Transplanting clean-tech paths from elsewhere: The emergence of the Chinese solar PV industry

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Keywords: cleantech; path creation; technological innovation system; solar photovoltaics; China; transnational entrepreneurship

JEL: O33; Q55; F64

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Abstract
New clean-tech industries emerge in increasingly complex spatial patterns that challenge existing explanations of industrial path creation. In particular, the case of latecomer regions quickly building up industries in fields such as clean-tech that are unrelated to their previous industrial capabilities is not well understood in the literature. This paper aims to address this gap with an analytical framework that draws on technological innovation system and catching-up literatures to specify the place-specific and extra-regional system resources that firms in latecomer regions can draw on to promote technology manufacturing in clean tech sectors. An in-depth case study of the emergence of the Chinese solar photovoltaics (PV) sector reveals an industry formation process that differs from existing models. Rather than depending on linkages with multinational companies, substantial policy support, or gradual recombination of pre-existing domestic capabilities, the Chinese solar PV sector emerged from path transplantation in a highly internationalized entrepreneurial project. Pioneering entrepreneurs mobilized knowledge, markets, investment and technology legitimacy developing outside China and re-combined them with the country's generic capabilities in export-oriented mass manufacturing. This implies that in some cleantech industries, globalization may enable a new model of industrial path creation based on bridging domestic resource gaps by directly mobilizing system resources emerging in the international networks.

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1 Introduction

The question how new industries emerge and locate in specific places is gaining renewed interest by scholars and policy makers, in particular in new environmental growth sectors like renewable energy, electric transportation or water recycling (Schmidt and Huenteler, 2016). To mitigate societal grand challenges while supporting economic development, policy makers around the world increasingly turn to support the formation of such 'green' or 'cleantech' industries. Still, to date our theoretical understanding of the industry formation and location process in these sectors (and in more general terms) remains limited at best (Martin, 2010; Schmidt and Huenteler, 2016). Existing theories in particular have problems explaining why clean-tech industries increasingly take root in latecomer countries like China, Brazil or India when the relevant markets, knowledge, firms, and value chains are already relatively well established in industrialized countries (Binz et al., in press; Fu et al., 2011; Lee and Lim, 2001; Schmidt and Huenteler, 2016).

The literature broadly argues that industry formation in technology latecomer regions has to be understood as a learning process in which firms (which we refer to as latecomer firms from now on) upgrade their technological capabilities (Lee and Lim, 2001; Morrison et al., 2008).[1] Two main theoretical perspectives exist on how this upgrading process works. Capabilities may be upgraded either in a gradual learning process from the integration of latecomer firms in global value chains (Gereffi, 1999; Morrison et al., 2008), which we refer to from now on as *catching-up*, or in a branching process out of a region's pre-existing related technological capabilities (Hidalgo et al., 2007; Martin and Sunley, 2006; Neffke et al., 2014), which we refer to from now on as *related diversification*.

In the former (catching-up) models, latecomer firms are expected to develop capabilities in a gradual learning process in interaction with foreign lead firms. By slowly absorbing best practices from global value chains they move from duplicative imitation (original equipment manufacturing, OEM) to creative imitation (original design manufacturing, ODM) and ultimately proprietary innovation (original brand manufacturing, OBM) (Gereffi, 1999; Malerba and Nelson, 2011). The emergence of a handful of cleantech sectors in latecomer

[1] Technological capabilities are the "skills—technical, managerial or organizational—that firms need in order to utilize efficiently the hardware (equipment) and software (information) of technology, and to accomplish any process of technological change. Capabilities are firm-specific knowledge, made up of individual skills and experience accumulated over time" (Morrison et al., 2008: 41-42)

countries, most prominently wind turbine manufacturing, has illustrated and validated this model and the central role of governments therein (Gallagher, 2014; Lewis, 2011; Surana et al., 2015). More recently, this account was contrasted with an evolutionary approach. Instead of emphasizing latecomer's coupling with lead firms in developed economies, evolutionary theories focus on start-ups, spin-offs, and labor mobility between related industries inside a given region (Boschma and Frenken, 2011; Hidalgo et al., 2007; Neffke et al., 2011). In this view, combinations of pre-existing firm routines and spin-offs from existing industries determine a region's structural diversification and long-term economic development potential (Boschma, 2014; Hidalgo et al., 2007; Neffke et al., 2011) — i.e., where and how new industries develop can be understood based on the stock of technological capabilities and routines that exists in the firms of a region (Frenken and Boschma, 2007).

Both perspectives provide influential explanations on why and how new industries develop (or not) in specific places, but may be overly deterministic when assessing latecomer's potential for developing radically new paths. In general, they both assessed slow and gradual upgrading of industries in much detail, while more unlikely - but arguably important – 'jumps in the product space' (Hidalgo et al., 2007), 'saltation' (Boschma et al., forthcoming) or 'path-creating catching-up' processes (Lee and Lim, 2001) were left underexplored. This gap is particularly relevant for cleantech sectors. Improving our understanding of the factors that shape the development of cleantech industries in latecomer countries has become paramount in global policy discussions regarding the 2015 Sustainable Development Goals and the Paris Agreement (Schmidt and Huenteler, 2016). Also at a national level, latecomer countries are increasingly interested in the policies and conditions that can lead to green growth.[2]

We argue that the gap in understanding of path creating catching up stems from two shortcomings in existing theorizing. First, to date the influence of economic globalization on industrial path creation is not well explored. Recent empirical studies increasingly show that emerging industries are influenced not only by regional path-dependencies or multinational companies, but also by more distributed networks of firm and non-firm actors forming in global innovation networks (Chaminade and Plechero, 2015; Coe and Bunnell, 2003), global technological innovation systems (Binz et al., 2014; Quitzow, 2015b; Wieczorek et al., 2015), global epistemic and professional communities (Coe and Bunnell, 2003; Wenger, 1998), or

[2] See e.g. http://www.oecd.org/greengrowth/

the interpersonal networks of transnational entrepreneurs (Drori et al., 2009; Saxenian, 2007; Yeung, 2009). Second, existing theories tend to emphasize firm- and knowledge-based dimensions of industry formation, while downplaying the role of interdependencies with non-firm actors, markets, policy making and institutional contexts in a broader systemic context. To better embrace innovation and industry formation dynamics in a globalizing knowledge economy, a more systemic and multi-scalar approach is thus needed (Coenen et al., 2012; Crevoisier and Jeannerat, 2009). This systemic understanding is particularly important in the cleantech space given the urgency of meeting environmental challenges and the related policy interventions.

This paper addresses these gaps by bringing together insights from evolutionary economic geography, catching-up, and innovation system studies and formulating an analytical framework for the multi-scalar innovation processes that enable early industry formation in latecomer regions. We conceptualize industry formation as a *systemic* innovation process, which depends on co-evolving technology innovation, demand side dynamics, policy intervention, and shifts in investor preferences (Choi and Anadon, 2013; Dawley, 2014; Surana et al., 2015; Tanner, 2014). We furthermore distinguish between the generic regional assets of a latecomer context (e.g. at a city, region, or country level) and four key system resources for early industry formation that may develop in multi-scalar networks: knowledge, financial investment, niche markets, and technology legitimacy. We argue that these relational resources[3] do not necessarily have to be created or evolve inside a given region. Instead, they can emerge from international networks and organizations or co-evolve between several distinct regions. Actors wishing to spur new industries in a latecomer context might be able to access extra-regional system resources (if they exist and are accessible in a particular industry) and use them to directly upgrade latecomer firms' capabilities (Binz et al., 2016).

We ground this framework - which was outlined in more general terms and with a different case in Binz et al. (2016) - in a new case study on the emergence of the solar photovoltaics (PV) industry in China. A comprehensive literature review and expert interviews with 26 key stakeholders in the Chinese PV sector reveal that the very fast industry formation process in China is not fully explained by existing catching-up and related diversification accounts, because: (a) Chinese companies operated outside the global value chains of Western and

[3] For a detailed discussion of the conception of relational resources See Bathelt and Gluckler (2005)

Japanese PV lead firms; (b) capabilities in related sectors emerged only after the PV industry took root in China; and (c) the central government initially showed relatively limited interest in promoting this particular industry. Our results rather hint at an underexplored mechanism for industrial path creation, which Martin and Sunley (2006) in their seminal contribution labeled 'transplantation from elsewhere'. We find industry transplantation to be the outcome of a direct, internationalized entrepreneurial process in which Chinese pioneers directly mobilized system resources for industry formation from outside the country and successfully combined them with (initially unrelated) generic assets like mass-production capabilities available in the Yangtze River delta region.

The remainder of the paper is structured as follows. Section 2 summarizes existing explanations of industry formation and identifies gaps in their theorizing of multi-scalar innovation dynamics beyond single regions/countries. We then formulate an analytical framework that specifies four multi-scalar system resources for industry formation and discuss how they might be anchored to latecomer contexts through the action of transnational entrepreneurs. Section 3 justifies the empirical case and describes the methodological approach. In section 5 we apply our framework to solar PV manufacturing in China, illustrating the need to further explore transplantation-based industry formation. Sections 5 and 6 discuss the generalizability of our framework and summarize our contributions to catching-up literature, innovation studies and environmental policy making.

2 Towards an analytical framework for transplantation-based industry formation

Among others, especially evolutionary economic geography, catching-up literature and innovation studies have analyzed new industry formation processes in most detail (for a review see e.g. Boschma et al., forthcoming; Martin, 2010; Martin, 2012). In the remainder we will first critically review the most influential theories from the former two strands of literature and then discuss how innovation studies may complement these perspectives in a new analytical framework.

2.1 Gaps in existing models of industry formation

Related diversification theories from evolutionary economic geography argue that regions tend to diversify into new industries that are close to existing knowledge base and manufacturing capacities (Frenken and Boschma, 2007; Hidalgo et al., 2007; Neffke et al., 2011). New industries accordingly emerge from an endogenous spillover process in which the organizational routines and manufacturing competence of existing firms get recombined to form a new industrial path that deviates from previous trajectories (Frenken and Boschma, 2007). Regional spin-offs, spinouts and territorially embedded knowledge recombination in clusters play a key role in this process (for an overview see Simmie, 2013). Firms in latecomer regions that either lack capabilities that could be creatively recombined (Frenken and Boschma, 2007), or have capabilities only in low-tech products which cannot be used to directly move to more complex product categories (Hidalgo et al., 2007), have low chances for quickly moving into new industries. Empirical studies in various European, US and Asian regions proved that the regional industrial composition indeed evolves in an incremental branching process, called ‘related diversification’. While this literature has convincingly proven the empirical relevance of related diversification in a wide set of contexts, it has devoted less attention to the question of how and why regions in some cases still manage to branch into new industries that are not directly related to activities present in the region (Boschma et al., forthcoming). This shortcoming is significant, since for latecomer regions, it is often “precisely the long jumps [to more unrelated industries] that generate subsequent structural transformation, convergence and growth” (Hidalgo et al., 2007: 487).

The catching-up literature, in turn, devotes more attention to this question by assessing how firms in latecomer countries or regions absorb outside knowledge to upgrade their technological capabilities and industrial structure (Fu et al., 2011; Gereffi, 1999; Lee and Lim, 2001). Catching-up is seen as the outcome of a gradual upgrading of latecomer firms’ technological capabilities, a process which typically unfolds over several decades (Fu et al., 2011; Gereffi, 1999; Malerba and Nelson, 2011). The notion of industrial upgrading in global value/production chains takes center stage here: latecomer firms acquire their capabilities through integration with the global supply networks of global lead firms (e.g., General Motors in the car sector or Apple in the ICT industry). They usually start in a basic supplier role (original equipment manufacturing, OEM) and subsequently move to more knowledge intensive manufacturing and management processes, ultimately including original brand design (Gereffi, 1999; Malerba and Nelson, 2011). In other cases, latecomer firms may partner with leading firms through licensing or joint ventures and over time develop more advanced technological capabilities and management routines (Lee and Lim, 2001; Lewis, 2007). In both cases, learning and upgrading happen through consecutive rounds of in-house

R&D and reverse engineering, as well as interaction with the lead firm and regional knowledge infrastructure, policy makers and other intermediary actors in an existing industry.

The empirical relevance of this generic catching-up model has been validated with a wide set of historical case studies from latecomer countries in Asia, South America and Africa (Fu et al., 2011; Gereffi et al., 2005; Malerba and Nelson, 2011). Among others, examples from Taiwanese PC manufacturing (Kishimoto, 2004), the apparel industry in several East Asian countries (Gereffi, 1999), or the automobile, consumer electronics, and mobile phone industries in South Korea (Lee and Lim, 2001), all showed that the integration of latecomer industries in existing global value chains and dense interaction with (Western) lead firms was of key importance in the learning and industrial upgrading process. Similar processes have been seen to be important in the wind sector (Lewis, 2011; Surana et al., 2015) or the electric car industry (Schmidt and Huenteler, 2016).

While both approaches have strong merits in explaining industry formation as a process of gradual learning and diversification, two main gaps stand out in our understanding of instances of quick industry emergence. First, an overarching focus on intra-firm routines and technological capabilities has come at the expense of insufficiently integrating the influence of non-firm actors like policy makers, investors, interest groups or industry associations on the industry formation process (Dawley, 2014; Jung and Lee, 2010; Simmie, 2012; Tanner, 2014). In particular, resources stemming from the wider systemic environment beyond the firms in a field of technology are not fully conceptualized (Binz et al., 2016). Second, the role of multi-scalar actor networks and extra-regional linkages beyond multinational corporations (MNCs) and well-structured global value chains (GVC) or production networks (GPN) is not well conceptualized in existing frameworks (Binz et al., 2016; Coenen et al., 2012). The explanatory power of conventional catching-up accounts thus applies mostly to industrial upgrading in well-established sectors in which global value chains with dominant lead firms have developed in the past. It provides less clearly defined concepts for dynamic industry formation in sectors like solar PV in the early 2000s, where value chains were more fluid, markets depending on policy interventions and (as we will show) key system resources were available in highly distributed international networks.

We here propose to address the above gaps by complementing existing industry formation theories with insights from two closely-related strands of literature: technological innovation system (TIS) and transnational entrepreneurship studies. The TIS literature is used to define the types of multi-scalar system resources that firms in latecomer contexts draw on in the industry formation process. Transnational entrepreneurship literature is in turn used to specify how mobile experts may anchor extra-regional resources in the industry formation processes in a latecomer context. This account of industry formation complements existing explanations by differentiating between ’classic catching-up’—which is more gradual and relies to a great extent on multinational corporations, global supply chains, and path-dependencies in regional industry clusters —and ‘industry transplantation’, which relies on globally dispersed resource formation processes and transnational entrepreneurship in spatially fluid actor configurations.

2.2 System resources for industry formation

Evolutionary economic geography and the catching-up literature agree with the resource-based view of the firm that firms depend on organizational resources (tangible and intangible assets like financial assets, know-how, routines, etc.) for their commercial development (Foss and Eriksen, 1995; Morrison et al., 2008; Peteraf, 2005). A firm’s strategies and limits of what it can achieve directly depend on its internal resource base, e.g. the technological capabilities, routines or reputation it accumulates over time (Barney, 1991). Yet, especially in newly emerging industries such as those in the cleantech space, key strategic resources develop not only inside firms, but also in inter-firm networks or even at the level of technological innovation systems (Musiolik and Markard, 2011; Musiolik et al., 2012). Latecomer firms that lack internal organizational resources and capabilities can be expected to be particularly dependent on such external network or system resources. In the remainder we differentiate between two generic types of external system resources: ‘generic regional assets’ (see Maskell and Malmberg, 1999) that are embedded in the latecomer context itself; and system resources developing in an emerging industry’s actor networks that may transcend national borders.

Generic assets developing inside the latecomer context

In terms of regional assets, Maskell and Malmberg (1999) emphasize that material assets and infrastructure; human assets like labor skills and knowledge; technological capabilities and firm routines; as well as institutional configurations of routines and norms equally influence industry formation potentials. In their sum, these assets denote the historically grown ‘absorptive capacity’ of the industrial system in a given place (Cohen and Levinthal, 1990). We here propose to frame this concept as a region’s ‘generic absorptive potential’ (cf. Table 1) for a new industry, which is constituted by a latecomer region's (1) basic infrastructure and macro-economic environment (Acemoglu and Robinson, 2012; Perkins, 2003), (2) its generic technological capabilities and knowledge exploitation system (Bell and Giuliani, 2007; Kishimoto, 2004), as well as (3) its institutional configuration and domestic policy interventions that attract foreign direct investment and enable technology transfer (Lema and Lema, 2012; Rock et al., 2009; Sauter and Watson, 2008). In latecomer contexts, these assets are often not adapted to emerging industries' needs. Local firms lack specialized knowledge, the education system does not reach international standards, and cooperation between various stakeholder groups are loose and unstructured, thus hampering the build-up of collective innovation strategies (Chaminade and Plechero, 2015; Freeman, 1987; Nelson, 1993). Latecomer firms aiming to upgrade their capabilities will thus have to rely on external resources to some degree.

Table 1: Generic absorptive potential for industry formation

Dimensions	Streams of literature	Key references	Basic argumentation
Material infrastructure	Development economics	(Perkins, 2003; Sauter and Watson, 2008)	Material infrastructure (roads, electricity or freshwater supply), generic technological capabilities (basic know-how and know-what) and conducive institutional infrastructures (legal systems and macro-political environments) are key prerequisites for any industrial activity to emerge
Technological capabilities	Catching-up literature	(Lee and Lim, 2001; Morrison et al., 2008)	
Comparative institutional advantage	Institutional sociology, Development economics	(Acemoglu and Robinson, 2012; Coenen et al., 2012; Hall and Soskice, 2001)	

System resources developing in multi-scalar networks

Catching-up literature assumes that these external resources are mostly conveyed by lead firms from developed countries (Gereffi, 1999; Morrison et al., 2008). Yet, especially in less established industries, global value chains and production networks do often not yet exist or are only loosely structured. System resources thus evolve in more distributed actor networks spanning small and medium enterprises, universities, government agencies, associations and end users that co-evolve with technology-related institutional contexts in various places (Bergek et al., 2008; Garud and Karnoe, 2003; Geels, 2004).

To understand how latecomers access such globally dispersed resources in a new technological field, a connection to the technological innovation system (TIS) literature appears promising. TIS are defined as "a network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure or set of infrastructures and involved in the generation, diffusion, and utilization of technology" (Carlsson and

Stankiewicz, 1991, p. 111). In this view, firm-based knowledge is a key resource for industry formation, but – in contrast to much of the catching-up and relatedness literature – it is interconnected with other important innovation processes related to entrepreneurial experimentation, guidance of the search, demand side dynamics (market formation), resource mobilization, or the embedding of innovation in existing institutional structures (creation of legitimacy) (Bergek et al., 2008; Hekkert et al., 2007). Based on this framework, four system resources can be distinguished that are instrumental to any early industry formation process: knowledge and competencies, market access, financial investment and technology legitimacy (Binz et al., 2016). Table 2 further specifies the four system resources and the streams of literature underlying each resource type.

Table 2: Key system resources for industry formation

Resource	Sub-dimensions	Streams of literature	Key references	Basic argumentation
Knowledge	Codified knowledge (Know-what) Tacit knowledge (Know-how)	Economic Geography Innovation studies	(Asheim and Coenen, 2005; Bathelt and Glückler, 2005; Crevoisier and Jeannerat, 2009; Freeman, 1987; OECD, 1996)	In a knowledge-based globalizing economy, knowledge (codified and tacit) is a key resource for any innovative activity.
Markets	Commodification Niche markets	Social construction of markets Transition studies	(Dewald and Truffer, 2012; Fligstein and Zhang, 2011) (Geels, 2002; Kemp et al., 1998)	In newly emerging industries, commoditized products and protected niche markets are not given, but actively created by early entrepreneurs, user groups, and/or government intervention
Financial investment	Venture capital, banks, equity and institutional investors Government subsidies	Management, entrepreneurship and business literature	(Gustafsson et al., forthcoming; Surana et al., 2015; Teppo, 2006; van den Bergh, 2013)	Entrepreneurial actors in a latecomer region need to mobilize various forms of financial investments to keep their new ventures in business and growing.
Technology Legitimacy	Institutional embedding Technology certification, standards	Institutional Sociology	(Johnson et al., 2006; Suchman, 1995; Zelditch, 2001) (Aldrich and Fiol, 1994; Rao, 2004)	New technologies that have no precedent in the social order are confronted with high skepticism by users, investors, and policy makers. They thus have to be aligned with the relevant (normative, regulative and cognitive) institutional structures

Three points are important to note about our concept of system resources. First, they are conceptualized as a necessary condition for industry formation; if access to one resource is missing, entrepreneurs will have to surmount the challenge of creating or obtaining it (assuming it is available elsewhere). If the emerging industry cannot mobilize one of the resources, a 'system failure' exists (Weber and Rohracher, 2012), which might justify deliberate action by governments or other actors to increase the chances of industry formation.

Second, as these resources are the emergent outcome of collective agency in a wider innovation system, they have to be understood in a relational conceptualization (Bathelt and Glückler, 2005). They cannot be mobilized and controlled by isolated actors, but rather depend on interaction in heterogeneous actor networks (Markard et al., 2011; Musiolik et al., 2012). This is also particularly the case in the cleantech or green-tech spaces since government regulation and, in some cases, additional support policies, have been shown to play an important role in the emergence of industries (Mazzucato, 2015). Once a resource has been constructed, it may become accessible to the other actors in the same (often multi-scalar) innovation system. For example, once a group of companies, government agencies and end-user organizations has constructed a new market segment, it becomes a resource that is available for other actors (and new entrants) in the same industry (Dewald and Truffer, 2011; Musiolik et al., 2012).

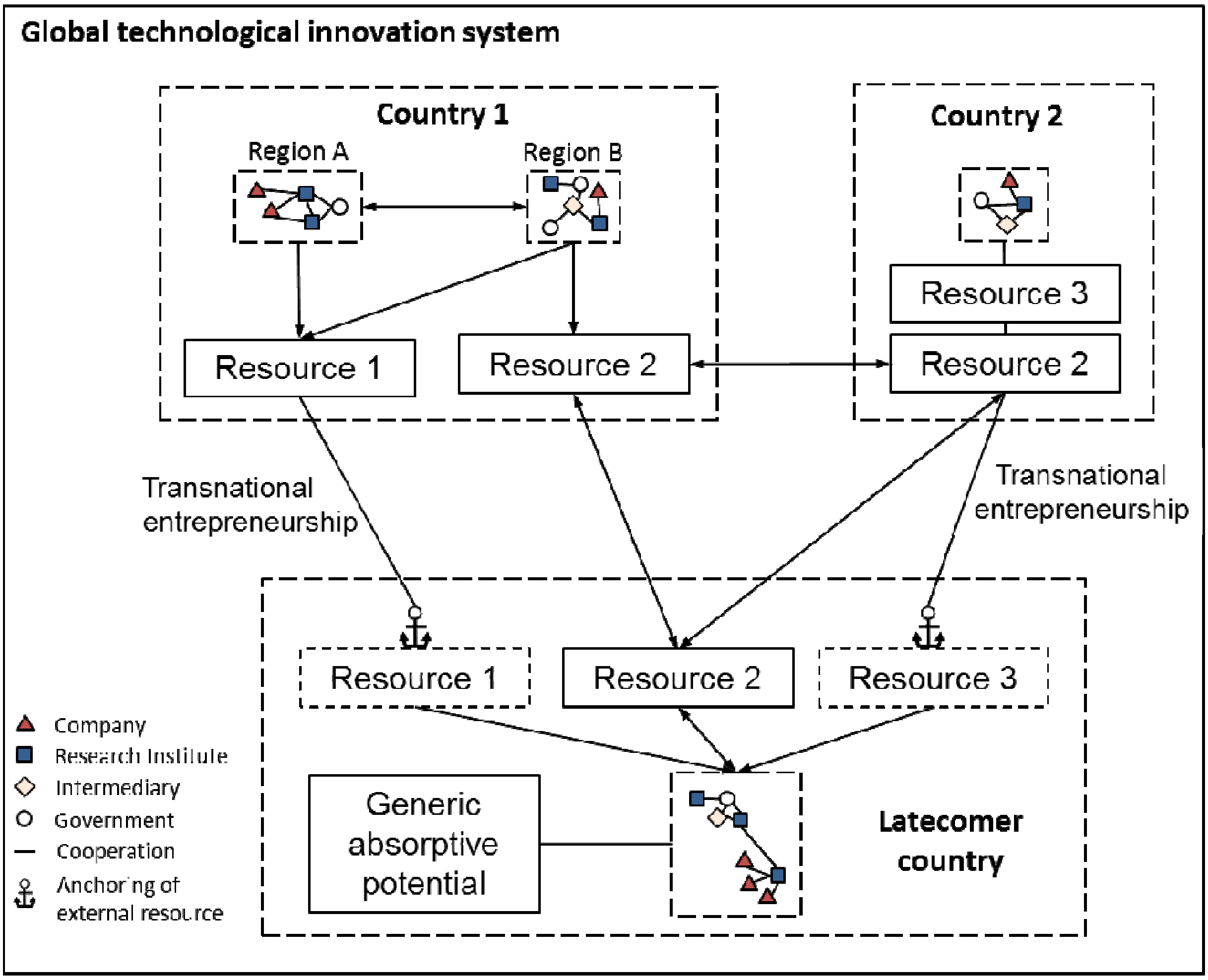
Third and finally, with accelerating globalization, the effects of resource formation might not be contained in specific regional contexts, but induce innovation processes in places far away (Binz et al., 2016; Coenen et al., 2012; Crevoisier and Jeannerat, 2009). For instance, a quality standard from one place can inform innovation efforts in another region, a financing tool developed in a specific country might be used to reap investment opportunities in various foreign regions and the same policy instrument may be applied in various countries around the world. To understand the wide range of possible mechanisms for industry formation, it becomes crucial to assess how latecomer firms mobilize system resources not only from their regional or national contexts or multinational companies, but also from distant regions and various actors in a global technological innovation system (Binz et al., 2016; Binz et al., under review; Crevoisier and Jeannerat, 2009). Put differently, to understand path transplantation processes, one thus needs to analyze how and where system resources emerge, and how they get accessed and anchored to the 'generic absorptive potential' in a given latecomer context.

2.3 Summary of the analytical framework

Figure 1 summarizes the framework outlined above. Innovative activity in a new industry may be concentrated in various regional or national subsystems, but at the same time be dispersed in trans-disciplinary and interpersonal networks developing through international research projects, communities of practice or temporal clusters in trade fairs (Crevoisier and Jeannerat, 2009; Hennemann et al., 2012; Maskell et al., 2006; Wenger, 1998). As shown in

Figure 1, system resources accordingly develop in increasingly multi-scalar 'systems of subsystems' (Binz et al., under review) —i.e., one resource (e.g. knowledge, resource 3) might be created in one specific regional context, whereas another resource (niche markets, resource 1) emerge form actor networks spanning several regions inside a given country. Yet another resource (e.g., financial investment, resource 2) might get mobilized in the strongly internationalized professional networks of venture capital firms and investment banks. Actors moving between subsystems of this global system accordingly play a key role in integrating activities from different parts of the world and anchoring them to a new path in latecomer contexts. As previously mentioned, the emergence of today's knowledge based world economy points to the notion that such path transplantation process may be feasible for some types of cleantech industries.

Figure 1: Anchoring extra-regional resources in early industry formation – conceptual model



In particular entrepreneurs are not only active in one region during all of their lives anymore, but move from one place to the next, studying and working in different regional contexts, often returning to their home-regions when founding new ventures (Drori et al., 2009;

Saxenian, 2007; Yeung, 2009). By moving between different subsystems they build up a specific form of social capital that puts them in a favorable position to act as system builders in latecomer regions (Drori et al., 2009; Saxenian, 2007). Being embedded in and accumulating experiences in several subsystems of the global innovation system allows them to perceive windows of opportunity in a technological field that are invisible to exclusively regionally embedded actors (Drori et al., 2009; Saxenian, 2007; Yeung, 2009).

When re-contextualizing their knowledge about the global structure of an emerging industry, they may mobilize and ultimately anchor extra-regional system resources in a new path that makes the latecomer competitive over a relatively short period of time. 'Born global' companies that master this globalized resource transplantation process have arguably become the spearheads of the globalizing world economy (Mathews, 2006). Or, as Crevoisier and Jeannerat (2009, 1231) put it, "the most competitive enterprises are today those that take the most rapid decisions regarding how they will act globally and that combine various types of knowledge that exist elsewhere. It is no longer a question of simply going out to find the appropriate competencies where they are the least expensive, but one of imagining new projects based on competencies that are currently accessible." To substantiate these arguments and illustrate our framework, we will now apply it to an emblematic empirical case, the formation of the crystalline solar PV module industry in China.

3 Case selection and methods

3.1 Case selection

The solar PV sector in China was chosen as an illustrative case study in the cleantech space because it contradicts key tenets of the catching-up and industrial relatedness literatures. China is also the largest emitter of greenhouse gases, has agreed to undertake ambitious climate mitigation efforts, and is a country that governments and investors in other latecomer contexts look to when thinking about policies and business efforts to promote industrialization.

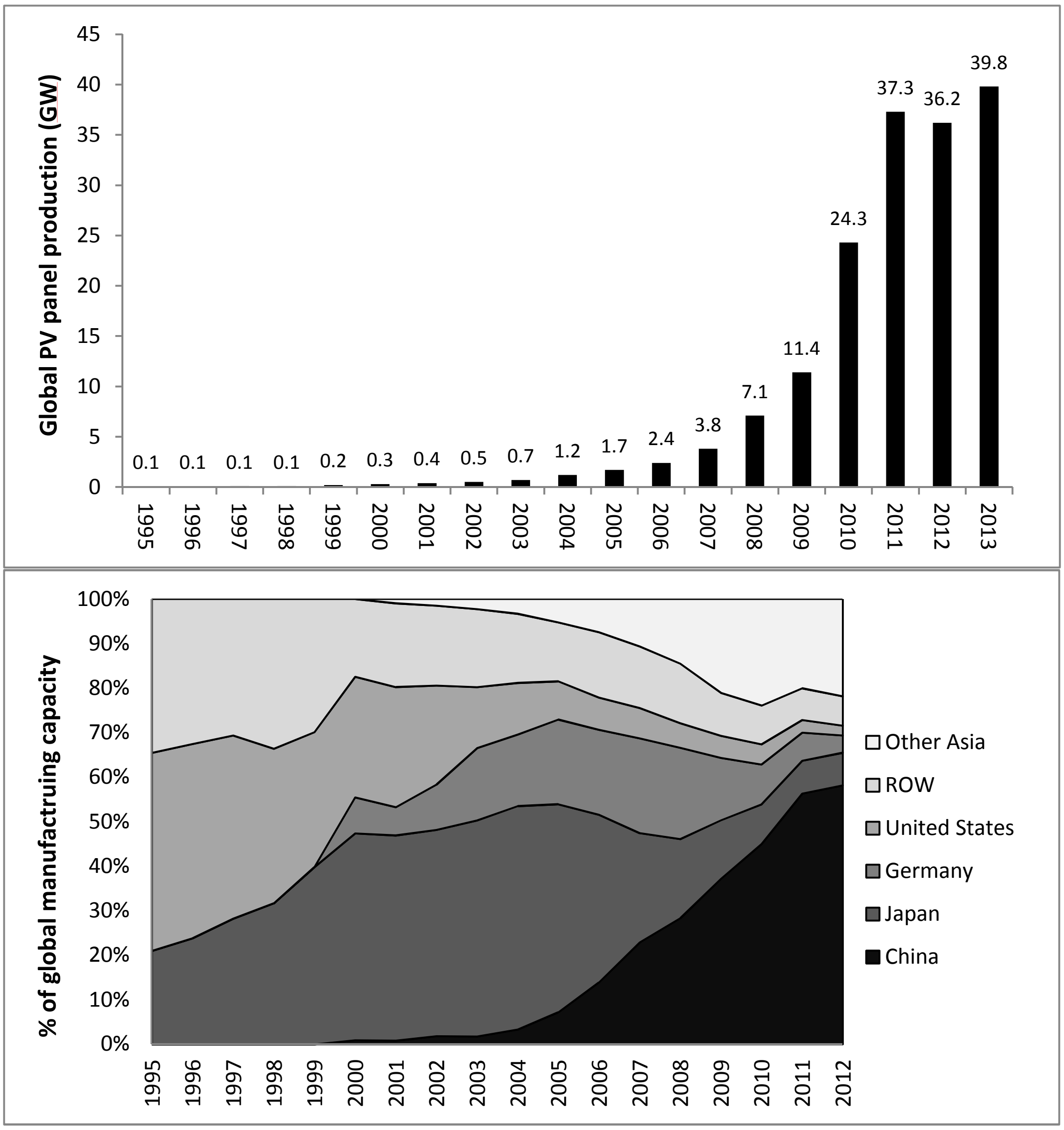
When the Chinese PV industry started growing quickly around 2000, *related* domestic technological capabilities were quite limited (Energy Research Institute, 2000; Zhao et al., 2013). A small PV sector had been established in China in the late 1960s for the national space program, as well as for rural electrification projects, e.g. in Tibet (Energy Research Institute, 2000; Zhao et al., 2013). Yet, by the late 1990s, only 17 PV module companies and

16 suppliers were active in China, all of which were small state-owned enterprises, except for one (ultimately unsuccessful) US-Chinese joint venture (Energy Research Institute, 2000; Zhang and White, 2016). By 1998, the local industry's production capacity was below 2.3 MW per year (compared to 277 MW globally) and companies were struggling with considerable quality problems (Cabraal, 2004; Energy Research Institute, 2000; Varadi, 2014; Yang et al., 2003). In 2000, a major synthesis report by the NDRCs Energy Research Institute identified large gaps between Chinese and foreign PV technologies (Energy Research Institute, 2000). The main problems identified were: "small production scale, low technology level, out-of-date auxiliary equipment" (ibid, 12).

Foreign direct investment was also absent during most of the 1990s and 2000s and none of the then lead firms from Japan, the USA and Europe were involved in outsourcing R&D or production to China (Zhang and White, 2016). Branching processes from closely related sectors — semi-conductors manufacturing and (poly-)silicon production (see Bruce, 2007) — initially also played a rather limited role. In the early 2000s, China's semi-conductor industry was mostly state-owned, global market shares of Chinese manufacturers were below 1% and foreign semiconductor MNCs were yet to establish manufacturing contractors in China (Choi and Anadon, 2013; de la Tour et al., 2011; SIA, 2014). The main spillover from the semiconductor to the Chinese PV industry appear to be engineers from Taiwan (which had 3% of market share in semiconductor manufacturing in 2000) that were hired by Chinese PV startups (SIA 2014). In the polysilicon industry, China developed its own technological capabilities only in the mid-2000s, forcing the pioneering Chinese PV manufacturers to import about 95% of their silicon supplies from abroad until 2008 (Fischer, 2012; Li, 2009).

Finally, also the Chinese central government took a rather critical stance against the development of solar PV in the early 2000s (Quitzow, 2015b; Zhang and He, 2013; Zhang et al., 2014; Zhao et al., 2013). Given the extensive quality problems in PV-powered rural electrification campaigns, government think tanks evaluated PV as a too expensive energy solution with substantial technology problems and rather limited market potential (Energy Research Institute, 2000; Zhang et al., 2014; Zhao et al., 2013). Some even argued that there was no comparative advantage for Chinese manufacturers in competing with the well-established PV manufacturers in Japan, the USA and Europe (Energy Research Institute, 2000; Zhang and White, 2016). In summary, around 2000, nobody - including the Chinese government which was actively supporting other cleantech industries such as wind - was expecting China to become a global powerhouse in PV manufacturing over less than a decade. This notwithstanding, between 2000 and 2010 China went from a 1% share in PV module production to shipping more than half of global PV panel output (Figure 2). Overall, given the lack of integration into global PV value chains and China's initial low level of capabilities in related sectors, this case promised unique insights into an industry formation process that differs from the well-established assumptions of catching-up and relatedness literatures.

Figure 2: Total global PV panel production (top panel) and global distribution of PV panel manufacturing capacity (bottom panel)



Source: Own design, based on data from Earth Policy Institute (2013)

3.2 Methods

We used an in-depth qualitative case study design (Yin, 2012) consisting of a two-step methodological approach based on our analytical framework to reconstruct the early resource formation dynamics in the global TIS and China. First, the emergence and accessibility of system resources in the global TIS was analyzed based on a review of extensive secondary literature on the PV sector's global evolution (cf. section 4). Second, the resource mobilization strategies of the pioneering Chinese entrepreneurs were assessed with an in-depth expert interview campaign in China.

In total, 26 semi-structured interviews were conducted with the founders, CEOs, CTOs and senior managers of the major pioneering Chinese PV companies, as well as with other key experts from China and abroad that were involved in the early development phase of the solar PV industry in China (see Appendix 1). Interviews were conducted during a two month fieldwork campaign and lasted between 45 minutes and two hours. All interviews were recorded, transcribed verbatim and codified according to the key resources framework defined above. Codified interview excerpts were analyzed with qualitative content analysis (Strauss and Corbin, 1998) in MAXQDA software to identify the core strategies through which entrepreneurs anchored foreign system resources to the Chinese context. To avoid interpretation biases and post-hoc rationalization, the information from interviews was extensively triangulated with secondary data and PV companies' annual reports.

4 The emergence of the Chinese solar PV industry

In this section we follow the analytical framework elaborated above by first summarizing the early history of the Chinese PV industry and then assessing the country's generic absorptive potential in the PV field. We then turn to analyzing the global evolution of each system resource and the way it either emerged in China or was anchored from the global PV TIS.

4.1 History of China's solar PV sector

Until the late 1990s, the Chinese PV sector was progressing very slowly and prone with quality problems. This situation changed around 2000, when four new PV panel manufacturers (Suntech, Trina, Yingli, and Canadian Solar[4]) were founded that would pioneer a new development trajectory the Chinese solar PV industry.

[4] Canadian Solar is a Canadian company, which was founded by an ethnic Chinese. While its headquarters are in Canada, it outsourced considerable parts of its PV panel production to China starting in 2003.

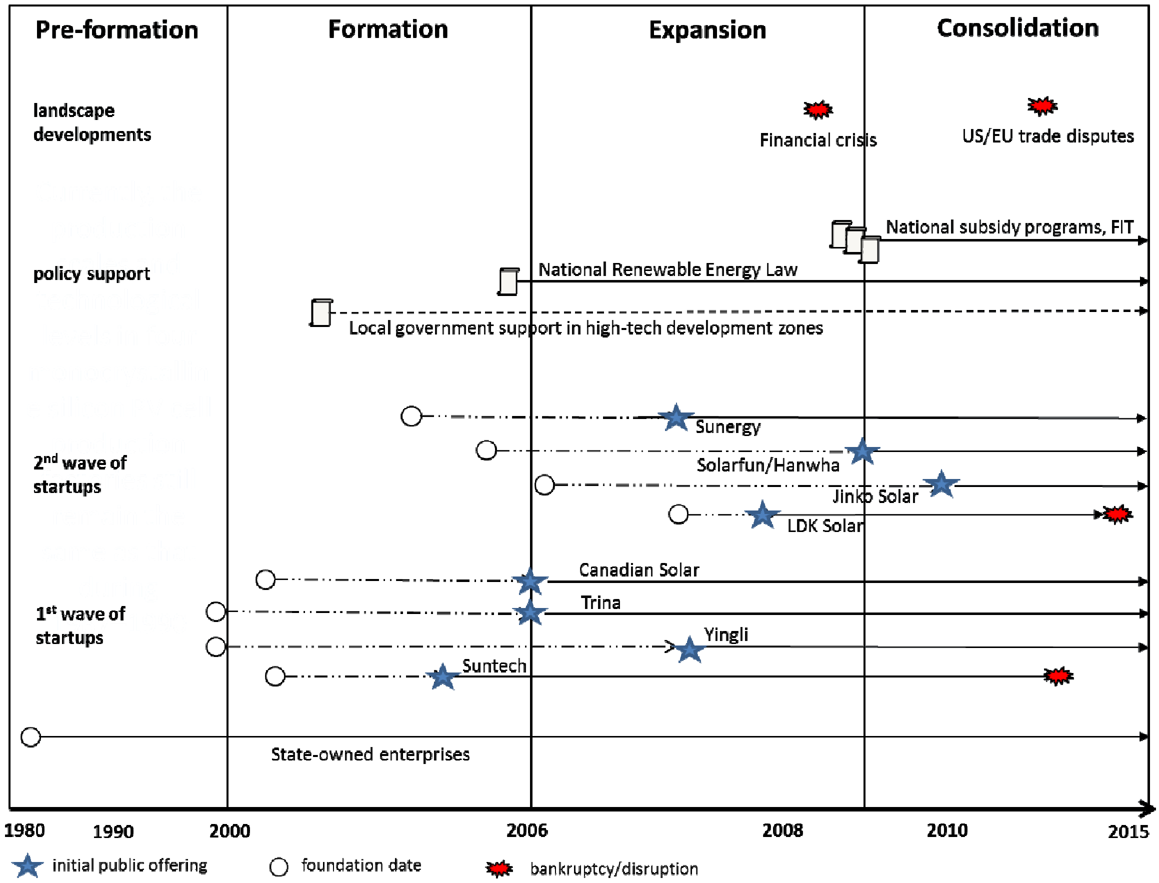
Table 2: Major PV panel manufacturers in China, 2014

Name	Foundation	IPO	Bankruptcy	Headquarters	Revenue (bn. US$, 2014)	Shipments (MW, 2014)
Yingli Solar	1997	2006	n.a.	Baoding	2.08	3’361
Trina Solar	1998	2006	n.a.	Changzhou	2.29	3’660
Canadian Solar	2001	2006	n.a.	Ontario CA	2.96	3’105
Suntech	2001	2005	2012	Wuxi	n.a	n.a.
Sunergy	2004	2007	n.a.	Tianjin	0.36	577
LDK Solar	2005	2007	2014	Jiangxi	n.a.	n.a.
JA Solar	2005	2007	n.a.	Shanghai	1.82	3’057
Jinko Solar	2006	2010	n.a.	Shanghai	1.61	2’943

Source: Company annual reports 2014

By the mid-2000s the four pioneering companies had all turned into privately-owned ventures with dominant global market shares and gotten listed at international stock exchanges. Their success motivated investors and other entrepreneurs to move into the solar PV industry in China, which initiated a second wave of startups (comprising companies like Jinko Solar, Sunergy, LDK, or JA Solar) and a domestic investment boom from 2004 (Quitzow, 2015b). The boom in the Chinese PV industry abruptly halted in 2008 with the global financial crisis, leading to a meltdown of government-subsidized PV markets overseas. After 2008, the Chinese government initiated domestic market deployment policies, included solar PV in its list of strategic industries, and Chinese development banks issued large loans to the tumbling companies (Dong et al., 2014; Fischer, 2012). Still, the industry increasingly consolidated; some major companies from the first and second startup waves took up dominant global market shares and developed into vertically integrated lead firms in the global value chain for crystalline solar PV products, while others crumbled under their excessive debt levels and the introduction of anti-dumping tariffs on Chinese solar PV panels in the US and the EU (Curran, 2015; Quitzow, 2015b).

Figure 3: Development phases in China's solar PV manufacturing industry



The catching-up path of the Chinese industry (cf. Figure 3) can thus roughly be differentiated into pre-formation, formation, expansion and consolidation phases (also see Quitzow, forthcoming). As our analytical framework emphasizes early industry formation dynamics, the subsequent analysis will mostly focus on the (pre-) formation and early expansion phases shown in Figure 3, spanning from the late 1990ies until about 2008.

4.2 Generic absorptive potential in China

The first step of our framework asks us to assess the generic absorptive potential for solar PV technologies in China. First and foremost, in terms of *basic material infrastructure*, China provided quite favorable initial conditions. Several interviewees stressed that access to world-class international trade infrastructure in the Shanghai and Tianjin region was of key importance for developing an export-based industry in the early phase (Interviews 1, 2, 13, 16). Second, our interviews revealed several generic *technological capabilities* that were available in the Chinese context and benefitted the emerging solar PV industry. I.e. China had a relatively well-developed education system that provided the new industry with university graduates with a basic engineering education (see section 4.2). In addition, throughout the 1980s and 1990s China had built-up a strong competence in contract mass-manufacturing of exportable consumer goods (toys, consumer electronics, furniture, etc.). This industry had developed generic capabilities in identifying and absorbing outside technologies and quickly scaling up mass-production (Nahm and Steinfeld, 2014). Several pioneering PV companies emerged from unrelated industries providing such generic capabilities: Yingli was founded by a serial entrepreneur with experience in agricultural technology and water treatment products; Trina Solar by a Chinese entrepreneur in the detergent business, LDK solar by the director of a firm in protective glove manufacturing (Zhang and White, 2016). Canadian Solar and Suntech were in turn companies with a strong background in the international PV field: Canadian Solar was founded by a Canadian-Chinese PV expert with business experience in Canada and France, while Suntech was a de novo start-up by an Australian-Chinese academic who had started his professional career in Australia.

In terms of *comparative institutional advantage*, China provided general macro-political stability, but other key factors like the rule of law and international intellectual property rights regimes were not rigorously enforced.[5] A key comparative institutional advantage for Chinese actors was the entrepreneurial culture in limited spheres of China's authoritarian capitalism system, especially in the Yangtze River Delta region (Witt, 2014). Several interviewees also pointed at the important role of pro-active, resourceful and entrepreneurial local governments (Interviews 3, 13, 20, 24), readily available seed funding for a wide range of high-tech businesses (Interviews 9, 11, 23), and dense interpersonal linkages ('guanxi'-ties) in the emerging industry cluster around Shanghai (Interviews 8,9,16). In addition, China's lax enforcement of environmental laws allowed for the very fast scaling-up of production facilities in designated high-tech development zones, without strictly enforced approval processes like environmental impact assessments (Interviews 10, 18). In China, new PV manufacturing plants could be built in a matter of months (Interviews 9, 10, 14), while the same process took foreign competitors up to three years (Zhang and White, 2016).

Given the limited amount of capabilities directly related to solar PV manufacturing, the pioneering entrepreneurs justified their decision to start new PV ventures in China either with environmental idealism or with the generic support by local governments and a certain home bias:

[5] In our interviews, IPR issues were never mentioned as a hindering or supporting factor for Chinese catching-up and to our knowledge, industry formation in China happened without major disputes on IPR infringement by Chinese PV companies.

"To be honest I could have started the company anywhere in the world – like Australia, US, or Europe. But the reason I choose China is because […] when I started a new business, I did not have much experience doing business overseas – you have to deal with laws and so on. So I thought China is my motherland. Same language, lots of support from local investors and the local government."[founder of a Chinese PV company]

Overall, the Chinese context provided relatively limited technological capabilities and system resources that were directly related to the solar PV industry in the early 2000s. Still, the quite plentiful unrelated capabilities and institutional comparative advantages later proved very important in enabling quick industry formation. To understand this process in more detail, we will now turn to assessing the four system resources of our analytical framework. For each resource we will first characterize its development in the global TIS of solar PV and turn to analyzing how Chinese actors accessed it and combined it with the generic absorptive capacity available inside China.

4.3 Key system resources

4.3.1 Knowledge

Knowledge creation in the global TIS

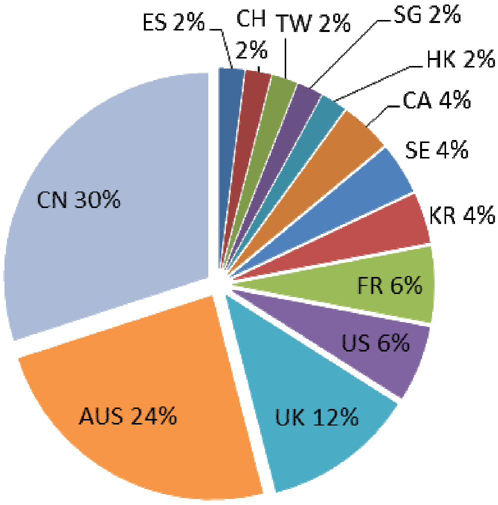
Solar PV modules are a highly standardized mid-tech commodity whose knowledge base and innovation potential relies on advances in material sciences, electric engineering, metallurgy, and semi-conductor manufacturing (Huenteler et al., 2016). Given these characteristics, knowledge about PV technologies is relatively easily codifiable and accessible in publications, patents and technical guidelines (de la Tour et al., 2011; Zheng and Kammen, 2014). From the early days of the industry, academics, entrepreneurs, engineers and idealists were moving between the USA, Europe and Japan in a global epistemic community, thereby facilitating intense global knowledge circulation (Binz et al., in press; Varadi, 2014). In addition, PV production-relevant knowledge can relatively easily be embedded in automated production machinery (Huenteler et al., 2016). To start PV panel production, one does not have to acquire knowledge about all parts of the value chain, but needs to re-combine existing production machines to a working manufacturing line. After 2006, turnkey production lines appeared on the market that automated the whole production process from wafer slicing to module assembly, thereby further accelerating global knowledge circulation (Dewald and Fromhold-Eisebith, 2015; Quitzow, 2013). Yet, to the Chinese pioneering firms in 2000, such turnkey solutions were not yet available (Quitzow, 2013; Zhang and White, 2016). They were forced to find other ways to access the technological capabilities needed for PV manufacturing.

Knowledge creation in China

Up until 2000, the knowledge and competencies developed in the Chinese solar PV sector were prone with quality issues and did not lead to any commercial success. This situation changed only around 2000, when returnee entrepreneurs founded new ventures and connected China to state-of-the-art knowledge networks outside the country. In the case of Suntech, the founder was a world-renowned expert on PV technology from the University of New South Wales, who owned 15 technology patents and had developed a small thin-film PV production line for an Australian company (Davila et al., 2010). When he established a start-up in Wuxi in 2001, he had accumulated both the theoretical knowledge and the practical know-how on state-of-the-art PV manufacturing technologies. Similar conditions applied to Canadian Solar, which was founded by a Sino-Canadian semiconductor technology expert that decided to outsource PV panel production of his Canadian start-up (which initially supplied the car manufacturing industry with solar-based battery chargers) to Changzhou. The other two pioneering companies, Yingli and Trina, were founded by domestic serial entrepreneurs, whose start-ups however also developed technological capabilities in more internationalized knowledge networks than their domestic peers (de la Tour et al., 2011). The first annual reports of the four pioneering companies show that 70% of the senior management and board members had degrees from foreign universities and extensive work experience in international companies (Figure 4). As one of the founders of a pioneering Chinese PV company put it:

> *"It was very clear in my mind that I would start the company with the most updated [crystalline silicon] technology. Since 1989 I had spent 12 or 13 years in [foreign country], working on solar technology. I had accumulated a lot of knowledge and experience and I felt that I could do something dramatically different."*

Figure 4: Master degrees of the board members of the four pioneering Chinese PV companies



Source: Annual reports of Yingli, Trina, Suntech, Canadian Solar (2007), N=50

To develop the first manufacturing lines, Chinese pioneers drew on a novel "low cost expansion" strategy, which relied heavily on their pre-established international network connections (Davila et al., 2010; Zhang and White, 2016). Key components and machinery like wire saws for wafer production or lamination machines were imported from abroad (Interviews 1, 2, 5, 9), and then adapted and combined with cheaper domestic components and materials (e.g. cover glass, cables) to form lower-cost, but still high-quality integrated production lines (Fu and Zhang, 2011). In several cases, second-hand production equipment was imported from Australian, Italian, or Japanese manufacturers, often with rebates of up to 90% (Interviews 10, 14, 21, Zhang and White, 2016).

At this early stage, the Chinese R&D and university system supplied the industry only with limited *codified knowledge* on solar PV manufacturing technology. The first integrated production lines were accordingly not developed in partnership with or within local universities and research institutes, but in close cooperation with foreign experts. In the case of Canadian Solar, the founder brought in key experts, PV production equipment and a management team from his previous position at Photowatt International (a then globally leading PV manufacturer based in France) and established first production lines in a bricolage process very similar to Suntech (Interview 1). In the case of Suntech, Australian experts from the University of New South Wales (UNSW) played a key role in establishing and fine-tuning the first production line.

> *"[Suntech] was relying on about 12 people [from UNSW] to set up the equipment, to fine tune the equipment, to commission it, to optimize the performance of it to get the product working properly. People from UNSW in the early stages directly provided all the technology support," (Interview 10)*

Also after the first production lines were established, connections to UNSW remained instrumental (de la Tour et al., 2011; Quitzow, 2015b). Suntech and other Chinese companies funded research centers at this global center of excellence and profited from free access to the intellectual property, simulation tools and production processes created there (Interview 10). One example was a virtual modelling tool for PV production lines that allowed the management of Suntech to virtually test and fine-tune all the parameters of their complex first production lines (Interview 10). Over time, networks with the Photovoltaics Centre of Excellence at UNSW turned into a key knowledge pipeline for R&D and education in the broader Chinese PV industry (de la Tour et al., 2011; Quitzow, 2015b). Between 2001 and 2006 graduates from UNSW physically established the first production lines at Suntech, China Sunergy and JA Solar and experts increasingly circulated between various companies (Zhang and White, 2016). The Sino-Australian connections became so tight that investment banks that were organizing the IPO for Chinese companies (see section 4.5) were forcing them to hire board members that were graduates from UNSW (Interview 10).

For the production of more *tacit* forms of *knowledge,* both regional and international interaction was important. As the technological know-how needed for running production lines are not prohibitively high, Chinese PV startups could rely on graduates from technical universities in China without PV technology expertise in their early operations:

> *"We hired only one experienced engineer from China. All the rest basically we hired as students, graduate students, and I would train them. We hired probably 1000. I'd spend two years training them. Three evening classes every week. I personally taught them lessons. [Their majors were in] science and engineering. Not related to solar."(Founder of a Chinese PV company)*

The companies in the 1st wave of start-ups were also key in upgrading capabilities in the domestic supplier industry. Many (often farmer-run) local suppliers of steel frames, glass, welding material or wiring cables lacked the most basic technological capabilities to produce high-quality inputs for PV panel production. The pioneering companies thus directly trained them, supported them in implementing ISO quality management procedures and sometimes even provided free patent licenses to increase their product quality.

> *"Some suppliers started from scratch. I taught them everything. I negotiate for them to buy equipment from Meyer-Burger for example. […] It was all volunteering." (Founder of a Chinese PV company)*

Overall, our interviews showed that most of the decisive knowledge of the Chinese PV manufacturing industry in the early 2000s did not originate from local sources. More importantly, the pioneering companies successfully mobilized their cutting-edge international knowledge networks to upgrade existing generic capabilities in mass-manufacturing sectors, specialized supplier industries and the human capital graduating from local universities.

4.3.2 Market access

Market formation in the global TIS

From 1970 until 1990, solar PV modules were a niche product without a clear mass market (Varadi, 2014; Zhao et al., 2013). Early niche applications comprised weather stations, oil platforms or calculators. These markets created learning opportunities for the early PV companies in the US and Japan, but they were too small to reap economies of scale in production and significantly reduce PV module prices. This changed only in the late 1990s, when Japan, Germany and Spain initiated ambitious government-supported deployment subsidies. In Germany, grassroots movements had over 20 years commoditized home-owned, grid-integrated solar PV systems as mass-market segment (Dewald and Truffer, 2011; Dewald and Truffer, 2012). They successfully lobbied the regional and national government to spur market deployment with a regional and later national feed-in-tariff (FIT) system (Hoppmann et al., 2014; Peters et al., 2012). In Japan, from 1993 the Ministry of Economy, Trade and Industry (METI) embarked on a comprehensive R&D and deployment support scheme for solar PV (the New Sunshine Project), in a strive to establish PV as a reliable national energy source (Vasseur et al., 2013). Especially Germany's national FIT system in 2004 created the world's first reliable mass market for solar PV modules which soared by 294% in that same year (Zhang et al., 2014). The policy-induced demand boom caused sharp global undersupply as the German, Japanese, and U.S. incumbents could not address skyrocketing demand (Quitzow, 2015b). Once a mass-market had been created in Germany (and to a lesser degree in Japan and Spain), a market-based system resource became available in the global TIS, which - given the nature of the PV industry – got available to other PV manufacturers all over the world.

Market formation in China

In China, between 2000 and 2008 PV module markets were emerging rather slowly (Fischer, 2012; Zhang et al., 2014). Several deployment programs[6] initiated by the central government and international donor agencies between 1995 and 2005 provided first learning opportunities for the Chinese industry (Zhang et al., 2014), but were not large enough to induce economies of scale in mass manufacturing. The *cumulative* installed capacity in China only reached 52 MW in 2003, compared to 140 MW *annual* capacity additions in Germany alone (Quitzow, 2013). The Chinese market support schemes furthermore brought to the forefront of policymakers considerable technology and management quality problems (Cabraal, 2004). Among the four pioneering Chinese manufacturers, Yingli and Trina were most active in these government-run programs. Yet, those firms used them not only for commercial purposes, but also for lobbying the central and local governments to back solar PV as part of their 'high-technology' support programs and long-term energy policy plans (Zhang and White, 2016).

The transnational entrepreneurs at Canadian Solar and Suntech were in turn in a favorable position to directly exploit new market opportunities forming in Europe and Japan. Being embedded in the global epistemic community of the PV sector helped them to perceive a market opportunity that was not visible to their nationally embedded competitors:

> *"[In 2003], solar PV was still a small circle of experts. People were saying to us: 'Hey do you want to go to this German inter-solar show?' We did not know anything about it. They said it was good, so we said: 'okay, we will go and see' […]. That was an eye opener for us. We had never been to a trade show before, and we loved it, we saw the products and we saw a lot of different customers who wanted to have these big PV modules for houses. So when we came back to China we started doing this right away." (Senior manager of a Chinese PV company)*

To get access to the European and Japanese markets Chinese startups had to establish a sales infrastructure in distant places and find ways to get regular feedback from their customer base to improve product specifications. At the early stages in 2003-2004, they scouted reliable sales partner and distributors at international trade fairs (Interviews 1, 2, 4, 8, 9). Starting from the mid-2000s, they established own representative offices in key foreign markets. One company opened sales representative offices and service centers in three European countries and deployed more than 50 Chinese engineers for service and maintenance work (Interview 8).

[6] The most relevant programs by the Chinese government were the Township electrification program (from 2001) and the Brightness Program (from 1996).

These teams were reporting back to the senior management in China on a weekly basis and briefing them about the requirements of Europe's high quality PV market (ibid.). Before the global economic crisis stopped European market expansion in 2008, Chinese producers consistently exported more than 95% of their production to overseas markets (Fischer, 2012; Zhao et al., 2013).

In summary, and similar to the knowledge dimension, also market-related system resources for the early Chinese industry were predominantly sourced from a global level. Instead of struggling with sluggish market demand inside China and trying to construct market segments in the complex institutional context of the Chinese power sector, the pioneering firms leveraged pre-existing trade infrastructure and their international networks to access booming foreign markets in Europe and Japan.

4.3.3 Financial investment

Financial investment in the global TIS

Between 1970 and 1990, financial investment for PV companies in the US, Europe and Japan was sourced predominantly from angel investors, equity funds and large oil companies (Varadi, 2014). As long as the technology was in a niche market stadium with unclear growth potentials, investors were reluctant to make risky long-term commitments (Hoppmann et al., 2014; Quitzow, 2013). Also this situation changed dramatically around 2000 with the implementation of FIT systems in Japan and Germany. Feed-in tariffs significantly decreased investment insecurities, which lead to a surge in annual demand side investment from below 1 billion Euros in 2002 to 6.2 Billion Euro in 2008 (Quitzow, 2015b). Regional banks, institutional investors and global investment banks now equally moved into the PV sector and started organizing high-profile IPOs of US and European PV companies like Q-cells, FirstSolar or Solarworld (Peters et al., 2012). By the early 2000s, global investment banks had accumulated sufficient sector expertise to target investment opportunities also in latecomer firms from Korea, Taiwan, Malaysia or China.

Financial investment in China

In China, initial seed funding for the pioneering PV companies was raised from domestic sources (Dong et al., 2014; Zhang and White, 2016). It consisted of equity investment from the company founders, private donors, local municipalities, high-tech development zone administrations as well as state-owned enterprises (for a comprehensive discussion see Dong et al., 2014; Zhang and White, 2016). Local municipalities often took a coordinating role in attracting new companies to designated high-tech development zones and broker seed funding from local SOEs, regional banks or the development zone management (Dong et al., 2014; Gallagher, 2014; Quitzow, 2015b).

> *"In those days it was very hard to find investors. So I talked to mostly state-owned investors, in [several cities]. […] I spent two weeks traveling around and talking to various investors and I finally thought, "it's possible." In [city Z], everybody thought it was a good direction, a good area. They were one step ahead of time. So I came to the conclusion to start the company there, and when we actually started I thought it was a perfect time." (Founder of a Chinese PV company)*

For Suntech as an example, the Wuxi local government convinced seven local SOEs to invest a total of 5.2 Mn. US$, while the founder contributed 0.4m US$ of his personal wealth as well as 1.6m US$ worth of technology shares (Dong et al., 2014). In addition to direct seed funding, the startups also received generic support from local governments in the form of cheap land for production facilities, tax cuts or deficit guarantees from SOEs for low-interest bank loans (Dong et al., 2014; Qinghua report, Gallagher, 2014). Much of this additional support was not targeted specifically at PV ventures, but part of the general support schemes in high-tech support programs around the country (Zhang et al., 2014).

In the first years, having locally sourced seed investment was beneficial for the Chinese startups, but when the companies started embarking on a fast growth path in the mid-2000s, the limits of this state-controlled investment model became obvious (Davila et al., 2010; Zhang and White, 2016). Several company founders complained that their regional state-owned investors lacked technological and financial expertise and refused to inject money, which considerably hampered the growth potential in international markets (Interviews 2, 9, 22). In 2004, they thus mobilized international networks to access financial investment from outside China.

> *"[By 2004] the company needed money. Our local stakeholders didn't really want to put in more money at the time. We needed access to the capital market. There were some American banks and investors that had followed us for more than a year, which I didn't realize."*
> *- "Who approached you with the idea of an IPO?"*
> *- "Some financial experts. Goldman Sachs, Morgan Stanley."*
> *(Founder of a Chinese PV company)*

Among the Chinese startups, Suntech became a pioneer in getting listed on the international stock market[7]. To make an initial public offering possible, the founder needed to buy out the state-owned investors, who accepted based on a 13-times return on their initial investment (Zhang and White, 2016). Suntech's IPO in December 2005 was the first IPO of a Chinese technology company at the New York Stock Exchange and it was the biggest technology IPO of the year, raising more than 400 Mn. US$. (Davila et al., 2010). American investment banks provided the know-how to prepare the IPO, helped restructure the company, added financial experts to its board of directors, and organized pre-IPO investor roadshows in the USA (Interviews 9, 10).

The spectacular success of Suntech in overseas financial markets motivated other Chinese PV manufacturers to equally list their shares at US stock exchanges (Table 3). As the investment raised from international IPOs was an order of magnitude higher than what had been raised beforehand in the Chinese context (Dong et al., 2014; Gallagher, 2014; Quitzow, 2015b; Zhang and White, 2016), the successful IPOs induced a subsequent investment boom in China. Chinese banks, private and institutional investors all rushed in to secure their shares of this thriving business (Interviews 18, 20, 22, Dong et al., 2014). After the financial crisis in 2008, additional money from the Chinese stimulus package and Chinese development banks was pumped into the industry. With very cheap loans and capital costs, many Chinese companies considerably extended their debt ratio and started aggressively extending their production capacity (Quitzow, 2015a).

Table 3: Revenues from Initial Public Offerings of four pioneering PV manufacturers

	Suntech	**Trina**	**Canadian**	**Yingli**	**Total**
IPO place/year	2005 NYSE	2006 NYSE	2006 NASDAQ	2007 NYSE	
Pre-IPO equity	$96 mn.	$40mn.	$12mn.	$22mn.	**$170mn.**
IPO revenue	$395mn.	$98mn.	$115mn.	$391mn.	**>$1bn.**

Source: Based on Quitzow (2013), Zhang and White (2016), company annual reports

Overall, our results confirm the findings of other studies that - even though seed funding was available in China - the significant influx of outside investment from global capital markets in

[7] The company got listed at NYSE on 14 December 2005

the mid-2000s was a key trigger for the subsequent fast expansion of the Chinese PV industry (de la Tour et al., 2011; Quitzow, 2015b; Zhang and White, 2016). Also for financial investment, the pioneering companies did thus not only develop the needed resources in-house or in connection to the local context, but also decisively by directly accessing state-of-the-art know-how of global investment banks.

4.3.4 Legitimacy

Creation of legitimacy at a global level

The last type of system resources in our framework, technology legitimacy, can be broadly defined as the overlap of a technology with the dominant cognitive, regulative and normative institutional structures of the places where it emerges (Aldrich and Fiol, 1994; Suchman, 1995). *Embedding* of solar PV in *existing institutional contexts* was not as contested as in other energy sectors like e.g. nuclear power (Geels and Verhees, 2011). Nevertheless, at the beginning of the industry formation process, PV entrepreneurs had to invest heavily in proving that solar power was not merely a dysfunctional niche technology, but able to compete with incumbent energy technologies in the long run (Jacobsson et al., 2004; Varadi, 2014). Skeptics emphasized the technology's high costs, missing market prospects, and long-term payback times (often more than 30 years) that raised questions about PV plant's long-term reliability and bankability (Varadi, 2014). Quality certification schemes thus became instrumental in legitimizing early claims about PV module's future performance levels (ibid.).

Starting from 1970, the (globally pioneering) American PV module industry and NASA's Jet Propulsion Laboratory jointly developed the first comprehensive quality management system for PV module manufacturers, which later got included in an ISO quality management standard that informed subsequent standardization and testing programs around the world (Varadi, 2014). Between 1980 and 2000, Underwriter laboratories (UL), TUV Rheinland, as well as the International Electrotechnical Commission (IEC) developed challenging testing procedures for PV modules (Quitzow, 2013; Varadi, 2014). From 1990, and similar to the other resources, these standards and certification schemes turned into a globally available system resource which could be used by latecomers to legitimize their quality claims both nationally and in international markets.

Technology legitimation in China

The early Chinese industry had to struggle with two additional problems related to technology legitimation. First, privately-owned PV companies were a new institutional form in China's power sector, which had to be legitimized by the pioneering actor's in a long-term collective lobbying effort (Zhang and White, 2016). Second, in the eyes of the central government, as well as domestic and international customers, the industry appeared illegitimate as it was prone with product quality problems and system failures (Cabraal, 2004; Zhang and White, 2016).

Chinese PV pioneers thus developed new narratives to prove that their products and production processes were worthy of the nation's high-tech support schemes and complying with international quality standards (Quitzow, 2015b; Varadi, 2014; Zhang and White, 2016). In 2000, China had no reliable quality certification system in place. The World Bank and other foreign donor agencies had decided in the early 2000s to induce a Chinese quality certification program (funded by the World Bank and the Chinese central Government) and invited key foreign experts to oversee it (Varadi, 2014). The 'Chinese General Certification Center' was established in 2002 and its founder worked ferociously on developing a Chinese quality standard and labelling system. Still, the first comprehensive domestic quality label for PV products became available only after 2006 (Interview 19).

Yet, by 2002, the Chinese PV manufacturers were already targeting overseas markets. Receiving quality certification was a vital element in legitimizing their operations and creating trust in their products in foreign markets. They thus decided to base their production processes completely on existing European and American quality standards and certification schemes (Interviews 1, 4, 9). In the case of Suntech, UNSW was directly involved in helping the company achieve the demanding foreign quality requirements (Zhang and White, 2016). As a result, the company was able to present its first internationally certified products at a trade fair already in 2003.

> *"In Spring 2003 we had our first exhibition in Berlin. We were the only Asian company. People said, "hey, who is this guy, where did he come from?" […] We were so proud. We had this international quality certification. No other Chinese company could do it. It had quite an impact in China." [Founder of a Chinese solar PV company]*

Other Chinese companies quickly followed suit in getting international quality certification for their modules and used this to further lobby the national government and access new foreign markets. By the mid-2000s the big four companies all had legitimized themselves to such a degree that they could sell their products in overseas market and get access to key political decision making processes (Quitzow, 2015b; Zhang and White, 2016).

In summary, for technology legitimacy, the PV pioneers combined domestic lobbying efforts with accessing system resources from the global technological innovation system. Associating Chinese PV products with international quality certificates and ISO management standards significantly improved the manufacturing and supplier industry's product quality levels and concomitantly secured access to foreign markets and further legitimation towards the Chinese central government.

5 Discussion

The results show that external system resources played a key role in all dimensions of our analytical framework, complementing domestic generic absorptive potential that mostly consisted of trade infrastructure and unrelated mass-manufacturing capabilities. China's fast catch-up in solar PV manufacturing has to be understood in the light of the early actor's outstanding capacity in connecting China's generic absorptive potential with key system resources developing elsewhere. This story contrasts starkly with that of e.g. the Chinese wind power industry, in which the central government and existing industries played a major role from the start (Lewis, 2011; Gallagher, 2014). Knowledge and market access were almost completely imported from other regions in the global TIS, while financial investment and legitimacy developed inside China to some degree over time, but also with decisive support from international networks (table 4).

Spillovers from domestic related industries, local government support and domestic R&D programs played a role in the knowledge, market and financial investment dimensions, but taken alone could hardly explain China's outstanding early industry formation dynamics (for similar arguments see Quitzow, 2015b; Zhang and White, 2016). Traditional foreign direct investment (FDI)-based manufacturing outsourcing from Western lead firms did not induce the industry formation process, and in the highly automated production process for PV panels also traditional labor-cost advantages played a relatively minor role (Goodrich et al., 2013). The key comparative advantage of Chinese actors was stemming mostly from the quick upscaling of operations and the early build-up of a low-cost and high quality local supplier industry (also see Goodrich et al., 2013). In contrast to what evolutionary theories assume, the pioneering companies did not build up their initial technological capabilities through related diversification, but by occupying a key brokerage position between cutting-edge international resource formation processes and the generic manufacturing capabilities in the Yangtze River Delta cluster.

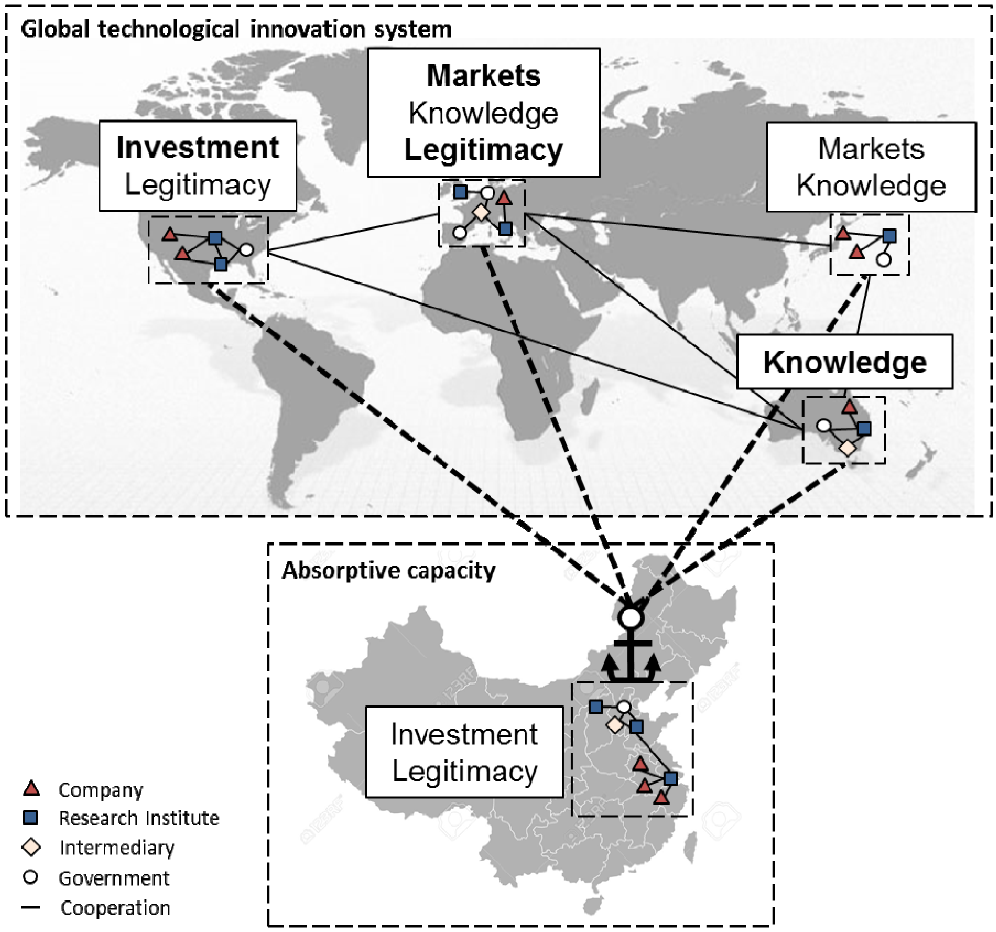
Table 4: System resources for industry formation in the early Chinese PV sector

System resource	Domestic	International
Knowledge	+ small incumbent industry, basic research at Chinese universities and research institutes	++ technology and know-how exchange with Australia, Canada, Germany, Japan
Market access	0 domestic market support schemes not functional	++ sales to booming markets in Germany, Spain, Japan
Financial investment	+ generic support and seed funding by local governments, state owned enterprises and regional banks	++ IPOs at US stock markets
Legitimacy	+ domestic quality certificate only emerging institutional entrepreneurship of the private PV industry	++ quality certification in Germany, Spain, USA

0: no activity +: weak activity ++: strong activity

Figure 5 further specifies the spatial origins of the system resources. Knowledge was imported from Australia through a knowledge pipeline with the University of New South Wales, but was also embedded in machinery components that were recycled from Italian, German, Japanese and American manufacturers in the first Chinese PV production lines. Markets were mostly accessed in Germany, Japan and Spain. Investment was raised inside China, but also from the global stock market as well as through investment banks and VC investors from Hong Kong, Europe and the USA. Legitimacy for the emerging industry was constructed inside China itself, but in the first instance entrepreneurs also leveraged quality certification in the USA, Europe and with ISO, IEC and World Bank standards.

Figure 5: Spatial origin of key resources for the Chinese solar PV industry



Source: Own design, bold words indicate key origins of resources for the Chinese industry

Overall, we argue that this pattern of industry formation differs from existing catching-up and related diversification models in several respects. The pioneering actors in China did not build their technological capabilities through conventional technology transfer and gradual upgrading in the supplier networks of foreign lead firms. They did also not (only) depend on recombining pre-existing capabilities and routines from closely related sectors. They rather transplanted an emerging industrial path by directly substituting missing local system resources with access to international networks – a path creation process that in our interpretation very nicely illustrates the direct 'transplantation from elsewhere' of a an emerging industrial path (Martin and Sunley, 2006). Instead of spending most effort in creating a full-fledged local innovation system to support the industry, they accessed key system resources in other subsystems of the global TIS and creatively recombined them with China's generic capabilities in mass manufacturing (Nahm and Steinfeld, 2014).

From 2000-2008 this led to the paradoxical situation that a new cleantech industry was forming and quickly upscaling operations in China, even though key capabilities and a supportive innovation system had formed only to a very limited degree in the local context. At least in the early development phases, the industry did not emerge from an orchestrated policy program or price dumping practices in China. The University of New South Wales, US investment banks, German policy-makers, as well as international standardization bodies and the World Bank played equally decisive roles in enabling Chinese PV firms to manufacture high-quality modules, access markets, finance quickly expanding ventures and legitimize private companies against pushbacks from national policy makers. This situation changed dramatically after 2008, when the Chinese government scaled-up industry support in various dimensions (Iizuka, 2015; Zhi et al., 2014). Still, at the time when strategic deployment policies emerged at a national level, the pioneering companies had already established global pipelines and transformed the local resource base to facilitate further expansion and capability upgrading in the Chinese PV industry.

It is important to note that the availability of system resources at the global TIS level and the ability of transnational entrepreneurs to access them might be attributable to the specific industry and product characteristics in the solar PV case. As noted before, solar PV panels are a standardized, easily shippable, and mass-produced commodity with an analytic knowledge base and relatively predictable technological trajectory (Huenteler 2015). These characteristics arguably increase the potential for international knowledge circulation and lower the entrance barriers for latecomers (Binz et al., in press; Huenteler, 2015; Jung and Lee, 2010). Transplantation-based catching-up seems most realistic for emerging industries with similar technology characteristics and value chain architectures (e.g., some types of battery manufacturing or LED lighting). Future comparative work should assess whether and how similar catching-up patterns may exist in sectors with non-tradable products, more fluid technological trajectories or more synthetic knowledge bases (e.g. wind power). Combining our framework with existing sector taxonomies from sectorial system of innovation literature (e.g. Malerba and Nelson, 2011) might be a promising way forward here.

6 Conclusions

This paper developed and tested an analytical framework for analyzing transplantation-based cleantech industry formation in latecomer contexts. The conceptual discussion and empirical results revealed an industry formation model for solar PV which relies more strongly on international interdependencies than what existing catching-up and related diversification theories assume to be possible. Our analytical framework broadened the focus of catching-up theories beyond (mostly knowledge- and firm-based) industrial upgrading processes to a wider systemic environment which includes demand-side dynamics, investor's interests, and institutional embedding of an emerging industry. Furthermore, the empirical case study in the Chinese solar PV sector revealed a need for a framework that allows analyzing industry formation dynamics which happen faster and use a wider set of network connections at multiple scales than assumed by existing models.

Our empirical results allow for a slightly more optimistic view on the potential of latecomer countries in making medium-to-long jumps to industries that are unrelated to the pre-existing knowledge and resource base. In the Chinese solar PV case, directly related industries were almost inexistent at the outset, but Chinese PV companies still managed to develop into a global lead firm position in less than ten years. Our findings thus support the view of Perez et al. (1985) that especially the formative phase of new technological paradigms (like emerging cleantech industries in the 'green' economy) present a window of opportunity for latecomers with basic generic absorptive potential to enable industry transplantation similar to the Chinese PV experience.

The aim of this article is not to substitute existing explanatory frameworks, but rather to argue in line with recent research that existing catching-up and relatedness theories should better embrace multi-scalar interdependencies in the industry formation process (Binz et al., under review; Neffke et al., 2014; Tanner, 2014). Our framework and empirical analysis confirm that basic technological capabilities and broader absorptive capacity are necessary conditions for industry formation processes. Yet, the fast emergence of China's solar PV industry is not explainable without reference to extra-regional resource formation and the strategic action of transnational entrepreneurs that helped transplant and anchor these resources in the latecomer context.

The presented framework also opens new rationales for policy making. In a nutshell our case showed that path transplantation in solar PV depended on three key ingredients: *generic absorptive capacity in the latecomer country*, *globally available system resources*, and *actors that are able to link these two elements*. Existing policy approaches focus mostly on the first dimension and tend to ignore the latter two. Creating effective links to extra-regional system resources and incentivizing the repatriation of highly skilled technology experts are two policy strategies that deserve closer attention in this respect, provided that basic absorptive potential is available. Also, conducting an analysis of the regional and international formation process for each system resource could be used to identify bottlenecks (system building and international interaction failures), that could then be used to justify targeted national/regional policy interventions and/or novel global governance schemes (Jacobsson and Bergek, 2011; Weber and Rohracher, 2012).

It goes without saying that our analysis has important limitations that warrant future research. First and foremost, the generalizability of our results is limited by the single case study design focusing on the solar PV industry and on China. We do accordingly not claim (statistical) generalizability to our empirical results, but analytical generalizability to our framework and a detailed account of the proof of existence of such an industry transplantation case. The analytical dimensions of our framework could provide a useful heuristic to other studies in various sectors (i.e., in this papers we have contrasted the PV story we uncovered with previous research on wind, but future work should further explore differences in the industry types) and national contexts, even though the specific configuration of local and international resource formation processes may look very different in other cases. Ultimately, combining insights from various contrasting cases should allow us to formulate a more generic and stylized theory of transplantation-based catching-up (see Binz et al., under review).

Second and related, comparative studies could explore why industry transplantation succeeded in mainland China and not in other latecomer contexts (e.g. India, Malaysia, Taiwan) which (as we hypothesize) had similar initial absorptive potential and local innovation system structures in place. Further research is clearly needed to disentangle in more detail what parts of the industry transplantation process are attributable to China's unique institutional context and which not.

Third, to facilitate better comparison, each of the identified system resources could be further specified by incorporating additional social science literature. For example, the resource of technology legitimation could be further specified by relating to institutional sociology. Investment mobilization could be reframed based on recent insights from business literature. Last but not least, a more dynamic process model could be developed to specify how the various system resources co-evolve and influence each other over time in various phases of the industry formation and maturation process. Ultimately, one could derive a stylized process theory on catching-up that covers several phases of the industry life-cycle beyond the formative phase which was in focus here.

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Appendix 1: Interviewees

Number	Organization	Chinese Name	Experts interviewed
1	Canadian Solar	阿特斯阳光电力集团	Senior manager, member of the founding team
2-4	Trina Solar	阿特斯阳光电力集团	CTO Senior financial manager Project engineer
5-7	Yingli Solar	英利绿色能源控股有限公司	Founder, CEO CTO Financial manager
8	Jinko Solar	晶科能源控股有限公司	Head of global market development
9-10	Suntech	无锡尚德太阳能电力有限公司	Founder, former CEO Former CTO
11	Qinghua Solar	清华光伏	Senior Vice President
12	Solarex	n/a	Founder, former CEO
13	Hareon Solar	海润光伏	CTO
14	Shanghai Solar Energy Science & Technology Co. Ltd.	上海太阳能科技有限公司	Former chief manager
15	Energy Research Institute of the NDRC	国家发展和改革委员会能源研究所	Senior Manager
16	China Solar PV Association	中国光伏行业协会	Director
17	China Renewable Energy Industry Association (CREIA)	中国可再生能源行业协会	Senior manager
18	Greenpeace China	中国绿色和平	Senior manager
19	China General Certification Center (CGC)	北京鉴衡认证中心	Director
20-23	Qinghua University	清华大学	4 professors and assistant professors
24-25	North China Electric Power University	华北电力大学	2 professors
26	Chinese Academy of Sciences	中国科学院	1 professor