning rates to eventually reach grid parity with traditional energy sources (AC/PE3; TC4; TC5). The construction plans of PV power plants were also revised, aimed at preventing local governments from approving ineffective projects, which were only started to reap the attractive government payments. To overcome the barriers of the conventional electricity system, quality- and service- based competition was implemented in different regions and the minimal grid capacity connected for PV-generated power was increased to reduce the curtailment of renewables (AC/PE4; AC/PE5; TC3; TC5). Further supportive policies followed since the introduction of the 13th Five-Year-Plan in 2016, such as for the development of decentralized solar PV systems (Shubbak, 2019). The new five-year-plan set priorities for the deployment of renewable energies. Since then, the domestic PV market in China started to function well. Most importantly, it led to a more proactive and well-aligned set of deployment policies, i.e., the formulation of market incentives that would at the same time encourage technological improvement of the PV products and their associated system integration.

The most representative deployment policy in this phase was the PV Forerunner Base Plan (Forerunner Plan) introduced in 2015 by the National Energy Administration. The main objective of this project was to demonstrate new PV technologies by prioritizing the installation of PV modules of high-performance (e.g., conversion rate, persistent electricity generation), and the monitoring of electricity grid connection. The first phase of the Forerunner Plan formulated the highest performance standards for solar PV panels endorsed by the government. The performance standards were applied to a number of other regions in the country in its second phase in 2016. In 2017, the third phase further increased the performance standards (AC/PE3; TC3; TC4). These high requirements were later adopted in the revised standards for Chinese PV manufacturing in 2018 (AC/PE3; TC4). In order to bid for new projects in the Forerunner Plan, PV manufacturers had to intensify their R&D efforts to be able to provide desired products. Thus, the Forerunner Plan shifted the competition among Chinese PV manufacturers from a cost-driven to a performance-driven approach (AC/PE3).

Another representative deployment policy was the 'PV Poverty Alleviation Project', which aims to help the poor (mostly in rural areas of the country) by building solar panels on residential rooftops for them to sell electricity to the government as a source of income (AC/PE3; IN1). Similar to the 'PV Forerunner Base Plan', the 'PV Poverty Alleviation Program' strictly imposed that only the best-quality PV panels could be used (TC2). Since the PV Poverty Alleviation Project covered even larger areas of China than the Forerunner Plan, it offered Chinese PV companies testbeds in terms of multiple market contexts, which provided ample learning opportunities for new social-technical configurations (TC2). Furthermore, recent studies showed that the 'PV Poverty Alleviation Project' indeed had contributed to reducing rural poverty in China (Liao and Fei, 2019; Zhang et al., 2020).

4.3.2. Beyond the pre-existing GVCs: shaping new alternatives

In the previous two development phases, Chinese PV manufacturers particularly scaled up the manufacturing of polycrystalline silicon solar cells due to its lower entry barriers and cost advantage in mass production. This strategy worked well for positioning the industry in the pre-existing GVC. However, the conversion rate of polycrystalline cells are relatively low compared to other alternatives such as monocrystalline silicon cells (NREL, 2022), which means less electricity generation, and longer time for a return on investment. Moreover, the improvement of polycrystalline silicon technology has been slowing down.

Although some Chinese companies experimented on new designs of solar cell and module such as monocrystalline silicon, thin-film, and the combination of thin-film on crystalline silicon cells (AC/PE1; TC11; TC1; TC3; TC4), the shift of the dominant design from polycrystalline silicon cells to monocrystalline silicon cells only started to accelerate after the introduction of those deployment policies prioritizing the performance of PV modules in 2015. Monocrystalline PV technology was preferred in the Forerunner Plan because of the higher conversion rate than polycrystalline PV technology. In the first phase of the Forerunner Plan in 2015, 60% of the installed solar panels used monocrystalline PV technologies (AC/PE3; TC3; TC4), which was significantly higher than the 20% among all solar panels installed in China in the same year (CPIA, 2019). The percentage further increased to nearly 90% in the third phase of the Forerunner Plan (AC/PE3; TC3; TC4). As a consequence, the market share of monocrystalline silicon solar cells overtook the polycrystalline silicon solar cells in 2016, and increased to 65% in 2019 (CPIA, 2019).

The most important actors that facilitated such a strategic shift include Longi—a company specialized in producing monocrystalline silicon ingots and wafers for many years. In 2013, Longi applied for the first time in the world the diamond wire in sawing silicon ingot into wafers. This new process was a breakthrough resulting in significant cost reductions in monocrystalline silicon PV cells and modules (TC8; TC9). To ensure market demonstration opportunities for this new alternative, Longi vertically expanded to manufacture their own solar cells and modules in 2014 (TC8; TC9). Longi's strategy aligned well with the abovementioned Forerunner Plan while the company continued its R&D in monocrystalline silicon, which later gained increasing credibility (AC/PE5). Longi made up to 20% of the installed PV panels in the first phase of the Forerunner Plan in 2015, much higher than its previous market share.

Another significant shift in the solar PV industry is the diffusion of new double-sided (or bi-facial) design in PV cells. Traditional PV cells only use one side for absorbing light. PV cells with the double-sided design can absorb light from both sides, thus increasing the conversion rate, especially on the water surface (TC3; TC4; TC6). The market share of double-sided PV cells increased rapidly from 3% in 2016 to 20% in 2018 (CPIA, 2019). This shift is also linked to the deployment policies, which facilitated the deployment of PV panels in different geographical contexts (e.g., floating solar PV panels, solar PV roofs for green buildings), and the emphasis on conversion rates in the Forerunner Plan. For example, double-sided design made up to 10% of the PV panels installed in the first phase of the Forerunner Plan in 2015 (AC/PE3; TC3; TC4). In sum, the transition to deployment policies that focus on experimenting new socio-technical configurations in this phase successfully led to the diffusion of alternative designs in the PV industry.

4.3.3. Beyond production-based value chains: system transformation

Increasing demand in the domestic market led to another shift in strategic focus of the Chinese solar PV industry from PV cell- and module manufacturing towards the configuration of entire socio-technical systems, i.e., the transformation of the Chinese electricity sector towards embracing renewables (AC/PE5; TC5). This is further strengthened by policies supporting decentralized PV deployment (Shubbak, 2019). System transformation of the electricity sector requires input from a broad range of industries, including large-scale grid connection technologies (e.g., high-voltage current grid connections), decentralized grid connection systems, multi-energy complementary system (e.g., PV and energy storage), and different market segments of the electricity sector (TC3; TC5; TC13).

During this transformation, domestic companies from other related industries (e.g., electrical engineering) became particularly active in the PV industry (TC13). One successful example is the growth of Chinese solar inverter companies (e.g., private-owned Sungrow or Huawei) specialized in converting energy output of solar panels to feed into electricity networks. Inverter is a critical component in the stage of balance-of-system to effectively integrate solar PV electricity into grid or off-grid systems. Local valuation is therefore particularly important. The innovative activities of these companies lowered the prices for inverter over the last few years substantially, leading to higher affordability of good quality inverters in PV applications (AC/PE5; TC2). Among them, Sungrow, a privately owned company founded in the late 1990s, became the world's largest PV inverter company in three consecutive years since 2015 (AC/PE5; TC2; TC13). Moreover, Sungrow is also leading in terms of profit margin compared to the world-leading inverter company SMA Solar Technology in Germany.[1] Started as a traditional inverter manufacturer, Sungrow argued that the availability of the domestic market has provided ample opportunities as testbeds for improving their products (TC2). For example, the company recently contracted the inverter system for the world's largest floating solar farm (with a total capacity of 40 megawatts) on a lake

[1] In 2016, SMA's profit margin was 14.89% while Sungrow's was as high as 34.26%.

which was a deserted coal mine in Anhui, China. This floating solar farm generates electricity to power 15,000 homes (TC2).

Incumbent PV companies also started to innovate in frontier ICT-based system integration technologies less related to PV technology such as smart grid to facilitate high-voltage current grid connections or decentralized grid systems (TC3; TC5; TC13). For instance, Trina, a Chinese PV pioneer founded in the 1990s, was a successful vertically integrated company producing PV modules (AC/PE5; TC7). In recent years, the company realized that the industry might not survive the price competition, hence began to outsource production while venturing into asset-lite downstream services of PV, e.g., using Internet of Things and cloud computing to effectively integrate PV products into electricity systems (TC7).

Another successful example of system integration driven by entrepreneurial experimentation is TBEA, which is a state-owned company specialized in providing one-stop smart energy solutions including power generation (e.g., PV grid-connected inverters), power transmissions, power router and smart micro-grid solutions, as well as energy management platforms through cloud computing (AC/PE3; TC10). Conventionally, there were about three mainstream architectures for solar PV power stations that shared a few major limitations, such as high maintenance of power frequency transformers, over-complexity of multi-level transformation systems, and conversion inefficiencies. TBEA developed a strategic system integration plan that simplified the four or five core steps of the conventional architectures to only three steps (TC10). Under the company's own label, TBEA introduced new-generation solutions to smart PV system integration. In sum, there was a rise in ICT activities that facilitated key innovations of PV system integration across different markets in China, such as balance-of-systems, energy storage, and multi-energy complementary systems (TC13).

We therefore observe a radical shift in the overall innovation strategy of the Chinese PV sector in Phase III. Both the leading companies and the government shifted away from a narrow knowledge-focused strategy, which conventionally targeted the extant GVCs of PV production as *the* quality benchmark (AC/PE1). Instead, a much broader set of strategies aimed at transforming the electricity system emerged, focusing on developing future technologies, business models, and agile organizational structures. The existence of a rapidly growing and diverse local market created many incentives to broaden the strategies and spawned a wide variety of entrepreneurial initiatives. This shift resulted in a new emphasis to experiment with alternative socio-technical systems aiming at transforming the national electricity supply regime, which in turn provided stronger conditions to gain leading roles in shaping new products and services both domestically and in new GVCs.

As a feedback to knowledge development, the valuation-focused strategy also led many PV companies into high degrees of automation in their manufacturing process, some to more than 90% (AC/PE2; AC/PE3; TC5; TC9). The quality of the products improved substantially with lower defect rates that might be due to human operation errors (TC9). This also indicates that the Chinese PV production had moved beyond the labor-intensive and lower-cost advantage model. In line with the growth of the domestic PV market, the Chinese technological companies are, for instance, also leading in the supply of advanced machinery tools (TC9; IN2; AC/PE2). While in the past Chinese PV manufacturers had low bargaining power with German machinery suppliers, Chinese manufacturers later collaborated with MNCs like Centrotherm to help improve their equipment by providing critical user feedback (AC/PE5; TC3). Since around 2018 Chinese manufacturers were able to mostly source for machineries from local indigenous suppliers as the competencies of the local companies increased significantly (AC/PE2; TC2; TC5; TC9). This allows a more independent and self-sufficient PV sector in China, where services became much more efficient. In this period, Chinese companies, which continued with the conventional catch-up strategy to serve a mature PV market with pre-existing dominant designs (i.e., polycrystalline PVs), were locked in to their full production line (including raw silicon materials) (IN2; TC7; TC11). These companies suffered the most when demand was low and were most vulnerable during the price competition.

4.3.4. Reconstructing the development trends through patent indicators

Thus far, we have mainly reconstructed the strategic shift in the industrial and innovation policy based on evidence from a limited set of interviews with leading innovative companies. In this section, we corroborate these findings with an analysis of patenting activities of the Chinese solar PV industry. Fig. 2 shows that the number of patents has been steadily increasing in the major countries since the mid-2000. There is, however, a significant decline in the patenting activities of the solar PV industry among major producing countries excluding China since 2011. The overall decline of patenting activities is due to the increasing number of innovating firms exiting during the global shakeout of the industry (Carvalho et al., 2017; Furr and Kapoor, 2018; Hipp and Binz, 2020). However, Chinese solar PV companies tend to have higher survival rates during the industry shakeout (Furr and Kapoor, 2018). This leads to a geographical consolidation of solar PV manufacturing activities in China (Fraunhofer ISE, 2020). In 2012, China took the leading position from Japan, becoming the biggest source of solar PV patents. Since 2015, the number of solar PV patents in China started to grow significantly again with even a higher growth rate on average than the period before 2013, while the decline in other major producing countries continued. In line with the aforementioned argument, the shifting focus of innovation activities towards downstream system integration has been key to the Chinese solar PV industry.

We further divided the value chain of the solar PV industry into three different segments, i.e., upper stream, midstream, and downstream. The upper stream segment includes silicon, ingot, and wafer manufacturing. The midstream segment comprises the manufacturing of cells and modules. In the downstream segment, solar modules are integrated into the system together with other components like inverters to form a PV power plant (Carvallho et al., 2017). Fig. 3 shows the evolution of the number and the share of system integration patents in China. We identify system integration patents among solar PV patents using the CPC codes Y02E10/56 and the 'balance of system' sub-trajectory in Kalthaus (2019). Both the number and the share of system integration patents in China increased significantly since 2010 following the implementation of the domestic deployment policies. The share of system integration patents in all PV patents nearly doubled in 2014 compared to 2010.

The shift to system integration can also be identified in the evolving knowledge base of the solar PV industry in China. The knowledge base of the midstream segment of solar PV supply chain is different from the downstream segment. The downstream

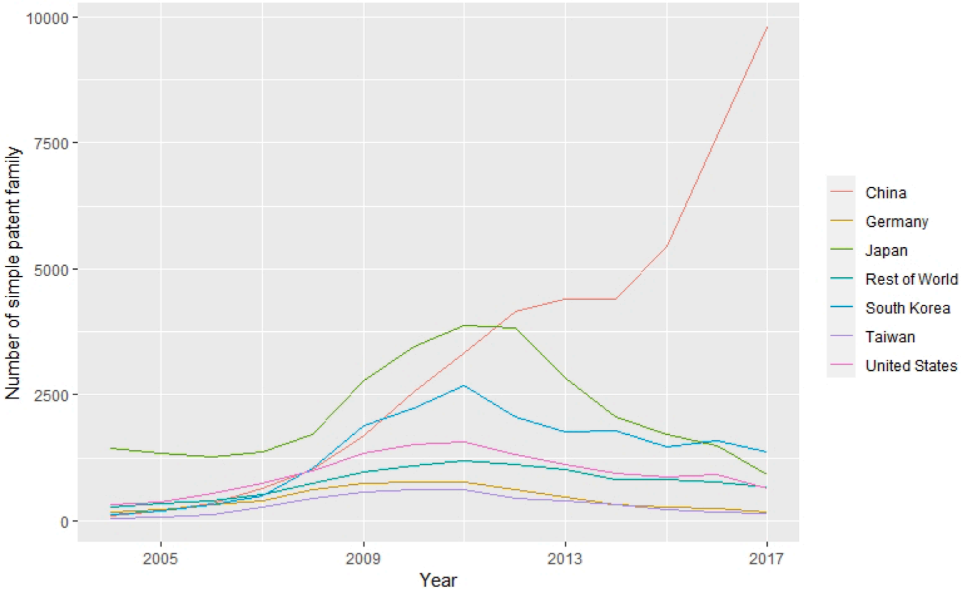

Fig. 2. Number of PV patents by the major producing countries.
Source: Own calculations by authors based on data from the European Patent Office.

segment of system integration relies more on electrical engineering knowledge, whereas the midstream segment of cell and module manufacturing relies more on semiconductor knowledge base (Huenteler et al., 2016; Malhotra et al., 2019). Fig. 4 shows the evolution of the knowledge base of solar PV technology in China. Since 2013, electrical engineering knowledge surpassed semiconductors knowledge as the largest component of the solar PV knowledge base in China. As mentioned in Section 4.2, the deployment policies in China since 2009 facilitated the formation of domestic markets. This allowed the mobilization of the existing domestic knowledge from other industries. Both Sungrow and TBEA mentioned in Section 4.3.3 had been active in the electricity sector for many years. Once the deployment policies were implemented, these companies were able to actively participate in experimenting new products in different market contexts. Therefore, the creation of domestic markets and the shifting focus towards PV system integration in turn helped mobilize the domestic knowledge from other technological fields within China's innovation system, facilitating the rapid innovation

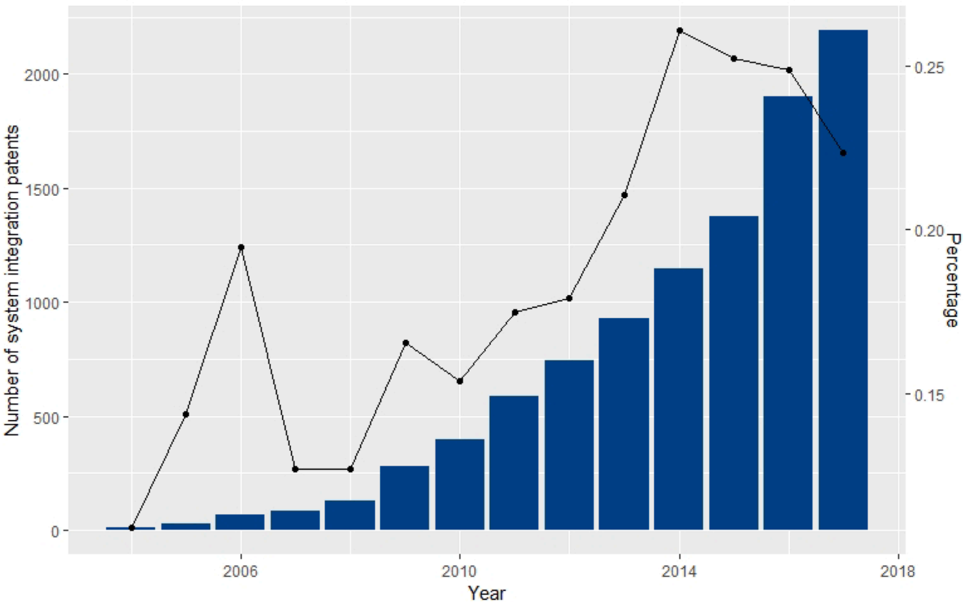

Fig. 3. The shifting innovation focus of the Chinese PV industry towards system integration.
Note: Bar: Number of system integration patents; Line: Percentage of system integration patents in all PV patents.
Source: Own calculations by authors based on data from the European Patent Office.

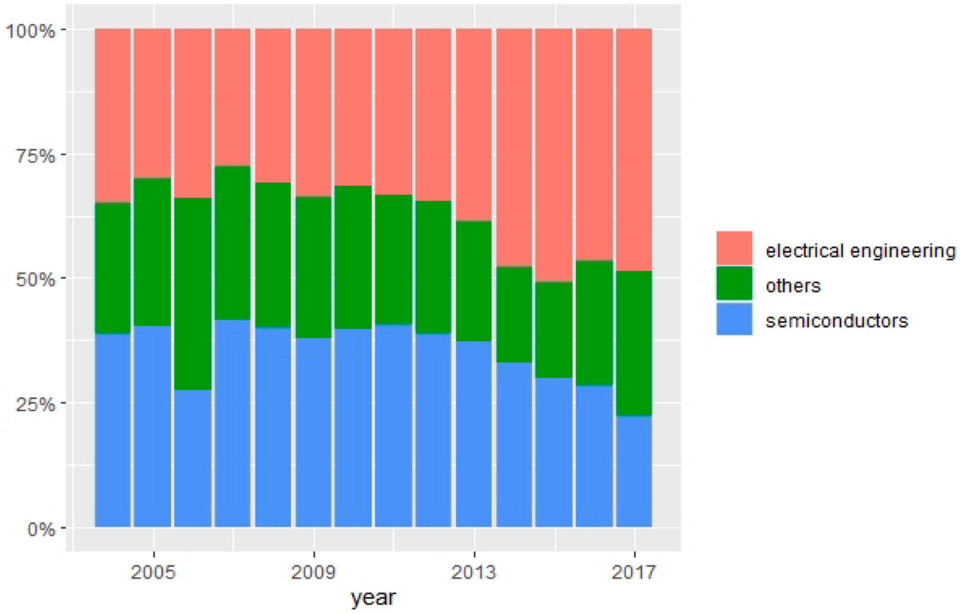

Fig. 4. The evolution of the solar PV knowledge base in China based on the technological fields of patents.
Source: Own calculations by authors based on data from the European Patent Office.

output.

5. Discussion: The relevance of valuation-focused strategies

Juxtaposing our empirical findings to the typology in Fig. 1 shows that the development of the Chinese PV industry followed the *technology catching-up* pathway and built on transplantation strategies in Phase I. National policies largely neglected—and at best tolerated—these industrial developments leading to a firm-level driven catching-up strategy (Dewald and Fromhold-Eisebith, 2015; Quitzow, 2015). The Chinese PV entrepreneurs focused on exporting PV panels to global markets by drawing on resources from the international level (Binz and Anadon, 2018). Phase II was initiated by the shock of Chinese companies losing access to the main foreign markets, which led to a strong shakeout and overcapacities. In this period, the Chinese PV industry— although profited from strong deployment policies that could have enabled the *greening of domestic sectors*—ended up with *forging ahead in pre-existing GVCs* via exaptation, which did not lead to higher-value products and services (Zhang and Gallagher, 2016). More specifically, following the first introduction of the domestic FIT policy, Chinese PV manufacturers vertically integrated upper-stream activities such as wafer and solar cell processing. In so doing, the Chinese PV industry 'moved up the GVC ladder', while building the entire production-based value chains inside China, increasing exports of PV modules, and driving down global prices. These Chinese firms also invested heavily in technological upgrading, substantially increasing the national patent stock in solar PV during this period. The Chinese government only started to promote a more proactive form of market deployment after the anti-dumping policies were imposed, mainly to buffer overcapacity. It therefore remained unclear whether the Chinese PV industry would represent just an example of a low-cost, high-volume manufacturing strategy – exemplifying another middle-income trap case.

Through drastic shifts in directionality policies and entrepreneurial strategies, Phase III demonstrated a period in which the Chinese PV sector mobilized a saltation strategy to move towards *transformative leapfrogging*. This happened through a mix of new types of deployment policies and company strategies that focused on diversification and experimentation. In particular, agile and innovative companies explored new markets as learning testbeds and venture increasingly into PV system integration. Since around 2013, the industry observed increasing dynamics in business models and vertical restructuration, as well as rapid and progressive technological experimentation at the frontier of PV system integration. For instance, one of the generative contexts was PV systems installed in rural areas to help mitigate poverty and integrated into buildings, transport systems, roads, and unproductive land areas (e.g., lakes, deserts). These initiatives required extensive innovation and experimentation in realms conventionally not addressed in the PV manufacturing industry, and which require interrelated knowledge and valuation capabilities.

The Chinese PV sector increasingly engaged in proactive market creation, systemic technological experimentation, and combining diverse knowledge fields (e.g., ICT, double-sided PV cells, power inverters) necessary for effective system integration. Alternative technological trajectories compared to the mainstream have been promoted to achieve higher levels of efficiency, e.g., monocrystalline PV and thin-film PV. Entrepreneurs furthermore introduced new solutions in PV system integration for electricity generation, with Chinese companies leading in the field of high-end installation and application services, such as in power generation, energy storage, and system efficiency. The valuation-focused strategy, therefore, also let Chinese PV companies to find internationally more competitive industry positions as they introduced new products or services, which overall enabled the Chinese PV sector to move away from the labor-intensive and low-cost advantage model towards a market-shaping pathway. Table 2 summarizes the shifts in the development strategy of the Chinese solar PV sector over the three phases.

Drawing on the literature discussed in Section 2 and the findings in this paper, we argue that *transformative leapfrogging* in view of grand challenges rests on three main conditions: (1) actors focusing on innovative options that might be in conflict with the established industry rules and value positions, therefore not following the pre-existing or dominant industry or technological trajectories; (2) building-up new markets by adding attractive features to the non-mainstream or alternative products by targeting new application areas; and (3) expanding the realm of innovation beyond the established technological regime and engaging in radical reconfiguration of the whole socio-technical system. First, in line with various dimensions of the proposed valuation-focused strategy in Table 1, the Chinese PV actors opposed established rules and value orientations in the extant PV industry and its established value chains. For instance, policymakers implemented increasingly strong deployment policies for PV even though the costs of PV-generated energy had not yet reached grid parity. In terms of industry structure, some large companies switched to asset-lite business models although the industry norm at that time was vertical integration along the value chain.

Second, the focus was set on shaping attractive features of PV based products to reach new market segments by convincing different stakeholders about the value of the new options (Jeannerat and Kebir, 2016; Binz and Truffer, 2017). More specifically, non-mainstream options related to manufacturing and product design, such as double-glass solar panels, were developed and brought to scale, which enabled wider PV applications that are less affected by unruly weather conditions. Other leading companies were actively shaping new market segments such as building walls and road trails enabled by thin-film solar PV despite pre-existing

Table 2
Structural shifts along the three development phases of the Chinese strategy in solar PV.

	Phase I: Technology catching-up (late 1990s - 2008)	Phase II: Forging ahead in pre-existing GVCs (2009 - 2012)	Phase III: Transformative leapfrogging (since 2013)
Drivers of change	Building up a regional industry base for PV panel manufacturing supported by German machine tool companies	Safeguarding the considerably grown manufacturing industry	Shaping the frontier of the electricity sector regime; providing clean energy to rural areas; successful implementation of electricity reconfiguration
Primary policy realms	Ignorance by the national policy in the beginning; minimal support by some regional policy makers	Poorly designed deployment policies	Increasingly aligned science, environmental, regional, and industry policy
Core resources	Cheap production costs	Mass manufacturing expertise	Leading scientific and engineering application knowledge; experimental markets; growing PV innovation system with strong indigenous partners
Entrepreneurial strategies	Reverse engineering; anchoring international linkages, e.g., collaboration with the German industry	Vertical integration to achieve high economies of scale	Competitive companies aiming for virtual vertical integration with strong networks of outsourcing partners; high degrees of specialization; emergence of asset-lite ICT based business model focusing on PV system integration
Technology focus	Manufacturing solar cells and modules	Upgrading along the value chain to wafer and solar cell processing	Broader technology portfolios; high-level manufacturing automation; machinery tools competitive with incumbent Western companies; introducing non-mainstream technologies in terms of manufacturing processes and product designs; focused on electricity system integration
Market availability	Global market supported by the EU and the US government deployment policies	First FIT but poorly designed and implemented	Creating new kinds of non-mainstream markets for PV applications including the thin-film solar market segments; extensive domestic deployment policies by the government to create learning and experimental testbeds for indigenous PV system integration companies, which overall help increase price competitiveness
Actor steering domains	Entrepreneurs pioneered the PV industry by leveraging on international resources	Strategies still fell within the realm of companies occupying the value chain; clearly distinctive roles between companies (to manufacture and upgrade) and policy makers (to provide subsidy through FIT)	Involvement of broader incumbent actors; traditional electricity supply companies increasingly transform to enable the use of higher shares of renewable energy; restructuration extends to even basic infrastructure like power grid connection
Leapfrogging aim	Enter the GVC as cheap manufacturers; lead in global market share	Vertically integrate to become a dominant self-sufficient manufacturing hub by internalizing most stages of the pre-existing GVCs	Strategize beyond PV production value chain; transition towards sustainable socio-technical energy systems through systemic market creation and entrepreneurial experimentation to establish new socio-technical configurations

Source: Authors' own elaboration.

skepticism towards thin-film technology among field actors. Third, the strategies building on expected sustainability transitions required the incumbent actors to step out of their established industry practices. PV manufacturing and traditional electricity supply companies increasingly engaged in ICT-related activities to enable more seamless solar PV system integration. Traditional electricity supply companies, meanwhile, took on a more active role in reducing traditional energy sources in the electricity supply mix. Moreover, actors increasingly understood that the entire grid infrastructure had to be reconceived in order to better integrate PV into the electricity system, e.g., by pushing for smart grids and decentralized or stand-alone applications. This also led to fundamentally reconfiguring the roles of and relationships among different system actors (Yang et al., 2021). Instead of focusing on single technologies—the PV cells—the companies increasingly aimed at leading the ICT management of alternative power systems to serve a diversity of market segments. Therefore, companies with a strategy beyond the formerly prevailing value chain catch-up perspective managed to sustain their competitiveness.

We hence argue that the shift to a valuation-focused strategy was necessary for the Chinese solar PV sector to shape newly emerging innovation trajectories, which simultaneously facilitated sustainability transitions. In turn, this may offer a higher potential for actors to endogenize the building of new GVCs and become global leaders of next-generation green energy systems and services. In terms of sustainability transitions, the focus on reconfiguring the domestic electricity system has been pertinent because it opens up new trajectories for accommodating high shares of renewables in the electricity provision, both in China and globally.

6. Implications for a future agenda

The new, green techno-economic paradigm may provide ample windows of opportunity for latecomers (Perez and Soete, 1988; Perez, 2013; Kaplinsky, 2022) to discover new development trajectories through shaping new knowledge and innovation activities, infrastructures, business models, and consumption patterns. To seize these opportunities, actors' strategies have to be informed by a broader understanding of the conditions to successfully develop new socio-technical systems, i.e., to concomitantly address the knowledge- and valuation aspects of innovation. Drawing from the recent experience of the Chinese PV industry, we argue that latecomers aiming to address grand challenges should consider breaking away from the conventional strategy of upgrading or forging ahead in pre-existing GVCs. The proposed valuation-focused strategy is crucial to help latecomers venture into more radical socio-technical developments and steer the directionality of those developments. The *transformative leapfrogging* pathway, as proposed, shows that the ambition of making simultaneous jumps in economic development and sustainability transitions does not always represent direct tradeoffs.

A limitation of the current paper is that China represents a very particular context with its huge and rapidly growing domestic markets in all sorts of basic infrastructures, its capacity to provide a plethora of experimental contexts, high capabilities in mass manufacturing, a huge resource base, and high problem pressures. We maintain, however, that the valuation-focused strategy is also important for other latecomers, especially smaller-sized and middle-income trapped countries such as Malaysia (Cherif and Hasanov, 2015), which could have embarked on successful *greening of domestic sectors*. Although Malaysia accumulated solid technological capabilities from manufacturing PV panels and became the world's third-largest PV exporter, the country has not succeeded in domestic sustainability transitions as it sustained a GVC-based, path-following catch-up strategy. A similar pattern was observed in the case of the semiconductor industry in Malaysia, which aimed at upgrading in the extant GVC in hope to replicate the trajectory of the Taiwanese semiconductor industry but did not succeed (Yap and Rasiah, 2017b, c). Smaller countries may not offer similar home market potentials and resource stocks like China, but only betting on knowledge upgrading to feed into pre-existing GVCs may prove to be a risky development strategy for them. Middle-income countries could focus on specific market segments that serve new applications for which dominant designs have yet to emerge. They may find strategic positioning by pioneering new socio-technical configurations and embedding them in potentially more sustainable sector structures.

Our typology of four development pathways points to a few core areas for future research. First, the valuation-focused approach for both pathways of *greening of domestic sectors* and *transformative leapfrogging* is especially pertinent to address grand challenges. Firmly rooted in catching up with pre-existing GVCs might therefore represent a high liability that may trap the long-term development of latecomers. In particular, we encourage future studies on latecomer catching-up and sustainability transitions to explicate further how valuation-focused mechanisms may endogenize green windows of opportunity (Yap and Truffer, 2019; Kwak and Yoon, 2020) for *transformative leapfrogging*. Admittedly, we have chosen to cast an optimistic outlook on the possibility of such a leapfrog by latecomers. We argue that latecomer *transformative leapfrogging* should not be given up, especially given the urgency of grand challenges. In addition, it will be important to apply and advance our proposed repertoire of valuation-focused strategies to other system transformation areas, such as leapfrogging in ethically sourced raw materials, ecologically sustainable production, and recycling of used materials.

The above points to the second research area addressing how latecomers may break away from their current pathways toward more sustainable ones. The presentation of the Chinese PV case as a 'sequential trajectory' might be interpreted as valuation representing just the final development step in an otherwise conventional knowledge-focused catch-up process. We maintain, however, that this would be a too narrow reading of the actual developments. The actual Chinese development trajectory was riddled with fundamental breaks and crises over all three phases, putting huge industry and environmental costs in the form of shakeouts and high production of waste. Our analysis suggests that an earlier embracement of the valuation-focused strategy could have prevented at least parts of this painful boom and bust cycle. Although it is beyond the capacity of this paper to argue with a historical counterfactual, the three disrupted development periods suggest that an integrated approach could have led to a more seamless trajectory. Therefore, future studies should explore how latecomers may embark early on valuation-focused pathways by building on their local resources.

Manifold tradeoffs will have to be considered as latecomers navigate across the different pathways towards *transformative* *leapfrogging*: goals of early industrialization, short-term economic gains, job creation, footholds in global industry structures, sustainability transitions, environmental and ecological repercussions, etc. Earlier assessments have shown that latecomers may find stronger footholds in future global markets if they invest early enough into 'greening now' than 'cleaning up later' (Pegels and Altenburg, 2020). Latecomer developments may also encounter incumbencies of other interrelated industries or sectors from a 'multi-system' perspective (Andersen and Markard, 2020; Rosenbloom, 2020). The pathway they choose for one industry or sector could limit their strategies in another, e.g., a narrowed *technology catching-up* strategy in generic semiconductors may affect the latecomers' strategic options in solar PV. Therefore, it is essential to explicate how valuation-focused strategies battle these tradeoffs and unconducive path dependencies towards *transformative leapfrogging*.

Last but not least, future studies should analyze how the proposed framework of latecomer development pathways may help address challenges related to *just* transitions (Swilling et al., 2015; Swilling, 2020). The transformative leapfrogging of a latecomer could lead to the entrenchment of new types of latecomers in a less sustainable pathway. In the presented case, the successful leapfrogging of China in the PV sector may have left limited leeway for the Malaysian PV sector to break out of the technology catching-up pathway. Meanwhile, studies found that the deployment of Chinese renewable energy infrastructures in sub-Saharan Africa led to only limited local economic benefits in sub-Saharan Africa (Lema et al., 2021) or conflicts with the local communities (Shen, 2020; Bhamidipati and Hansen, 2021). These examples point to the urgency for the new latecomers to switch to the valuation-focused strategy in order to reduce their dependencies on foreign resources, although this may seem unrealistic to those without the necessary basic conditions. This overall suggests that there is a need to better understand the competitive power struggles among latecomers situated at different development stages and as they move across the different pathways. These are indeed important research questions to be addressed in view of ever complex grand challenges of our time.

Declaration of Competing Interest

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

Data availability

Selected data can be made available on request.

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Appendix 1. List of interviews conducted

No.	Stakeholder type	Interviewee	Code	Expertise
1	Academia (AC)/ Policy Expert (PE)	Chinese Academy of Sciences 中国科学院	AC/ PE1	Innovation policy
2		Tsinghua University 清华大学	AC/ PE2	Innovation policy
3		PV committee of China Green Supply Chain Alliance 光伏专委会	AC/ PE3	Industry policy, alliance committee
4		North China Electric Power University (NCEPU) 华北电力大学	AC/ PE4	Policy research and consultancy
5		China National Renewable Energy Center (CNREC) 国家可再生能源中心	AC/ PE5	Policy research and consultancy
6	Intermediary (IN)	Green Peace 绿色和平	IN1	Non-governmental organization
7		China PV Industry Development Association中国光伏产业发展协会	IN2	Policy consultancy
8	Technological company (TC)	Hanergy 汉能	TC1	Thinfilm solar
9		Sungrow 阳光电源	TC2	Inverters, energy storage
10		Shanghai Institute of Microsystem & Information Technology (spin-off) 上海新微	TC3	Inverters, energy conversion, testing, thinfilm silicon cell, ICT
11		Sunpreme 上澎太阳能	TC4	Thinfilm silicon cell on double glass

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(*continued*)

No.	Stakeholder type	Interviewee	Code	Expertise
12		CETC Solar Energy Holdings CETC太阳能	TC5	Vertical integration (from modules to inverters)
13		Flat Glass Group 福莱特	TC6	Double glass manufacturing
14		Trina天合光能	TC7	Virtual vertical integration (towards asset-lite)
15		LONGi 隆基	TC8	Vertical integration (monocrystalline)
16		LONGi 隆基	TC9	Vertical integration (monocrystalline)
17		TBEA特变电工	TC10	Inverters, energy storage
18		Former Suntech 尚德	TC11	PV modules
19		GCL System Integration Technology 协鑫	TC13	Vertical integration (from silicon raw materials to power stations)

Source: Authors

Appendix 2. Patent statistics for reconstructing the knowledge development of the Chinese PV industry

We extracted solar PV patent applications filed between 2004 and 2017 from the European Patent Office (EPO) Worldwide Patent Statistical Database PATSTAT (2020 spring version) using both the Y02E10/5 code in the recently developed Cooperative Patent Classification (CPC) (Veefkind et al., 2012) and the search strategy proposed by Kalthaus (2019). We assigned solar PV patents to countries based on the country information of the first inventor listed in the patent document following Mancusi (2008). The residence addresses of inventors provide a good proxy for the locations of R&D activities (de Rassenfosse et al., 2013). We further used patent classes in the International Patent Classification (IPC) to measure the knowledge base of countries in solar PV. We aggregated patent classes to different technology fields using the World Intellectual Property Organization (WIPO) IPC-Technology Concordance Table developed by Schmoch (2008). In order to remedy the issue of multiple equivalent patents for one invention in multiple offices, we used the simple patent family definition in the PASTAT as the unit of analysis (Martinez, 2011). The year of a simple patent family is the application year of the earliest patent in the family. One 'patent' represents one 'simple patent family'.

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