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Xiao-Shan Yap, Bernhard Truffer, Deyu Li & Gaston Heimeriks

Utrecht University Human Geography and Planning

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Xiao-Shan Yap1,2,*, Bernhard Truffer1,2, Deyu Li1,3, Gaston Heimeriks1

1 Copernicus Institute of Sustainable Development, Utrecht University, the Netherlands
2 Eawag, Swiss Federal Institute of Aquatic Science and Technology, Switzerland
3 Center for Environment, Energy and Natural Resource Governance, University of Cambridge, United Kingdom

*Corresponding author
Email: xiaoshan.yap@eawag.ch
Full postal address: Department Environmental Social Sciences, Eawag, Ueberlandstrasse 133, 8600 Dübendorf, Switzerland.

**Abstract**

Recent research in catching-up and leapfrogging literature has been at pains to explain how latecomer countries, besides a few exceptional cases, could achieve leadership positions in global industries. We propose to extend the potential development strategies by drawing on recent insights at the interface between economic geography and socio-technical transition studies. Whereas the extant catch-up literature has strongly focused on conditions of knowledge development, we claim that processes of "valuation" and in particular the formation of new markets needs to be considered more explicitly. Drawing on recent developments in the Chinese solar photovoltaics industry, we show how companies in the country moved from a knowledge based catch-up strategy, to increasingly leading the innovation frontier of the PV sector. However the most promising leapfrogging opportunity only seems to take shape in the most recent phase, where market deployment and entrepreneurial experimentation increasingly target a transition of the electricity sector towards accommodating a high share of renewables. In a nutshell, the experience of the Chinese solar photovoltaics industry progressed from manufacturing PV cells, to climbing the value chain ladder, and finally towards the construction of entirely new socio-technical systems. We argue that this approach is increasingly necessary as sustainability requirements become more urgent and that other countries may learn in order to move out of the middle-income trap.

Keywords: Catch-up; Leapfrog; Middle-income trap; Socio-technical systems; Knowledge; Unrelated diversification

## Introduction

Studies concerning industrial catching-up in developing countries have very much emphasized the overarching importance of (technological) knowledge base and capabilities for latecomer countries to leapfrog global incumbents. As one of the core inspirational cases, the semiconductor industry served as a model for how developing countries could successfully leapfrog. These experiences drew primarily from a few exceptional success stories of South Korea, Taiwan, and to a lesser extent, Singapore (Hobday, 1995; Lee and Lim, 2001; Lee and Malerba, 2017). The underlying factor of these successes have been closely associated with the interplay between supportive national institutions in the latecomer countries and firm strategies for driving the accumulation of technological knowledge and capabilities (Lall, 1992; Kim, 1997; Lee and Lim, 2001; Mathews and Cho, 2007; Figueiredo, 2008). A number of other countries such as China and Malaysia have subsequently envisaged to follow the footsteps of these successful cases. However, experience proved that success is not easily replicated and that not every latecomer will be able to leapfrog global incumbents in high-tech industries. At the same time, the increasing international sustainability debate challenges developing countries to achieve additional goals through their industrial policy strategies (Schot and Steinmueller, 2018; Yap and Truffer, 2019).

In the present paper, we argue that the prevailing focus of catch-up studies on conditions for knowledge generation has to be extended in order to simultaneously achieve broader sectoral goals. Such a broader approach complements catching-up theories with recent insights from economic geography and transition studies. We will derive core mechanisms and processes associated with this broader perspective from an in-depth case study of latest developments in the Chinese solar photovoltaic (PV) industry. We will show how in the latest phase, an orientation on socio-technical system transformation has moved center stage, which addresses sustainability concerns more explicitly and which also promises to prevent the country from falling into the middle-income trap.

The need for extending the knowledge-based view on industrial success has recently been resonated in a field of scholarship related to industrial catching-up - economic geography. Research in evolutionary economic geography repeatedly proved that “related knowledge” is the key success condition for national or regional industrial path creation (Boschma, 2017), i.e. cities, regions or countries will be more successful in the creation of new industrial paths if they have a strong knowledge base in technologies that are similar in terms of capabilities and knowledge stocks. However, while the majority of industrial path creation can be well explained with this argument, it was also shown that this works better for incremental innovations than for radical jumps in the knowledge space (Saviotti and Frenken, 2008). Therefore, processes of unrelated diversification have gained increasing interest. Boschma et al (2017) argued in their theory of regional diversification that complementary resources had to be considered for explaining success cases that lacked strong related technical knowledge and capabilities. Building on recent insights of socio-technical transition studies, they highlighted the importance of competencies for managing the “valuation” part of innovation, which encompasses the building of markets, the mobilization of financial resources and the leveraging of legitimation for the new technology (Binz and Truffer 2017; Jeannerat and Kebir 2016; Binz et al. 2016a). Instead of drawing primarily on the best available knowledge leading to an emphasis on high technical education and supportive policies for university-industry exchange – or in the case of catching-up studies, support of knowledge exchange between multinational corporations (MNCs) and local companies – the valuation focused approach suggests to include deployment policies, market formation and legitimation aspects of the new industries. Or in other terms, the focus of innovation has to change from single technologies to the reconfiguration of entire new socio-technical systems.

In the context of the established catching-up literature, indigenous industrial development is mostly based on export-oriented strategies. Hence, valuation related processes are mostly considered as exogenous, defined by global markets with clearly defined product characteristics. The role of developing countries has therefore mostly been perceived as suppliers of components to an otherwise predetermined socio-technical system, which pre-exists elsewhere (Pietrobelli and Rabellotti, 2011; Lee and Malerba, 2017). At the same time, these technologies are also considered as the gold standard for their own domestic use. Global markets therefore represent an external selection environment, which can hardly be shaped by any specific country (Yap and Truffer, 2019). We therefore argue that in order to achieve leading positions in emerging cleantech sectors, developing countries should start proactively strategizing on new products and services by simultaneously working on legitimation, resource mobilization and new market formation, in order to shape and demonstrate new socio-technical systems. In other words, developing countries should 'endogenize' the valuation processes.

In this paper, we conceptualize and illustrate the endogenization strategy by a major recent development of which China became a global leader in the solar PV industry. We observe an emblematic shift of a national industrial strategy, which started as a knowledge focused approach and increasingly shifted to a valuation oriented one. We start from the observation that knowledge-based strategies provided a basis for Chinese firms in catching up and ultimately reaching a leading position in the global value chain (GVC) of solar PV. It however only led into a position as a low-cost mass manufacturers with limited potential to achieve higher income status. Valuation-oriented activities became more and more prominent only in the last decade. They enabled Chinese companies to co-shape more radical shifts in the electricity sector, which opened up entirely new trajectories for PV based and potentially more sustainable future electricity sectors.

The paper proceeds as follows: Section 2 discusses recent developments in the catching-up, economic geography and sustainability transitions literature, which suggest a broader understanding of how latecomers could embark on new industry paths. Section 3 will shortly retrace the historical development of the Chinese PV industry and elaborate the methods used to analyze the empirical case. Drawing from expert interviews, section 4 analyses how actors in China are increasingly implementing a more integrative strategy of knowledge and valuation. We complement the micro-level evidence for a new quality of innovation processes with an analysis of the patent portfolio of leading companies in China which provide more macro-level indicators for these shifts. Section 5 discusses how the integrative strategy has overall led to a highly promising socio-technical reconfiguration of the electricity sector in China, which therefore brings leapfrogging opportunities to the Chinese PV companies. Section 6 concludes by pointing to the broader relevance of these arguments for theorizing catch-up and leapfrogging.

## 2. From knowledge-based to valuation focused industrial strategies

### 2.1 Catching-up studies: moving beyond knowledge

Studies concerning latecomer catching-up became increasingly prevalent since the 1990s, following the successful cases of South Korea and then Taiwan and Singapore (Amsden, 1989; Mathews, 1997). Scholars in this field adopt different theories and methods for analyzing the catching-up processes. The main arguments have heavily centered on the role of an appropriate knowledge base in the respective countries. As a consequence, research asks how institutions can improve national absorptive capacity for knowledge accumulation, for instance by building on the national innovation systems framework (Lundvall, 1992; Fu et al., 2011). Other research focuses on how latecomers should strategize for acquisitions of external knowledge by drawing on the management literature like the resource-based view (Mathews, 2002; 2006); the role of broader institutional systems for knowledge generation (Mathews and Cho, 2007); firm-level knowledge accumulation (Lall, 1992; Figueiredo, 2008); organizational strategies to leapfrog in terms of technological capabilities (Kim, 1997; Lee and Lim, 2001); and knowledge insourcing via linkages to GVCs (Mathews, 2002; 2006; Vind 2008; Pietrobelli and Rabellotti, 2011; De Marchi et al., 2018).

Among these different approaches, external linkages at the international level and with MNCs are reckoned as the most promising sources of knowledge as these knowledge stocks mostly did not pre-exist in developing countries. These latecomers thus are most attracted to sourcing the external knowledge in order to increase and broaden their technological capabilities with the hope to develop new indigenous industries or to attract foreign direct investments. Therefore, the notion of leveraging on GVCs is strongly anchored in studies concerning catching-up, focusing on how latecomers may strategically insert themselves into existing GVCs in order to internalize knowledge from the MNCs (often through reverse engineering practices) and then gradually move up the GVC ladder (Kim, 1997; Mathews, 2006; Figueiredo, 2008; Vind 2008; Pietrobelli and Rabellotti, 2005; 2011). More often than not, these approaches represent rather linear trajectories as most latecomers begin by becoming contract manufacturers to the MNCs (i.e. original equipment manufacturers) due to lower cost of production. They may later move up to become original design manufacturers and eventually original brand manufacturers (Hobday, 1995; Gereffi, 1999; Humphrey and Schmitz, 2002; Pietrobelli and Rabellotti, 2011). Non-linear catch-up trajectories were discussed under the label of leapfrogging, of which latecomers skip certain technological steps and jump to more advanced progresses through institutional or organizational strategies (Lee and Lim, 2001). The focus however still remains on improving technological capabilities as the key determinant to success.

Latecomer countries thus often invest considerable amounts of their resources into building a knowledge economy with the hope to embark on new technological pathways. However, histories show that many developing countries are still not able to build indigenous industries that generate high-income economic activities. Catch-up studies are therefore in need of new approaches that offer strategies broader than the conventional view of building up knowledge or technological capabilities. This call becomes all the more imperative as industrial economists have recently argued that the world is entering into a new techno-economic paradigm, of which a number of longer-term economical and societal trends emerge as a result of increasing globalization, technological revolutions building on information and communication technologies, and environmental sustainability concerns (Perez, 2013; Mathews, 2013). Latecomer countries as a consequence face the simultaneous challenge of driving economic growth while solving environmental sustainability issues in their nations.

Recent studies concerning catching up have increasingly pointed to new elements that can play equally decisive role for latecomers, such as creating markets, mobilizing resources, entrepreneurships, and directionality in shaping sectoral selection environments (Binz and Anadon, 2018; Yap and Truffer, 2019). Scholars furthermore pay increasing attention to the role of windows of opportunity and how latecomers may appropriate such windows (Lee and Malerba, 2017; Yap and Truffer, 2019). Catching up in the emerging green techno-economic paradigm is a complex process. The global shift towards green growth means many cleantech industries are currently emerging for which no dominant designs exist yet; this might provide ample windows of opportunity for latecomers to leapfrog if they find broader, alternative solutions to effectively position themselves in future global industries.

**2.2 From technology focused catching-up to reconfiguring socio-technical systems**

To extend the extant catch-up theorizing, we draw on recent insights from related fields. Economic geography, for instance, focuses on how countries and regions can diversify onto new industrial and technological development trajectories, and how they develop new growth paths (Neffke et al., 2011; Rigby, 2015; Trippl et al., 2017; Martin, 2010). Recent research in this field showed consistently and in countless studies that the creation of new regional industrial development paths depends on the availability of prior related knowledge stocks in the region (Boschma, 2017). This "related variety" argument has been robustly reproduced even when using different dependent variables, different measure of relatedness, different geographical units and different time periods (Boschma, 2017). Like most of the catch-up literature, also these studies therefore 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, which is the focus of most catch-up studies, or they may bet on specific natural context conditions or simply trust in serendipity (Trippl et al., 2017).

Despite explaining the large majority of new industry formation processes in regions of OECD countries, there are still a number of cases that cannot be explained by a relatedness argument (Castaldi et al., 2015). New industries sometimes emerge in places that have no particularly competitive related knowledge (Binz et al., 2016b; Yap and Truffer, 2019). It has been argued that cases of "unrelated" diversification are particularly relevant for disruptive novelty and also for tackling grand challenges like sustainability transitions. Related diversification is mostly contributing to the incremental improvement of existing development paths, which risk to be soon exhausted (Saviotti and Frenken, 2008). As a consequence, the explanation of unrelated diversification processes received increasing attention over the past few years (Boschma et al., 2017).

Drawing on these insights, Boschma et al. (2017) proposed a "general theory of diversification" borrowing on insights from the recent socio-technical transitions literature. The latter suggests that latecomers should seek for success conditions 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). This means that the object of innovation should not be limited to the nuts and bolts of the technology, but that equal attention should be paid on how these technologies align with broader institutional structures, i.e. how valuation processes are managed.

Due to the fundamental uncertainties that are associated with the multi-dimensional innovation process, new socio-technical systems will rarely be developed on the spot by a genius inventor or even a single company. Rather, successful transformations will be the result of longer-term efforts of system building in aligning new technologies, infrastructures, user habits and preferences, institutional contexts and discourses (Hughes, 1993; Markard et al., 2012; Geels, 2002). The literature on socio-technical transitions proved particularly fruitful in analyzing such socio-technical innovation processes in the context of grand challenges like sustainability, climate change, ageing, internet crime and youth employment (Coenen et al., 2015). The argument here being that these grand challenges ask for fundamental transformations of our production and consumption patterns, which cannot be achieved by incrementally changing current technologies, products and lifestyles. Sustainability transitions research has meanwhile gained increasing attention in policy circles and in academia (Markard et al., 2012) and numerous cases of successful transformations have been analyzed all over the world.

Transition theorizing emphasizes the importance of analyzing multi-actor learning, innovation and institutionalization processes in experimental settings where new technologies, new business models, user patterns and new institutional frameworks are tried out and tested (Hoogma et al., 2002; Schot and Geels, 2008). Once a specific region has been able to elaborate stable socio-technical structures in local testbed markets and demonstrate the functionality of these technologies and products, this will provide a comparative advantage to secure strong positions in the respective emerging industries for long into the future.

The sustainability transitions literature mainly evolved by drawing on cases from OECD countries. However, more recently, catch-up and leapfrogging problems have gained increasing interest (Coenen et al., 2012; Truffer and Coenen, 2012; Hansen and Coenen, 2015). Recent studies on the successful catch-up of China in cleantech sectors, for instance, showed how actors in Beijing were able to anchor international competences in their region by building up conditions for early market formation and by providing an experimental context in the sector in which start-ups could learn and expand (Binz et al., 2016b). In a similar vein, Yap and Truffer (2019) showed how the Chinese urban water management sector experienced a fundamental shift in its dominant technology. This provided the context in which Chinese companies were able to leapfrog the respective global industry. Leading Chinese companies, together with universities, design institutes and government departments managed to align societal visions and expectations, new policies and regulations, a reform of sectoral structures and the creation of rapidly growing markets into a socio-technical configuration that is able to achieve globally unmatched water quality standards.

Building on these partial studies, Binz and Truffer (2017) recently introduced the framework of Global Innovation Systems, which conceptualizes formation processes of new socio-technical systems at different scalar levels (local, regional, national, global). Essentially they argue that actors in different regions can play essential roles in developing new technologies, products and services if they find a supportive institutional environment within their local territories and if they are able to "structurally couple" with resources from other places across the world. The core processes which have to be covered to generate innovation success have been categorized into either valuation or knowledge related. Valuation refers to those processes in technology development that lead different stakeholders to appreciate the new option as being more attractive compared to established alternatives (Jeannerat and Kebir 2016). Valuation therefore relates to the formation of new markets by specifying attractive features of the innovation for specific segments of customers. But beyond that it also encompasses those activities that influence support or opposition of broader stakeholder groups 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 funding or legitimacy which are essential for the new technology or industry to develop (Markard et al 2016; Binz et al. 2016b). Valuation is key for entrepreneurial activities in the form of marketing, corporate communications or lobbying. The success of valuation can, in general, not be controlled by single companies but will result from the interplay between different actors like companies, users, advocacy groups, governments, etc.

We take from these recent insights into socio-technical innovation processes for the catching-up strategies of developing countries that they have to increasingly target the construction of entirely new socio-technical systems instead of single components, technologies or products. This requires capabilities for managing broader innovation processes than those for building new knowledge or technological capabilities. They have to increasingly endogenize valuation aspects. Policy implications will be that more emphasis has to be put on experimental settings and on balancing broader societal goals like sustainability transitions, distributional justice and industrial catch-up (Yap and Truffer, 2019). In particular, market creation policies have to be seen as an integral part of catch-up and innovation policies not only to provide secure outlets for a rapidly expanding indigenous industry, but more importantly as prime opportunities for learning about how to align technologies with their institutional contexts.

Applying these insights to the challenges of countries seeking to break out of the middle-income trap suggests integrated strategies encompassing valuation alongside indigenous knowledge processes. The valuation oriented innovation competencies may relate in particular to the formation of markets, in terms of new product and system configurations and addressing new user segments. It also addresses the co-shaping of technology legitimation in public discourses, as well as leveraging material and symbolic resources from different actors in the country. This could eventually allow catch-up companies to take leaderships in emerging GVCs, which offer products and services that serve new kinds of market contexts. Table 1 summarizes the main structural differences between a conventional knowledge based catching-up strategy and the new valuation focused approach.

Table 1: Structural differences between knowledge-based and valuation-focused strategies of catching up

| | **Knowledge-based perspective** | **Valuation focused strategy** |
|---|---|---|
| **Policy goal** | Competitive position in GVCs | High added-value positions and/or sustainability transition |
| **Core resources** | Related or imported knowledge; understanding global market conditions | Capability of system building and experimenting; leveraging local conditions |
| **Technology focus** | Existing value chains | Creating new socio-technical systems |
| **Market formation** | Exogenously given | To be shaped indigenously |
| **Entrepreneurial strategies** | Re-engineering; collaboration with MNCs | Experimenting; coordination within relevant innovation systems |
| **Primary policy realms** | Science, education and industry policy | Science, environmental and industry policy; deployment policies |
| **Catch-up mechanism** | Climbing up the value chain | Leapfrogging; leading socio-technical transitions |

Source: Authors.

### 3. Background for case selection and methods

In order to identify and specify key mechanisms of the valuation focused strategy, we conducted an inductive approach based on process tracing of a single exemplary case study (Yin, 2016). The development of the Chinese solar PV industry has been analyzed by many researchers in the past years, mostly reporting the rapid takeover of market shares in manufacturing PV modules in the 2000s and gaining world leadership after 2010 (Dewald and Fromhold-Eisebith 2015; Binz et al. 2017). Solar PV represents one of the key industries related to sustainable transitions in the electricity sector and gaining global leadership as an emerging economy has been repeatedly presented as a poster case of a new kind of green catch-up (Fu and Zhang, 2011; Zhang and Gallagher, 2016; Shubbak, 2019). However, the benefits as a result of the catching-up process in terms of substantially higher incomes remains unaddressed. In particular also, the Chinese government was initially very reluctant to support this industry (Zhang and White, 2016). It therefore appeared as if it would end up as yet another case of a conventional industrial development path, which led straight into another middle-income trap. However, more recently we observed fundamental changes in the framing of the innovation task of many Chinese actors, along with a more proactive uptake of market creation policies and a rapid shift in the structure and orientation of the PV innovation system in China. As these developments correspond largely with what we would expect for a value focused development trajectory, we chose this case for a deeper analysis of process tracing to identify key mechanisms, strategies and goal orientations that may be associated with a value focused approach.

China began as a manufacturing base producing PVs to export to the US and European markets in the 1990s. Since 2008, the Chinese government introduced domestic market deployment policies following the anti-dumping tariffs on Chinese solar PV panels introduced in the US and the European Union (EU). The production level of Chinese owned PV panels increased and China quickly became the world's largest PV producer and user. Since the early 2010s, the Chinese solar PV industry has experienced a restructuration process of which PV companies increasingly moved into broader innovation activities that are beyond the focus of PV production. While earlier studies emphasized the role of private entrepreneurships in the early industry formation of the Chinese PV industry (Zhang and White, 2016; Binz and Anadon, 2018), this paper will focus on the most recent strategies deployed in the Chinese PV industry since the early 2010s (analyzed in Section 4). In the following, we will set the background of our analysis by providing a brief history to the earlier development of the Chinese PV industry based on two phases, i.e. late 1990s to late 2000s; and late 2000s to around 2013. Subsequently we will outline the methods we used for analysis in this paper.

### 3.1 The development of the Chinese solar PV industry

*Formation, boom and crisis (late 1990s – late 2000s): positioning in pre-existing GVCs*

China did not have a strong knowledge base in solar PV in the early phase of the industry formation. The Chinese government was furthermore not convinced to channel large financial resources into building this industry. During this period of time, Chinese entrepreneurs (including internationally well-connected returnees from abroad) played the crucial role in forming the infant stage of the industry (Zhang and White, 2017). The entrepreneurs mainly drew different resources through international networks, including knowledge, finances, markets, and technology legitimacy (Binz and Anadon, 2018).

The GVC position of the Chinese solar PV manufacturers during this phase was mainly to produce solar modules in order to export to foreign markets, i.e. the US and Europe. German PV companies were attracted to outsource their module production to the Chinese manufacturers at that time due to lower costs of production (Dewald and Fromhold-Eisebith, 2015). Some Chinese PV companies at that point in time sought to engage with the more advanced MNCs to exchange on innovative activities. However, Chinese PV manufacturers were very much reliant on the supply of advanced machineries from German companies (Quitzow, 2015). Sometimes, the waiting time to receive machinery components from the German suppliers was as long as nine to twelve months, taking into account the shipment period. Such a rather long waiting period slowed down the production process of the Chinese manufacturers, as their orders were not the top priority of the suppliers.

The global market share of the Chinese PV production increased quickly as more Chinese entrepreneurs entered the industry scene and their products improved in terms of quality. During that phase, Chinese solar PV companies have secured a strong position in the GVC of PV. Around 2005, China became the largest PV producer worldwide. At that time, these manufacturers mainly relied on foreign markets due to the lack of a domestic PV deployment policy.

The boom of the Chinese solar PV industry however came to a halt when the global financial crisis in 2008 led to the end of subsidized PV in many markets overseas. Moreover, the US and EU decided to impose the anti-dumping tariffs on all PV products imported from China in order to protect their home industry as they had lost substantial market share to the Chinese producers by then. As exporters, many Chinese PV firms encountered losses at that point. Most of the Chinese PV manufacturers, as a consequence, suffered and crumbled over substantial financial debts. The industry experienced the first restructuration process, of which many companies did not survive.

*Exponential growth (late 2000s – around 2013): bigger and stronger in pre-existing GVCs*

Following the financial crisis and the introduction of the anti-dumping policies, the Chinese PV industry became increasingly consolidated. Large companies moved towards becoming vertically integrated producers for polycrystalline solar PV while smaller companies did not survive the competition due to shrinking demand. The common rationale for pursuing a vertically integrated business model during this phase was to achieve higher economies of scale, hence lower cost per unit and higher returns. The intensified price war caused some large companies like Suntech and LDK Solar to eventually file for bankruptcy, in 2012 and 2014 (Binz and Anadon, 2018). To salvage the weakened domestic PV industry, the Chinese government decided to initiate the national feed-in-tariff (FIT) around 2010 to support indigenous market deployment. The subsidy program was meant to induce the growth of Chinese PV manufacturing and provoked high entry of new companies. This consequently led to an overcapacity situation, of which large companies began to lower their prices at an increasing rate. On the other hand, the exports of Chinese PV recovered, including the exports to other developing countries. New types of companies also entered the industry focusing on technologies beyond the mainstream polycrystalline PV, but also monocrystalline and thinfilm technologies. The Chinese solar PV industry became stronger with companies venturing into upper stream activities such as silicon, ingots, and battery cells. Instead, market deployment policies for PV were not well implemented in China at that time. Several problems plagued the market development: late incentive payments by the government which caused financial issues to a number of large PV companies, low quality products, and excessive promotions by regional governments without close monitoring created an explosive boom of newly built plants which never actually started operating.

These two development phases of the Chinese PV industry built on the nation's related capabilities in manufacturing in general and in the semiconductor industry in particular. Despite China was never able to leapfrog in the semiconductor industry, the PV industry could rely on some semiconductor competences (e.g. processes involving silicon and wafer slicing). Vertical integration into upper stream activities is a typical strategy suggested by conventional catch-up studies. However, the strategies were not sufficient to create high-value industry paths that would eventually support industrial and environmental leapfrogging. Section 4 will therefore analyze how Chinese actors began to embark on broader-than-knowledge strategies to build new socio-technical systems after the early 2010s.

### 3.2 Methods

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 (associations, alliances, consultancies and expert committee members); domestic PV manufacturers, domestic and foreign technological companies; as well as key part and component suppliers. The interviews were conducted in 2018 in the cities of Beijing, Shanghai, Anhui, Zhejiang, Jiangsu and Xian. To identify the potential for leapfrogging among the Chinese PV companies, the priority of interviews was given to companies that proactively seek new business models and entrepreneurial experimentation. The interviewed companies for this study were therefore selected on the basis that they are leaders of particular activities concerning PV production or system integration in China, for example in installations and maintenance, balance-of-systems, information and communication technologies (ICT), energy efficiency and storage, as well as servicing. The interviewees also included the most representative industry association and consultants, which carry a rather neutral stand, and an exemplary failed PV company known as a core indigenous pioneer in the 1990s. All interviews in this 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 to build an in-depth case study on the Chinese solar PV industry (Yin, 2011; 2014).

In order to assess developments of the knowledge base over time, we also reconstructed patent indicators (see section 4.4). We identify solar PV patent applications filed between 1986 and 2014 from European Patent Office Worldwide Patent Statistics Database PATSTAT (EPO, 2017 spring version) using the Y02E10/5 code in the recent developed Cooperative Patent Classification (Veefkind et al., 2012). The value chain of solar PV industry can be divided into three different segments, upper stream, midstream and downstream. The upper stream segment includes silicon, ingot and wafer manufacturing. The midstream segment comprises the manufacturing of cell and module. In the downstream segment, solar modules are integrated into the system together with other components like invertor to form a PV power plant (Carvallo et al., 2017). We assign solar PV patents to different value chain segments using the search strategy developed by Kalthaus (2019).

The subsequently paper uses backward citations of patents to measure the knowledge origins of solar PV patents. We used information on inventor location and technology class to place a cited patent in different categories along geographical and technological dimensions. First, we label a cited patent of inventors in the same country as inventors of the citing patent as domestic knowledge, otherwise foreign knowledge. Second, we aggregated the backward citations to different technology fields developed by Schmoch (2008). In order to remedy the issue of multiple equivalent patents for one invention in multiple offices, we used the DOCDB patent family definition (Martinez, 2011). The year of the DOCDB patent family is the application year of the first patent in the family.

## 4. Tapping emerging windows of opportunity: towards a new socio-technical system

Since around 2013, i.e. largely after the conventional technology-based strategy had almost let into an economic crash in the then rising Chinese PV industry, a rather fundamental change in the overall innovation approach took place. This led to the development of a much broader range of business model and innovation strategies. Drawing from the interview insights, we will in the following elaborate on i) the shift of the Chinese PV industrial policy towards emphasizing the valuation contexts such as through the introduction of the deployment policies; ii) the impact on company innovation strategies for strengthening valuation; and iii) how this eventually leads to a widening innovation system boundary with a stronger orientation on the whole socio-technical configuration. We will finally provide a background patent analysis on how the knowledge dimension of the Chinese PV industry evolved over the time in which the shift of the strategy took place.

## 4.1 From a knowledge focused to a market oriented industrial policy approach

Although domestic market deployment of PV was already introduced by the Chinese government in the early 2010s especially following the anti-dumping policies of the US and the EU, a number of impediments did not allow the PV deployment process to take off smoothly. Typical examples of issues were the inertia caused by incumbent actors (i.e. traditional grid and energy suppliers), curtailment problems, inefficient grid connections, prices of renewable energy supply, etc. The implementation of PV deployment in China only started to be efficient around the mid-2010s. The 13$^{th}$ five-year-plan began in 2016, of which national policies greatly promoted large deployment of renewable energies. It also encouraged a more endogenized understanding of deployment policies, i.e. the formulation of market incentives that would at the same time encourage technological improvement of the PV products and the associated system integrations.

One of the most crucial of these market deployment policies was the "PV Forerunner Base Plan". The main objective of this policy was to overcome the quality issue of the PV panels by imposing strict monitoring on the performance of the PV panels being installed. The Forerunner Plan formulates the highest quality standards for PV panels endorsed by the government. This standard was subsequently applied to a number of different regions in the country in order to control the quality of PV panels supplied. This induced intense R&D competition as only highly innovative companies were able to acquire new projects. Imposing the PV Forerunner Base Plan across different regions provided on-the-ground demonstration sites for Chinese PV companies offering the best quality of products. Later, the government furthermore introduced the "PV Super-Forerunner Base Plan", which only selects the products of a few top Chinese PV companies to serve as the next-generation technology trials.

Another critical market deployment policy during this period of time was the PV Poverty Reduction Policy, which aims to help the poor (mostly in rural areas of the country) by building PV panels on residential rooftops in order for them to sell back the electricity to the government as a source of income. The policy moreover strictly imposed that only the best-quality PV panels could be used in these development projects. As of the end of 2016, the first PV Poverty Reduction project accounted for scale of a total of 5.16 million kilowatt, of which village-level power plants produced 2.18 million kilowatt and centralized power plants 2.98 million kilowatt.

In this process, the pricing policies for grid connected solar energy was also revised to a more affordable level. Furthermore, the construction plans of PV power plants aimed at preventing local governments from approving excessive projects (often left un-operated) due to attractive incentives. To overcome the barriers of the conventional electricity system, quality and services based competition was implemented in different regions and the minimal grid capacity connected for PV generated power was increased to reduce curtailment of renewables.

As a consequence of these specific deployment policies, the technological capabilities of Chinese PV companies in turn also further improved. The Forerunner Base and Super-Forerunner Base Plans in particular induced technological competition among the industrial players. This led to Chinese PV manufacturers gaining a competitive edge beyond lower costs of production, which in turn boosted innovativeness and the quality of the products. The companies were furthermore provided with a large and easily accessible test bed in terms of multiple market contexts, which provided ample learning opportunities for new system configurations.

### 4.2 Dynamics of business restructuration

These market deployment policies also led to a shift in the business rationales of most of these companies. Overall, wider applications of PV induced new experimental initiatives and new business models across different companies in the sector, including vertical integration or disintegrations of value chain activities, as well as, innovations outside the production value chain (i.e. integrating PV technologies into the electricity system, into house facades or broader renewable energy applications). Moreover, many of the recent successful companies have entered the industry from the traditional energy supply sector on the search for new business opportunities in renewable energy.

As a consequence, the Chinese PV companies increasingly embraced a much wider range of technological innovation strategies. While the dominant technology during the earlier phase was polycrystalline PV, the Chinese companies experimented on new alternatives during the post-crisis restructuration phase, mostly monocrystalline and thin film. These technologies were already available in other countries but they were not the focus of the Chinese firms as their main strategy was to position themselves in the manufacturing of the globally pre-dominant technology. For instance, to introduce monocrystalline PV cells into the Chinese market, an indigenous monocrystalline company Longi (specialized in ingots) vertically integrated into assembling PV modules in order to demonstrate the first operational monocrystalline PV products inside China. Longi remained constant in its R&D activities and the quality of its products gained much credibility over the years. By 2018, monocrystalline PVs were able to gain about 30% of the total Chinese PV production.

At that time, a number of large companies that were locked-in to the old manufacturing business model continued to suffer. While top companies like Jinko, for instance, reduced the selling prices of their PV modules substantially to win bidding projects, it had become rather controversial in the industry about whether that would be a sustainable strategy for the whole Chinese PV industry. Once successful companies like Yingli was suffering financially due to the financial crisis and anti-dumping policies, and was filing for insolvency in 2018. As a result, major transformations happened at the level of industrial composition. The intense price competition among PV module manufacturers in China smothered a number of smaller companies, which were not able to compete against larger manufacturers.

With regard to the manufacturing approach, a rethinking of the former strategies could be observed. Many PV companies have recently switched to high degrees of automation of their manufacturing process (some to more than 90%). The quality of the products improved substantially with lower defect rates that might be due to human operation errors. This also indicates that the Chinese PV production has already moved away from the labor-intensive and lower cost advantage model, which still applies to the manufacturing scene in many developing countries.

In line with the growth of domestic PV market, the Chinese PV industry was able to increasingly mature across the different parts of the PV production value chain (including upstream suppliers as well as downstream parts and components). Chinese technological companies have for instance moved into the realm of supplying advanced machinery tools. These companies usually have a background in supplying equipment for the semiconductor companies in China. In 2016, five out of the world top ten machinery tool suppliers belonged to Chinese companies. While the Swiss company Meyer Burger remains the world's number one PV machinery tool supplier with 4.54 billion USD revenue in 2016, the best Chinese PV machinery tool company Zhejiang Jingsheng was placed at number four with 1.1 billion USD revenue. It is only a minor gap to American owned Applied Materials and German owned Centrotherm (both estimated at between 1.5 to 1.6 billion USD revenue). While in the past Chinese PV manufacturers had to rely heavily on German suppliers for machinery tools, Chinese manufacturers since around 2018 mostly sourced for machineries from local indigenous suppliers as the competencies of these companies have also increased significantly. This overall provides a boost for Chinese companies in other parts of the value chain as they could now source most of the key machineries internally within China, where support of services becomes much more efficient. This allows a much more independent and self-sufficient PV industry in China.

Another specific example is new Chinese entrepreneurships in PV glass manufacturing. Over the years, crystalline silicon PV module has been the mainstream technology for the industry. The majority of the modules used single glass assembly process. In recent years, as China began to deploy PV into different parts of the country using different application methods including water surface (i.e. floating solar farms) and deserts, new innovations in double glass assembly process were required. A number of entrepreneurs ventured into innovative glass manufacturing business. Since the last four to five years, innovativeness in this area increasingly gained traction among large PV module manufacturers. As of 2017, double glass assembly process earned the first five percent of PV module manufacturing. Among these, Chinese owned Zhejiang Flat Mirror Glass Co., Ltd. is now the world's top two companies in PV glass manufacturing. The company is as of today supplying to big PV module manufacturers like Trina, Yingli, Jinko, JA Solar, Canadian Solar, etc. The availability of such double glass assembly process allows a quicker deployment of PV into the abovementioned application areas in different parts of China, building an overall stronger PV innovation system in the country.

Meanwhile, it became increasingly controversial whether Chinese PV manufacturers should further strive for vertical integration or rather disintegrate into more specialized companies. Chinese companies, which pursued the conventional catch-up strategy vertically integrated their value chain activities in order to achieve economies of scale when serving for a mature PV market with pre-existing dominant designs, i.e. monocrystalline PV. However, that led to huge inertia since the companies were locked-in to their full production line (including raw silicon materials). Hence, their businesses became highly dependent on manufacturing orders. These companies suffered the most when demand was low and hence were most vulnerable when driven into price competition. Since policy makers and leading enterprises in China began focusing on wide-spread experimentations of PV system integration, companies that pursued a disintegration or virtual vertical integration (through partnerships, alliances, etc.) were able to channel most of their resources to specialized R&D to remain strategically competitive. When demand was low, specialized companies were much more agile and could outsource based on manufacturing orders.

Therefore companies increasingly sought for new ways to remain competitive. For instance, Trina - a leading Chinese company existed since the 1990s - was a very successful vertically integrated PV company producing PV modules. In recent years, the company realized that the industry might not survive the price competition and decided to gradually move towards an asset-light business model. In so doing, the company has been outsourcing most of their production to other PV module manufacturers and increasingly moved into the downstream services of PV, i.e. using ICT technologies like internet of things and cloud computing to embed PV products into the electricity systems effectively (more explanations follow in section 4.4). These ICT-based activities took place across different large and small enterprises, and had become crucial to facilitate key innovations related to PV system integration in different markets in China, such as in terms of balance-of-systems, energy storage, energy complementary systems, etc.

### 4.3 Beyond production-based strategy: system integration for PV deployment

Over the years, the introduction of endogenized market deployment policies and the broadening of the innovation strategies overall led to a shift of attention from the core technology (PV cells and modules) to the configuration of entire socio-technical systems. For instance, a Chinese owned company Hanergy has proactively promoted the thinfilm technology in China. Thinfilm PV enables a much broader range of applications compared to the conventional polycrystaline approach, leading to applications in buildings, roads, consumer products, satellites, planes, etc. using soft and flexible PV panels. The company in 2017 took the initiative to build a "solar PV track" in a public park in Beijing that generates electricity as a demonstration project. Although the project is arguably not successful as it was a trial and error experiment, it implies proactive entrepreneurial experimentations of the company to progressively promote a new socio-technical configuration, which is believed to have wider application potential. Strategically, the company implemented a rather radical knowledge acquisition strategy. Instead of spending years and resources to extensively build up related knowledge, the company acquired five international thinfilm MNCs in order to leap towards the frontier of thinfilm development *vis a vis* the world leading counterparts in the US and Europe.

The rapid, large-scale and wide applications of solar PV deployment in China have induced a great deal of new business entrepreneurships within the realm of PV system integration. One successful example is the growth of solar inverter companies specialized in converting the energy output of a solar panel in order to feed into the electrical grid system or off-grid electrical networks. It is the critical component in the stage of balance-of-system in order to effectively integrate PV into the electricity systems. Sungrow, a Chinese-owned solar inverter company, although already founded in the late 1990s, gained new opportunities to innovate their products due to the rapidly expanding home market. The company recently contracted the inverter system for the world's largest floating solar farm, which was built on a lake in Anhui, China. The project was a key example of the country moving into a new phase of development as the lake was once a deserted coal mine but is now generating electricity to power 15, 000 homes with a total capacity of 40 megawatts.

Sungrow became the world's largest PV inverter company in terms of watt production in three consecutive years since 2015, followed by Huawei. In terms of profit margin, Sungrow is furthermore leading since early 2010s as compared to the world leading inverter company SMA Solar Technology (German owned energy equipment supplier). In 2016, SMA's profit margin was 14.89% whereas Sungrow was as high as 34.26%. In 2013 and 2014, SMA encountered negative profit margins (-0.6% and -7.3%) while Sungrow made 24.09% and 25.22%. Although it started as a traditional inverter manufacturer, the company argued that the availability of the domestic market has provided ample opportunities as test beds for innovative system integration activities. As of 2018, the company had more than 3'000 employees with 30% of them being R&D personnel. Meanwhile, there were also smaller business entrepreneurs from research and academia venturing into the inverter segment, building up an entire innovation system for PV in China. The overall innovative activities in the segment lowered the prices for inverter over the last few years quite substantially, leading to higher affordability of good quality inverters in PV applications.

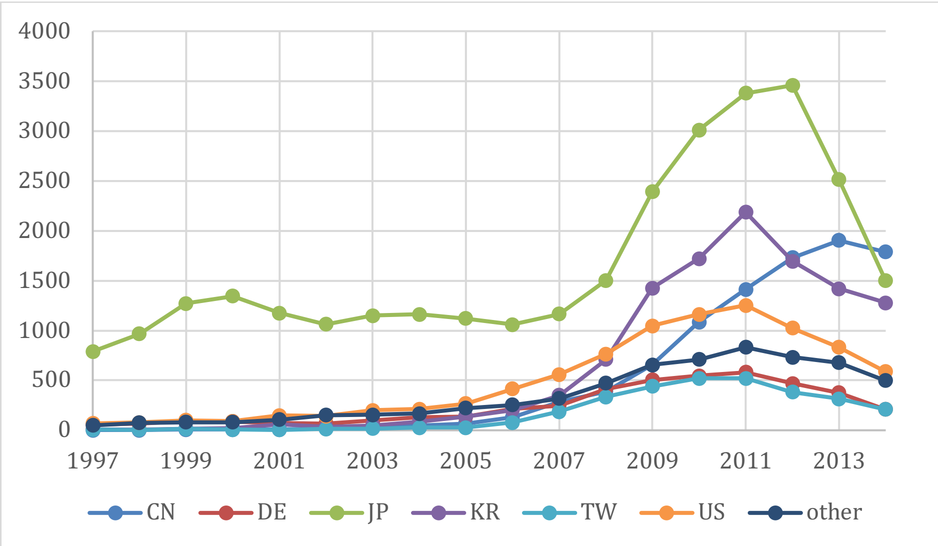
In terms of overall integration of PV into the Chinese electricity system, Chinese policies and companies quickly moved into a broad range of ICT-enabled innovations following the rapid development of PV applications in the country. This includes innovative activities and R&D in the areas of large-scale grid connection technologies (e.g. high-voltage current grid connections), decentralized grid connection systems, multi-energy complementary system (e.g. PV and energy storage system control), and new PV applications in broader sectors (e.g. solar storage for electric-vehicle charging stations, power generation systems for floating thin-film PV, etc.). These innovations require new skills and knowledge in other realms, especially with the combination of ICT and the Internet of things. More importantly, they are crucially driven by entrepreneurial experimentations of Chinese actors. A successful case 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 microgrid solutions, as well as energy management platform through cloud computing. Conventionally, there were about three mainstream architectures for solar PV power stations of which they share a few major limitations, such as high maintenance of power frequency transformers, over-complexities of multi-level transformation systems, and conversion inefficiencies. TBEA came up with a strategic system integration plan to solve the typical issues by simplifying the four or five steps of the conventional architectures to only three steps. Under the company's own label, TBEA introduced new-generation solutions to smart PV system integrations.

We therefore observe a rather radical shift in the overall industrial strategy in the Chinese PV sector over the past few years. Both the leading companies and the government moved away from a narrow technology- and knowledge focused strategy, which conventionally targeted a clear reference point in extant GVCs of PV productions. Instead, a much broader set of strategies emerged to develop future technologies, business models and 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 initiatives of systemic entrepreneurial experimentation. This shift in focus also resulted in a new emphasis to experiment with new socio-technical systems, which in turn provided a much stronger starting position to gain leading roles in new products and services, both domestically and in new GVCs. We therefore maintain that the need for a more valuation oriented understanding of leapfrogging opportunities can be substantiated very well with this case.

4.4 Reconstructing the development trends through patent indicators

So 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 analyses of patenting activities of the Chinese solar PV industry. Figure 1 shows that the number of patent applications has been steadily increasing in the major countries since the mid-2000. There is however a significant decline of patenting activities of solar PV industry among major producing countries except for 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 after the establishment of crystalline PV as the dominant "production innovation" (Carvalho et al., 2017; Furr and Kapoor, 2018). However, Chinese solar PV firms tend to have higher survival rate during the industry shakeout (Furr and Kapoor, 2018). This leads to a geographical consolidation of innovation activities in China, following the geographical consolidation of manufacturing activities (Binz et al., 2017). In 2014, China took the leading position from Japan, becoming the biggest source of solar PV patents.

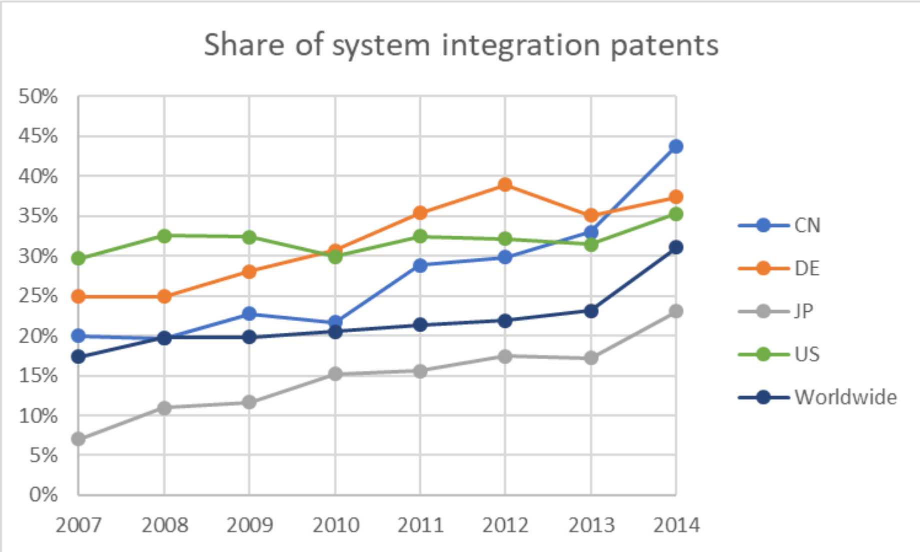
Figure 1. Number of patents filed worldwide and by the major producing countries




Source: EPO (2017), calculated by authors (CN = China; DE = Germany; JP = Japan; KR = Korea; TW = Taiwan; US = United States).

The shifting focus of innovation activities towards system integration is key to the resilience of the innovation activities of the Chinese solar PV industry. The value chain of solar PV industry can be divided into three different segments, upper stream, midstream and downstream. The upper stream segment includes silicon, ingot and wafer manufacturing. The midstream segment comprises the manufacturing of cell and module. In the downstream segment, solar modules are integrated into the system together with other components like invertor to form a PV power plant (Binz et al., 2017; Carvallo et al., 2017). Figure 2 shows the evolution of the share of system integration patents in all solar PV patents worldwide and in major producing countries with large domestic markets for solar PV. The shift of innovation focus towards system integration in the solar PV industry in China started in 2010 following the implementation of domestic deployment policies. The share of system integration patents in the overall solar PV patents filed in China nearly doubled in 2014 compared to 2010, surpassing the United States in 2013 and Germany in 2014.

Figure 2. The shifting innovation focus towards system integration in major producing countries with large domestic market




Source: EPO (2017), calculated by authors (CN = China; DE = Germany; JP = Japan; US = United States).

Table 2 further shows the change in the number of patent applications in the midstream and downstream segment in major producing countries of the solar PV supply chain between 2011 and 2014. The decline of number of system integration patents is smaller compared to the decline of the number of cell and module patents in most producing countries because the major shakeout concentrated in the midstream segment of the solar PV industry. During the same period, the number of Chinese system integration patents almost doubled, whereas the number of cell and module patents remained stable.

The knowledge base of the midstream segment of solar PV supply chain is different from the downstream segment. Table 3 shows that the downstream 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. More than 50 percent of backward citations made by cell and module patents come from semiconductor sector. The importance of electrical engineering knowledge is becoming increasingly important for both segments. The share of backward citations to electrical engineering knowledge in system integration patents surpassed the share of backward citations to semiconductor knowledge during the period 2012-2014.

Table 2. Change of number of solar PV patent applications from different countries in the core and downstream segments of the value chain during 2011-2014

| | Midstream | Downstream |
|---|---|---|
| | Cell and Module | System integration |
| Worldwide | -48.1% | -13.3% |
| China | 0.4% | 92.4% |
| Germany | -64.9% | -61.8% |
| Japan | -58.7% | -34.3% |
| Korea | -49.8% | -21.7% |
| Taiwan | -60.8% | -44.5% |
| United states | -53.7% | -49.0% |

Source: EPO (2017), calculated by authors.

Table 3. Share of backward citations to different technological fields

| | Cell and Modules | | System Integration | |
|---|---|---|---|---|
| | Semiconductors | Electrical Engineering | Semiconductors | Electrical Engineering |
| 2006-2008 | 51.2% | 9.2% | 38.3% | 18.4% |
| 2009-2011 | 51.5% | 10.7% | 32.9% | 27.3% |
| 2012-2014 | 51.1% | 11.4% | 28.6% | 34.9% |

Source: EPO (2017), calculated by authors.

The shifting innovation focus of global solar PV industry offers opportunities for latecomer countries to catch up through the social-technical reconfiguration of the electricity sector. As mentioned in Section 4.1, the deployment policies in China started from 2010 facilitated the formation of domestic market in China. This allows the mobilization of the pre-existing domestic knowledge from other industries. With the pre-existing knowledge, China poses stronger capabilities in downstream segment of system integration in the solar PV value chain compared to the midstream segment of cell and module manufacturing. As shown in Table 4, the share of backward citations to domestic electrical engineering patents in downstream segment is both higher than that in midstream segment and higher than the share of backward citations to domestic semiconductor patents in downstream segment. This is in line with the findings in Section 4.3 that both Sungrow and TBEA have been active in the electricity sector for many years. Once the market deployment policies were implemented, these companies were able to actively participate in experimenting new products in different market contexts made available. The creation of domestic market and the shifting focus towards system integration of PV therefore helped mobilize the domestic knowledge from other technological fields inside China's innovation system hence facilitated the quick innovation output.

Table 4. Share of domestic backward citations to different technological fields of Chinese solar PV patents in midstream and downstream segments

| | Cell and Module | | System Integration | |
|---|---|---|---|---|
| | Semiconductors | Electrical Engineering | Semiconductors | Electrical Engineering |
| 2006-2008 | 4.1% | 7.3% | 2.4% | 13.6% |
| 2009-2011 | 6.9% | 9.1% | 6.1% | 15.6% |
| 2012-2014 | 10.6% | 9.9% | 7.8% | 16.4% |

Source: EPO (2017), calculated by authors.

**5. Discussion**

The Chinese solar PV industry underwent a series of major structural changes since the early formation phase in the late 1990s. Extant studies have shown how Chinese entrepreneurships formed the early phase of the industry by turning the country into a popular manufacturing base of PV modules to serve the US and EU markets (Zhang and White, 2016; Binz and Anadon, 2018). The industry grew substantially but came to a major halt following the 2008 financial crisis and the anti-dumping policies of the western countries. The Chinese government subsequently introduced the domestic FIT policy in order to salvage the local tumbling industry. Leveraging on the growing domestic market, Chinese manufacturers were catching up quickly by vertically integrating into upper-stream activities including activities in the wafer and solar cell processing. In so doing the Chinese PV industry so called 'climbed the GVC ladder', by building the entire value chain manufacturing for PV panels in China, increasing exports of PV modules to other countries in the world and driving down global prices. At the same time, Chinese firms invested increasingly in technological catch-up, pushing up the national patent stock in solar PV substantially. The Chinese government only started to promote indigenous market deployment after the crisis, which was mainly a means to buffer overcapacity. It remained therefore unclear up to that point in industrial history whether the Chinese PV industry would be yet another example of the national strategy to invest into lower cost and high-volume manufacturing that would lead directly into the middle-income trap.

The domestic FIT policy was revised to support the formation of new markets to curb the overcapacity problem. However, much more importantly, it motivated companies who were increasingly engaged in innovation activities to consider these 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, closing the gap with advanced German machinery tool companies, as well as rapid and progressive technological experimentation at the frontier of PV system integration. One of the generative contexts was for instance PV systems installed in rural areas to help mitigate poverty, integrated into buildings, transport systems, roads, and on unproductive land areas (e.g. lakes, deserts). These initiatives required extensive innovating and experimenting in realms that are conventionally not addressed in the PV manufacturing industry and which require broader knowledge and valuation capabilities.

While conventionally national governments favored policies that focus on building up the indigenous knowledge base or accumulating technological capabilities, the latest experience of the Chinese PV industry shows that broader strategies than promoting knowledge accumulation may be critical to move to higher income potentials and to achieve high environmental goals. The Chinese PV industry has only very recently begun moving towards this direction through effective market creation strategies, systemic technological experimentation, and combining diverse knowledge fields (e.g. ICT, glass manufacturing, power inverters) necessary for PV system integration. Alternative technological trajectories compared to the mainstream have been promoted to achieve higher levels of efficiency, e.g. monocrystalline PV and thinfilm 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, for example in power generation, energy storage and system efficiency. Table 5 summarizes the shifts of the Chinese industrial strategy in solar PV along the three development phases.

We therefore argue that the Chinese PV industry has shifted its development focus from climbing up the GVC towards reconfiguring entire socio-technical systems. It is through these initiatives that China might be able to generate radically new trajectories for both industrial and environmental leapfrogging. Through the valuation oriented strategy, some Chinese companies have already leapfrogged by leading in emerging GVCs, e.g. Sungrow in solar inverters and TBEA in one-stop smart energy solutions. By reconfiguring the socio-technical configuration of the electricity sector, these companies are actively shaping the future trajectories of their respective industries in order to serve the newly developed market contexts. In so doing, they are highly potential to be key global exporters of a next generation of products and services.

## 6. Conclusion

The emergence of cleantech sectors provides ample windows of opportunity for latecomers as the required innovations need new knowledge, infrastructures, business models and consumption patterns. This set of opportunities has to be informed by a broader understanding of what it takes to successfully develop new socio-technical systems, i.e. it has to integrate valuation related concerns. It is therefore crucial to inform existing catching-up studies on how latecomer may endogenize the emerging windows of opportunity by incorporating valuation concerns on par with the prevailing focus on knowledge bases. Drawing from the recent experience of the Chinese PV industry, this paper shows that latecomers should quickly move beyond the conventional strategy of “moving up the GVC” or upgrading within the structure of production-based value chains. Valuation strategies are crucial to help latecomers venturing into more radical industrial development paths. The goal of simultaneously leapfrogging in industries and sustainability transitions might not always represent hard tradeoffs, but might provide a number of synergies for rapidly growing economies.

Table 5:Structural shifts along the three development phases of the Chinese industrial strategy in solar PV

| | **Phase I:**<br>**early catch-up**<br>**(late 1990s - 2008)** | **Phase II:**<br>**climbing the GVC ladder**<br>**(2009 - 2013)** | **Phase 3:**<br>**socio-technical transition**<br>**(since 2014)** |
|---|---|---|---|
| **Policy goal** | Building up regional industry base for panel manufacturing supported by German machine tool companies | Safeguarding the considerably grown manufacturing industry | Pushing the technology frontier; providing clean energy to rural areas; transitioning electricity sector structures |
| **Core resources** | Cheap production costs, in particular labor | Mass manufacturing expertise | Leading scientific and engineering application knowledge; experimental markets; growing PV innovation system with strong indigenous partners |
| **Technology focus** | Manufacturing PV panels | Upgrading along the value chain into wafer and solar cell processing | Broad technology portfolios; leaderships across the value chain with high-level manufacturing automations; machinery tools competitive with incumbent Western companies; introducing non-mainstream technologies in terms of manufacturing processes and product designs. |
| **Market formation** | Global market supported by EU and US government deployment policies | First feed-in-tariff; but poorly designed | Large number of new kinds of markets for PV applications including for the non-mainstream product designs; extensive deployment policies by the government that serve as learning and experimental testbeds for indigenous PV system integration companies; the availability of domestic markets also help increase the price competitiveness of Chinese indigenous companies. |
| **Entrepreneurial strategies** | Re-engineering; collaboration with German industry | Vertical integration to achieve high economies of scale | Competitive companies transformed towards 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. |
| **Policy realms** | Ignorance by national policy; support by some regional policy makers | Poorly designed deployment policies | Science, environmental, regional and industry policy |
| **Industry development goal** | Entering the value chain as cheap manufacturers | Leading the GVC as a dominant manufacturing hub | Transition towards sustainable socio-technical energy systems through systemic market creation and entrepreneurial experimentation to offer technological solutions that are only starting to emerge. |

Source: Authors' own elaboration.

The present paper showcased how a latecomer country like China has moved beyond the production-based catching-up strategies and started building new socio-technical systems to leapfrog in industries and environmental sustainability in a particular sector. Solar PV however represents a specific type of technology, which has been characterized as footloose, i.e. both the manufacturing base and market customization is quite independent of local conditions. This enables shifts of geographical centers of the industry rather quickly (Binz and Truffer, 2017). We however maintain that the processes identified in this paper will only be stronger in the case of industries that are spatially more sticky in aligning its characteristics of knowledge development and customized market penetration (Binz and Truffer, 2017). We would therefore expect processes that go beyond knowledge management to even play a more important role in any sector that is less reliant on standardized modular products.

A limitation of the current paper is that China represents a very particular context with its huge and rapidly growing market in all sorts of basic infrastructures, its capacity to provide a plethora of experimental contexts, high expertise in mass manufacturing, a huge resource base and high problem pressures. All this has enabled Chinese actors to act quickly and forcefully when confronted with opportunities (like quickly growing PV markets in major western countries), but also to absorb major shocks (e.g. after the global financial melt-down and the anti-dumping regulations let to strong overcapacities in the Chinese PV industry). We maintain however that our results are also relevant for other countries, especially smaller sized, middle-income trapped countries like Malaysia. These can of course not offer similar market potentials and resource stocks like China. However, we would expect that only betting on upgrading the indigenous knowledge base that feed into pre-existing GVCs might prove to be a risky development strategy also for these countries. Despite smaller home markets, these middle-income countries could focus on specific market segments that serve new kinds of applications for which dominant designs have yet to emerge. This might open up new strategic positioning by pioneering new socio-technical configurations and their embedding in potentially more sustainable sector structures.

The proposed valuation based strategy in this paper becomes especially pertinent under conditions of emerging sustainability debates, which will require fundamental restructuring of socio-technical systems across several sectors. Being strongly rooted in pre-existing GVCs might therefore represent a high liability for the longer-term development. The history of sustainability transitions has also proven that small countries have been able to outcompete large countries in the development of new industries, as in the well substantiated comparison between Denmark and the US in the early formation of the wind industry (see Garud and Karnoe, 2003). This paper therefore encourages future studies on latecomer catching-up and industrial development in green sectors to provide a closer scrutiny to mechanisms concerning the valuation-based approach in general, and proactive market formation strategies in particular.

## References


Amsden, A. 1989. Asia's next giant: South Korea and late industrialization. Oxford University Press, New York.

Binz, C. and Anadon, D.-L. 2018. Unrelated diversification in latecomer contexts: Emergence of the Chinese solar photovoltaics industry. Environmental Innovation and Societal Transitions, 28: 14-34.

Binz, C., Harris-Lovett, S., Kiparsky, M., Sedlak, D. and Truffer, B. 2016a. The thorny road to technology legitimation — Institutional work for potable water reuse in California. Technological Forecasting & Social Change, 103: 249-263.

Binz,C., Tang,T. and Huenteler,J. 2017. Spatial life cycles of cleantech industries – the global development history of solar photovoltaics. Energy Policy 101, 386-402.

Binz, C., Truffer, B. 2017. Global Innovation Systems – towards a conceptual framework for systemic innovation conditions in transnational contexts. Research Policy 46, 1284 – 1298.

Binz, C., Truffer, B. and Coenen, L. 2016b. Path creation as a process of resource alignment and anchoring. Industry formation for on-site water recycling in Beijing. Economic Geography, 92, 172–200.

Boschma, R., Coenen, L., Frenken, K. and Truffer, B. 2017. Towards a theory of regional diversification: combining insights from evolutionary economic geography and transition studies. Regional Studies, 51(1): 31-45.

Carvalho, M., Dechezleprêtre, A. and Glachant, M., 2017. Understanding the dynamics of global value chains for solar photovoltaic technologies (Vol. 40). WIPO.

Castaldi, C., Frenken, K. and Los, B. 2015. Related variety, unrelated variety and technological breakthroughs. An analysis of US state-level patenting. Regional Studies, 49, 767–781.

Cherif, R., Hasanov, F., 2015. The leap of the tiger: how Malaysia can escape the middle income trap. IMF Working Papers, WP/15/131.

Coenen, L., Benneworth, P. and Truffer, B., 2012. The geography of transitions. Addressing the hidden spatial dimension of socio-technical transformations. Research Policy 41 (6), 955-967.

Coenen, L., Hansen, T. and Rekers, J. V. 2015. Innovation policy for Grand Challenges. An economic geography perspective. Geography Compass, 9, 483–496.

Coenen, L., Moodysson, J. and Martin, H. 2015. Path renewal in old industrial regions: possibilities and limitations for regional innovation policy. Regional Studies, 49, 850–865.

De Marchi, V., Giuliani, E. and Rabellotti, R. 2018. Do Global Value Chains Offer Developing Countries Learning and Innovation Opportunities? The European Journal of Development Research, 30(3): 389–407.

Dewald, U. and Fromhold-Eisebith, M. 2015. Trajectories of sustainability transitions in scale-transcending innovation systems: The case of photovoltaics. Environmental Innovation and Societal Transition, 108-123.

Figueiredo, P. 2008. Industrial policy changes and firm-level technological capability development: evidence from northern Brazil. World Development 36 (1), 54–92

Fu, X., Pietrobelli, C. and Soete, L. 2011. The role of foreign technology and indigenous innovation in the emerging economies: technological change and catching-up. World Development, 39 (7): 1204-1212.

Fu, X. and Zhang, J. 2011. Technology transfer, indigenous innovation and leapfrogging in green technology: the solar-PV industry in China and India. Journal of Chinese Economic and Business Studies, 9(4): 329-347.

Furr, N. and Kapoor, R., 2018. Capabilities, technologies, and firm exit during industry shakeout: Evidence from the global solar photovoltaic industry. Strategic Management Journal, 39(1), pp.33-61.

Garud, R. and Karnøe, P. 2003. Bricolage versus breakthrough: distributed and embedded agency in technology entrepreneurship. Research Policy, 32, 277–300.
Geels, F. W. 2002. Technological transitions as evolutionary reconfiguration processes: a multi–level perspective and a case-study. Research Policy, 31, 1257–1274.
Gereffi, G. 1999. International trade and industrial upgrading in the apparel commodity chain. Journal of International Economics, 48 (1): 37-70.
Hansen, T. and Coenen, L. 2015. The geography of sustainability transitions: Review, synthesis and reflections on an emergent research field. Environmental Innovation and Societal Transitions, 17, 92–109.
Hobday, M. 1995. Innovation in East Asia: The challenge to Japan. Hants: Edward Elgar.
Hoogma, R., Kemp, R., Schot, J. and Truffer, B. 2002: Experimenting for Sustainable Transport. The approach of Strategic Niche Management. Spon Press, London. pp. 212.
Hughes, T. P. 1993. Networks of power: electrification in Western society, 1880–1930. Baltimore: John Hopkins University Press.
Humphrey, J. and Schmitz, H. 2002. How does insertion in global value chains affect upgrading in industrial clusters? Regional Studies 36 (9), 1017–1027.
Jeannerat, H. and Kebir, L. 2016. "Knowledge, Resources and Markets: What Economic System of Valuation?" Regional Studies 50(2): 274-288.
Kalthaus, M. 2019. Identifying technological sub-trajectories in patent data: the case of photovoltaics. Economics of Innovation and New Technology, 28(4), pp.407-434.
Kim, L. 1997. From imitation to innovation. Cambridge: Harvard Business School Press.
Lall, S. 1992. Technological capabilities and industrialization. World Development, 20(2), 165-186.
Lee, K. and Lim, C. S. 2001. Technological regimes, catching-up and leapfrogging: Findings from the Korean industries. Research Policy, 30, 459-483.
Lee, K. and Malerba, F. 2017. Catch-up cycles and changes in industrial leadership: Windows of opportunity and responses of firms and countries in the evolution of sectoral systems. *Research Policy,* 46:338-351.
Lundvall, B. 1992. *National Systems of Innovation - toward a Theory of Innovation and Interactive Learning*. Pinter, London.
Markard, J., Raven, R. and Truffer, B. 2012. Sustainability transitions: An emerging field of research and its prospects. Research Policy, 41, 955–967.
Martin, R. 2010. Roepke lecture in Economic Geography – Rethinking regional path dependence: Beyond lock-in to evolution. Economic Geography, 86, 1–27.
Martínez, C. 2011. Patent families: When do different definitions really matter? Scientometrics, 86(1), pp.39-63.
Mathews, J. 1997. A Silicon Valley of the East: Creating Taiwan's semiconductor industry. California Management Review, 39, 26-54.
Mathews, J. 2002. Competitive advantages of the latecomer firm: A resource-based account of industrial catch-up strategies. Asia Pacific Journal of Management, 19, 467-488.
Mathews, J. 2006. Catch-up strategies and the latecomer effect in industrial development. New Political Economy, 11(3), 313-335.
Mathews, J. 2013. The renewable energies technology surge: a new techno-economic paradigm in the making? Futures 46, 10–22.
Mathews, J. and Cho, D-S. 2007. Tiger technology: the creation of a semiconductor industry in East Asia. Cambridge: Cambridge University Press.
Neffke, F., Henning, M., and Boschma, R. 2011. How do regions diversify over time? Industry relatedness and the development of new growth paths in regions. Economic Geography 87:237–65
Perez, C. 2013. Unleashing a golden age after the financial collapse: Drawing lessons from history. Environmental Innovation and Societal Transitions 6: 9-23.

Pietrobelli, C. and Rabellotti, R. 2011. Global value chains meet innovation systems: Are there learning opportunities for developing countries? World Development, 39 (7): 1261-1269.
Pietrobelli, C. and Rabelotti, R. 2005. 'Upgrading in global value chains: Lessons from latin American clusters'. In: E, Giuliani, R. Rabelotti and M.P. van Dijk (Eds.), Clusters facing competition: The importance of external linkages. Ashgate: Aldershot, pp. 13–38.
Quitzow, R. 2015. Dynamics of a policy-driven market: The co-evolution of technological innovation systems for solar photovoltaics in China and Germany. Environmental Innovation and Societal Transitions, 17, 126–148.
Rigby, D. L. 2015. Technological relatedness and knowledge space. Entry and exit of US cities from patent classes. Regional Studies, 49, 1922–1937.
Saviotti, P. P. and Frenken, K. 2008. Trade variety and economic development of countries. Journal of Evolutionary Economics, 18, 201–218.
Schmoch, U., 2008. Concept of a technology classification for country comparisons. Final report to the world intellectual property organisation, WIPO.
Schot, J. and Geels, F. 2008. "Strategic niche management and sustainable innovation journeys: Theory, findings, research agenda, and policy." Technology Analysis and Strategic Management 20(5): 537-554.
Schot, J. and Steinmüller, W. E. 2018. Three frames for innovation policy: R&D, systems of innovation and transformative change. Research Policy, 47(9), 1554-1567.
Shubbak, M. 2019. The technological system of production and innovation: The case of photovoltaic technology in China. Research Policy, 48(4), 993-1015.
Smith, A. Voß, J.-P. and Grin, J. 2010. Innovation studies and sustainability transitions: The allure of the multi-level perspective and its challenges. Research Policy, 39 (4): 435-448.
Trippl, M., Grillitsch, M. and Isaksen, A. 2017. Exogenous sources of regional industrial change:Attraction and absorption of non-local knowledge for new path development. *Progress in Human Geography,* 42**,** 687-705.
Truffer, B., and Coenen, L. 2012. Environmental innovation and sustainability transitions in regional studies. Regional Studies, 46, 1–21.
Veefkind, V., Hurtado-Albir, J., Angelucci, S., Karachalios, K. and Thumm, N., 2012. A new EPO classification scheme for climate change mitigation technologies. World Patent Information, 34(2), pp.106-111.
Vind, I., 2008. Transnational companies as a source of skill upgrading: the electronics industry in Ho Chi Minh City. Geoforum 39, 1480–1493.
Yap, X.S. and Truffer, B. 2019. Shaping selection environments for industrial catch-up and sustainability transitions: A systemic perspective on endogenizing windows of opportunity, Research Policy 48(4):1030-1047.
Yin, R. 2011. Qualitative research from start to finish. New York: The Guilford Press.
Yin, R. 2014. Case study research: Design and methods (5th ed.). California: SAGE Publications.
Yin, R. 2016. Qualitative Research from start to finish. Second edition. Tailor and Francis.
Zhang, F. and Gallagher, K.S. 2016. Innovation and technology transfer through global value chains: evidence from China's PV industry, Energy Policy, 94 (2016), pp. 191-203.
Zhang, W. and White, S. 2016. Overcoming the liability of newness: entrepreneurial action and the emergence of China's private solar photovoltaic firms. Research Policy 45 (3), 604–617.