Journal of Cleaner Production 158 (2017) 122–133

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Development trajectories in China's wind and solar energy industries: How technology-related differences shape the dynamics of industry localization and catching up

Rainer Quitzow [a, b, *], Joern Huenteler [c, 1], Hanna Asmussen [d, 2]

[a] Institute for Advanced Sustainability Studies, Berliner Str. 130, 14467 Potsdam, Germany
[b] Chair of Innovation Economics, Technische Universität Berlin, Marchstraße 23, 10587 Berlin, Germany
[c] Belfer Center for Science and International Affairs, John F. Kennedy School of Government, Harvard University, 79 John F. Kennedy Street, Cambridge, MA 02138, USA
[d] Chair of Energy and Resource Management, Technische Universität Berlin, Steinplatz 2, 10623 Berlin, Germany

ARTICLE INFO

Article history:
Received 1 September 2016
Received in revised form
21 April 2017
Accepted 22 April 2017
Available online 25 April 2017

Keywords:
International technology transfer
Demand-side policy
China
Wind power
Solar photovoltaics

ABSTRACT

China has been very successful in creating conditions for industry localization in solar and wind energy manufacturing. In terms of their competitiveness in foreign markets, however, Chinese solar photovoltaics firms have shown significantly greater achievements than their counterparts in the wind energy sector. Moreover, the success of China's solar photovoltaics industry has come in spite of significantly lower levels of domestic market support. The paper argues that technology-related factors and their implications for international technology transfer are critical for explaining the different speeds with which Chinese firms have been able to catch up in the two sectors. This is supported by a comparative analysis of technology transfer in the two sectors.

1. Introduction

Technological change is "at once the most important and least understood feature driving the future cost of climate change mitigation" (Pizer and Popp, 2008, p. 2768). Trends in overall emissions growth indicate that an increasing share of investments in climate change mitigation will need to flow into infrastructure in developing countries. Better understanding the long-term patterns of international diffusion in low-carbon energy technologies is therefore crucial to inform related public policy.

Both developed and developing countries are supporting the wider deployment of low-carbon energy technologies (IEA, 2015; REN21, 2016). In a number of industrialized countries, early promotion of a national market was intended to spur technological innovation and provide local firms with a competitive advantage (Jänicke and Jacob, 2004). In a number of developing countries, governments have hoped to benefit from the early deployment of these technologies by attracting technology transfer from abroad and, eventually becoming global or regional manufacturing hubs. However, empirical evidence of the success of demand-side instruments in terms of industry localization and international competitiveness is mixed: In some cases, the formation of a local industry was seemingly only possible in the presence of strong domestic demand-side policies, as often observed in wind turbines (Lewis and Wiser, 2007). In the case of solar photovoltaics (PV), decisions on industry location seem to depend less on domestic demand-side policies and more on other aspects, such as economies of scale and the maturity of supply chains (Goodrich et al., 2013). In this case, countries adopting new demand-side policies often experienced increased technology imports, with a local industry focusing mostly on installation and operation and maintenance (O&M), while a few large manufacturing hubs dominate supply. These differences are epitomized by developments in China: Chinese solar PV firms

* Corresponding author. Institute for Advanced Sustainability Studies, Berliner Str. 130, 14467 Potsdam, Germany.
E-mail addresses: rainer.quitzow@iass-potsdam.de (R. Quitzow), jhuenteler@worldbank.org (J. Huenteler), hannamasmussen@gmail.com (H. Asmussen).
[1] Present address: World Bank, 1818H Street NW, Washington, DC 20433, USA.
[2] Present address: Boston Consulting Group, Fischertwiete 2, 20095 Hamburg, Germany.

http://dx.doi.org/10.1016/j.jclepro.2017.04.130
0959-6526/

have come to dominate global exports without depending first on a significant demand-side policy at home (de la Tour et al., 2011). Chinese wind firms, in contrast, have the world's largest wind market at home and relied entirely on the domestic market to grow. Their performance on competitive foreign markets has been relatively modest compared to US and European turbine manufacturers (Gosens and Lu, 2014).

Thus far there has been relatively little systematic empirical research on the effect of technology deployment policies on industry localization and international competitiveness (Bell, 2012), especially research comparing different technologies (Huenteler et al., 2016; Hughes and Quitzow, 2017; Schmidt and Huenteler, 2016). The original notion that ambitious demand-side support offers domestic firms with a competitive advantage in emerging environmental technology fields goes back to Porter and van der Linde's essay on the relationship between environmental policy and national competitiveness (Porter and van der Linde, 1995). The authors proposed that environmental regulations, which anticipate international regulatory trends, may confer domestic firms with an early mover advantage in the affected sectors. Building on this, the literature on lead markets for environmental technologies has shown that pioneering demand-side policies have indeed frequently found imitators in foreign countries, thus stimulating the global diffusion of the corresponding environmental technologies (Beise and Rennings, 2005; Quitzow et al., 2014). It was, therefore, argued that the creation of early demand could function as an important source for the competitive advantage of domestic firms. However, the recent developments in the wind and PV sectors suggest that the relationship between ambitious demand-side policies, industry localization and international competitiveness is conditional on technology- and country-specific factors. Pegels and Lütkenhorst (2014), for instance, argue convincingly that German market support for renewable energy has been significantly more successful in building a competitive advantage for German suppliers in the wind energy sector than in solar PV. Simultaneously, China has grown a competitive PV industry, while lagging behind in terms of domestic deployment (Quitzow, 2015).

This paper analyzes the cases of wind power and solar PV in China to explore what explains the differing outcomes in the two sectors. The paper proposes a basic framework for the consideration of technology-specific factors in the analysis of industrial catching up processes in the wind and PV sectors. Of particular importance, it is argued, are differences in the acquisition of knowledge across technology fields with important implications for the required international technology transfer mechanisms. This is supported by a qualitative empirical analysis of knowledge transfer mechanisms in the wind and solar PV sectors.

The paper proceeds as follows. Section 2 discusses the underlying theoretical perspective of the paper. Section 3 introduces the conceptual framework for the subsequent empirical analysis and presents the data sources used in this paper. Section 4 provides a brief overview of developments in the solar and wind energy sectors in China, which is followed by the presentation of empirical results in Section 5. The empirical results are discussed in Section 6. Section 7 concludes and summarizes the main policy implications.

2. Theoretical perspective

This section discusses the theoretical perspective of the paper based on the literature on technological capabilities and catching up. It provides the rationale and underlying framework for a technology-based comparison of industrial development in the wind and solar PV sectors.

2.1. Technological capabilities and the role of home markets

According to the literature on technological capabilities and catching up, successful industry localization in developing countries depends on the presence and continuous accumulation of local capabilities (Cimoli et al., 2009; Bell, 2010; Bell and Pavitt, 1992).[3] While deployment of technologies always requires a certain level of O&M capabilities, the available capabilities need to go beyond O&M in order to foster a competitive industry[4] that develops and manufactures technologies (Bell, 1990; Hansen and Ockwell, 2014; Ockwell et al., 2014). Even in mature technologies, manufacturers need to master continued technology adaptation and incremental cost and performance improvements to compete. These capabilities can only be acquired through international exchange and the time-consuming, purposeful process of learning (Bell and Figueiredo, 2012; Gosens et al., 2015).

Whether or not firms in developing countries can catch up without a large home market depends on the nature of this learning process (Huenteler et al., 2016; Schmidt and Huenteler, 2016). If the learning process involves learning by using and strong user-producer interaction, close proximity to the locus of use is an imminent advantage. It requires what Huenteler et al. (2016) refer to as "local learning". In such a case, a large domestic market can provide firms that exploit their 'home market advantages' – e.g., in the form of lower transaction costs, lower transport costs, and lower regulatory and institutional market entry barriers – with the opportunity to experiment and learn, and thus to accumulate relevant capabilities. If learning is mostly related to experimentation in the laboratory and the production facility, firms accumulate technological capabilities even if they export all of their goods and they barely interact with users. Hence the development of a competitive local industry will not depend on the development of a significant domestic market.

2.2. Technology life-cycles, capabilities, and learning

The literature on technology life-cycles has established that technologies differ with regard to these characteristics of the learning process. Resulting from this, capabilities and learning processes that determine competitiveness differ significantly across technologies (Abernathy and Utterback, 1988; Davies, 1997; Magnusson et al., 2005). In particular, the literature provides evidence for two contrasting types of technology life-cycles (Huenteler et al., 2016): In *mass produced goods*, the growth and maturation of technology is accompanied by the emergence of dominant designs (Anderson and Tushman, 1990; Abernathy and Utterback, 1988). Since the product design is more or less standardized throughout the industry, competitiveness is mostly determined by capabilities related to efficient production, scaling up, and the coordination of complex value chains (Utterback and Abernathy, 1975). In contrast, *complex products and systems* never reach a dominant design, and firms continue to improve and

[3] Technological capabilities can be defined as "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" (Morrison et al., 2008, p. 41).

[4] In this paper, we follow the definition of international competitiveness as employed by the European Commission in its Member States Competitiveness Reports. It defines a country's competitiveness as "the ability of its industrial sector to maintain and strengthen its competitive position in the world market relative to that of other countries focusing on price and cost developments of production and other parameters potentially affecting the growth performance, market shares, and investment and location decisions of firms in the industrial sector" (European Commission, 2010).

modify the product (Miller et al., 1995; Davies, 1997; Huenteler et al., 2016). Products are often designed and manufactured on demand for specific orders or even produced in one-off projects—such as nuclear power plants—in which no two projects are exactly the same (Hobday, 2000). Even in later stages of the life-cycle, competitiveness is determined by capabilities related to system integration and product design, rather than capabilities related to high-volume manufacturing and supply chain optimization (Magnusson et al., 2005). Table 1 provides an overview of the characteristics of the innovation and production processes in the two alternative models of the technology life-cycle.

As indicated in Table 1, the different life-cycle patterns are linked to different forms of learning. In the field of mass-produced goods an important emphasis is on learning-by-doing in the manufacturing process, while complex products and systems rely more heavily on learning-by-using and user-producer interactions. Huenteler et al. (2016) demonstrate that patenting dynamics in PV cells and modules largely adhere to the pattern observed in mass-produced goods, while the field of wind turbines exhibits dynamics which conform to the life-cycle model for complex products and systems. More specifically, in the PV sector, patenting in the field of product innovation was quickly followed by a surge in patenting in process innovations. In the wind sector, patenting has not shifted from product to process innovation but rather across different aspects of the product design. Building on these insights, Schmidt and Huenteler (2016) suggest that technology-specific patterns of learning and capabilities can be linked to different outcomes in terms of industry localization. They do not explore in depth, however, how these differences are linked to different processes of technology transfer and catching up.

2.3. Linking technology-specific life-cycles to modes of technology transfer and catching up

In this paper, we build on the recent literature on technology lifecycles, capabilities and learning in the energy sector and link it to the literature on technology transfer and catching up. We propose that the different modes of learning that characterize innovation and technological development in complex products and systems, on the one hand, and, mass produced goods, on the other, translate into distinct opportunity structures for international technology transfer and catching up in the respective technology fields, leading to different outcomes in industry localization and international competitiveness. In complex products and systems user-producer interaction remains important even in later stages of the life-cycle as product- or project design requirements and component technology continue to change over time (Huenteler et al., 2016; Schmidt and Huenteler, 2016). Moreover, products have important firm-specific attributes and are less reliant on industry-wide standards. This makes the transfer of production to foreign countries more challenging, and firms are much less likely to move manufacturing away from large product markets (Davies, 1997; Miller et al., 1995). A strong presence in a home market is often a prerequisite for export success (Lewis and Wiser, 2007). Firms in late-comer countries are only able to catch up if they can exploit their home market advantages to gain manufacturing and design experience and have access to foreign design knowledge. This in turn can only be accessed via direct transfer of knowledge by foreign producers over a prolonged period of time.

In the field of mass produced goods, technology design has a higher degree of standardization, and learning by doing in the production process is key (Schmidt and Huenteler, 2016). Catching up primarily requires access to up-to-date technological know-how and related production equipment. Hence, technology transfer does not require the direct involvement of manufacturing firms. The transfer of tacit knowledge related to the production process may be required in early stages of the transfer process but will rapidly decline in importance once production and hence learning by doing has been initiated in the recipient firm. This allows manufacturers of mass-produced goods to geographically disconnect production from product markets and to shift manufacturing facilities to the locations that offer the best conditions for large-scale manufacturing, often including low-wage countries (Vernon, 1966). Moreover, it offers opportunities for firms in follower countries to catch-up more rapidly with lead firms, even when no home market is present.

3. Empirical approach and methods

The arguments outlined in the previous section are tested based

Table 1
Characteristics of the innovation and production processes in the two alternative models of the technology life-cycle.

	Era of ferment	Era of incremental change	
		Mass-produced goods	Complex products and systems
Competitive emphasis on …	Functional product performance	Cost reduction	Functional product performance
Innovation stimulated by …	Revealed user needs and users' technical inputs	Pressure to reduce cost and improve quality	Evolving user needs as well as internal and external technical opportunities
Product line	Diverse, often including custom designs	Mostly undifferentiated standard products	Product variations that share common architecture but are customized to user needs
Predominant type of innovation	Frequent major product innovations	Incremental innovation in processes and materials	Sequences of systemic and incremental component changes
Important sources of knowledge	Product R&D, learning-by-doing and learning-by-using	Process R&D, learning-by-doing	Product R&D, learning-by-using
Plant	General-purpose plant located near user or source of technology	Large-scale plant tailored to particular product designs to realize economies of scale	General-purpose plant with specialized sections located near user or source of technology, little emphasis on economies of scale
Production process	Flexible and inefficient: major changes easily accommodated	Efficient, capital-intensive. and rigid: cost of change is high	Remains flexible: individual projects or small-batch production
Production equipment	General-purpose equipment, requiring highly skilled labor	Special-purpose, mostly automatic with labor tasks focused mainly on monitoring and control	Some sub-processes automated, but mostly requiring highly skilled labor

Source: Huenteler et al. (2016).

on an empirical analysis of technology transfer to China in the wind and solar energy sectors, presented in section 5. This section briefly introduces the main categories considered in the empirical analysis of technology transfer mechanisms in the wind and solar photovoltaics industries, linking these to the technology-related categories highlighted above. It then presents the scope of the empirical cases considered and the methods of data collection that were employed.

3.1. Key concepts and definitions

The literature on international technology transfer includes a range of studies on the determinants of technology transfer modes. Taking a transaction cost theory perspective (Coase, 1937; Williamson, 1979), many of these studies focus on the costs and benefits for the supplier firm of choosing one particular mode of technology transfer over another (for an overview see Reddy and Zhao, 1990, pp. 297–298). Studies taking a knowledge- or resource-based perspective on technology transfer also consider the ability of the recipient firm to successfully adopt and put the transferred technology to productive use. Studies from this school of thought have recognized the role of technology characteristics in influencing the choice of transfer mode. More specifically, the relative importance of tacit knowledge to the technology in question has been identified as an important influencing factor (Hakanson and Nobel, 2000; Stock and Tatikonda, 2000; Tsang, 1997). Tsang (1997) argues that intrafirm transfer modes involving a high level of direct human interaction are more effective than so-called arms-length transfer mechanisms. This is of particular relevance for technologies with a higher degree of complexity, which, as a result, require a significant degree of tacit knowledge. Similarly, Stock and Tatikonda (2000) find that arms-length transfer mechanisms are less effective in the presence of high levels of “technology tacitness”. More recently, Lema and Lema (2012) have distinguished transfer mechanisms according to the degree of interaction between supplier and recipient. Moreover, they point out that technology transfer mechanisms are no longer always characterized merely by the flow of know-how from the original technology supplier to the recipient, but that arrangements, like collaborative research and development (R&D) or mergers and acquisitions (M&A) with foreign firms, may involve mutual learning and two-way technology flows between the participating firms. They point out that the latter type of transfer mechanisms have played an increasing role in the build-up of capabilities in the Chinese wind and PV sectors.

In this paper, the focus is not on the directionality of the technology flows facilitated by different transfer mechanisms. Instead, this paper focuses on the *scope* and *type* of tacit knowledge that is transferred from the supplier to the recipient, linking this to the two technology types described in section 2. Firstly, it proposes that the successful transfer of complex systems and products requires a higher degree of tacit knowledge transfer than mass produced goods.[5] Correspondingly, they depend on international technology transfer mechanisms, which enable a large degree of tacit knowledge transfer. We refer to this as the *scope of tacit knowledge transfer* associated with the respective mechanism. Secondly, the two technologies differ in terms of the type of knowledge transfer that is needed. Catching up in the field of complex systems and products requires international technology transfer mechanisms that facilitate the transfer of design- or product-specific knowledge. In the field of mass produced goods, on the other hand, process-related knowledge transfer is more relevant than knowledge about design features of the final product (i.e. solar modules or wind turbines). Hence, knowledge transfer does not require involvement of suppliers with comprehensive and specialized design knowledge. In other words, not only the *scope of tacit knowledge transfer* but also the *type of tacit knowledge* that is transferred differs across these two technology types. Finally, in the case of mass produced goods, we propose that the transfer of tacit, process-related knowledge is more important in initial stages and is quickly replaced by learning-by-doing within the recipient firm itself. In the field of complex systems and products, technology transfer processes take longer and require continuous transfer of tacit knowledge, as designs are renewed and adapted over time.

Table 2 below lists and defines the mechanisms of international technology transfer that we studied in this paper. We suggest that the different types of international technology transfer differ in the *scope and type of tacit knowledge transfer* that they facilitate. The former is strongly linked to the degree of human interaction involved in the process of technology transfer, as suggested in the classification in Lema and Lema (2012). In this vein, intrafirm transfer modes are likely to offer the largest *scope of tacit knowledge transfer*. They facilitate the sustained cross-border interaction, which is required for the transfer of tacit knowledge. Moreover, intrafirm transfer modes, such as a joint venture or the establishment of a foreign subsidiary, involves a comprehensive transfer of corporate practices across different aspects of the technology and its production. A similar *scope of tacit knowledge transfer* cannot be achieved with arms-length transfer mechanisms, such as the purchase of machinery or a technology license. Such one-off transactions lack the sustained human interaction required for a significant transfer of tacit knowledge. Accordingly, it has been recognized that foreign direct investment is more suitable for the transfer of complex technologies, which require “a prolonged and sustained relationship to effect the transfer” (Baranson, 1970).

Simultaneously, it is important to acknowledge that in practice arms-length market transactions often combine the one-off transfer of physical or codified knowledge with a certain degree of tacit knowledge transfer. For instance, the sale of production equipment often includes not only the transfer of physical equipment but also commissioning services. Another example is licensing, which is frequently accompanied by training or quality assurance agreements (WIPO, 2015). In this paper, we consider the role of tacit knowledge transfer in the actual practice of these international technology transfer mechanisms (rather than their generic form). Nevertheless, we argue that such market-mediated transfer channels lack the *sustained* interaction for significant tacit knowledge transfer to occur.

Finally, joint R&D or design projects involving international partners as well as the acquisition of human resources with foreign experience are further channels for facilitating tacit knowledge transfer. In both cases, knowledge transfer may take place at the recipient firm's technology frontier. Nevertheless, compared to intrafirm mechanisms, the *scope of tacit knowledge transfer* is more limited in terms of its impact on the recipient firm as a whole. The international transfer of human resources is limited to the knowledge carried by the individual professional and thus severely constrained as a channel for transmitting the comprehensive technological know-how needed for the successful production and commercial exploitation of foreign technology. Joint R&D activities, while likely to involve repeated human interactions among the partners, are limited by the project-based nature of the interactions.

Regarding the *type* of tacit knowledge transfer, intrafirm transfer mechanisms are also the most comprehensive, enabling the

[5] For the purpose of this paper, the successful transfer of technology is defined as the production and commercial exploitation by a firm of a technological artefact, which was first produced and commercially exploited in a foreign country.

Table 2
Classification and definitions of international technology transfer mechanisms used in this paper.

Mechanism	Definition
Intra-organizational technology transfer	
Foreign subsidiaries	Investment by foreign companies in local subsidiaries. This enables the transfer of hardware and know-how. The specific mix depends on what firm functions are transferred.
Joint ventures	Formal cooperation between a foreign firm and a local firm involving the sharing of equity capital as well as risks and profits. Even though subsidiaries typically result in significant technology transfer, certain know-how necessary for the design of the product and the production process is often not shared with the joint venture.
Outward M&A	Acquisition of foreign firm by a local firm, usually giving the acquiring firm full access to technology.
Inter-organizational technology transfer modes	
Trade in production equipment	Production equipment produced in the supplying country is imported by the recipient. This is sometimes accompanied by commissioning services and/or quality assurance contracts.
Turnkey production facilities	"Turnkey projects" refer to the case when the supplier is responsible for the implementation of the technology in the recipient country, which means for example that manufacturing equipment is accompanied by engineers to transfer the knowledge related to the operation and use of the machine. Thus, the level of transfer in turnkey projects is broader than other forms of trade involving only the embodied product.
Design licensing	A legal contract where the technology supplier (licensor) transfers specific rights related to the design of a product to the recipient (licensee) for a specific duration. It typically involves production and distribution rights as well as the related technical information. It is frequently accompanied by some form of training.
Process licensing	A legal contract where the technology supplier (licensor) transfers specific rights related to a manufacturing process step to the recipient (licensee) for a specific duration. It is frequently accompanied by some form of training.
Joint research and/or development (with foreign firms or research institutes)	R&D cooperation by a local firm with a legally independent foreign firm or research institute. The new innovations and improvements resulting from the partnership are made under case-specific arrangements concerning the intellectual property rights.
Human resources	
Inter-firm transfer of human resources	Native or foreign employees with experience working for foreign firm move to a local firm and thus facilitate the diffusion of know-how.
Foreign education	The foreign education of entrepreneurs and key employees can be transferred when these individuals return home after studying abroad and apply the accumulated know-how in their home market through founding their own business or working in existing businesses.
Training	Training of recipient firm's employees by foreign partners.

Source: Lema and Lema (2012); Lewis (2013); Lin and Tao (2012).

transfer of both product- and process-related know-how. Other mechanisms may be focused mainly or exclusively on either one or the other type of know-how. While a training delivered in combination with a design license, for instance, is likely to focus on product-related questions, the sale of production equipment would be accompanied by services related to the process of production. The relative importance of process- or product-related knowledge within international research and development partnerships will strongly depend on the partner and the aim of the specific project. In the case of specialized design firms, the focus may be on developing a new product design, while in other cases it may be focused on optimizing an existing process.

Fig. 1 locates the different transfer mechanisms in terms of the *scope and type of tacit knowledge transfer* that they facilitate. As suggested by Lema and Lema (2012), it is understood that the specific nature of each transfer mechanisms may vary in the context of its practical application. Nevertheless, the graph provides an approximation of what is considered a typical case. We do not consider transfer mechanisms, such as the trade in final products or components, which do not involve any significant tacit knowledge transfer.

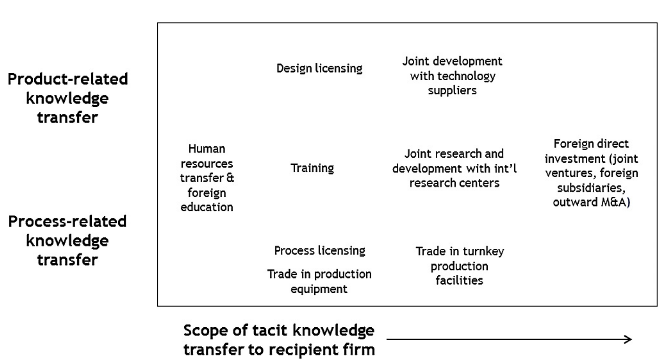

Fig. 1. Overview of international technology transfer mechanisms and the scope and type of tacit knowledge transfer.

3.2. Empirical data

The empirical analysis in this paper focuses on the process of technology transfer in the solar photovoltaics and wind energy industries to China from the 1990s until the present. The starting point of the analysis in both cases coincides with the process of industry formation in China and focuses on technology transfer processes involving firms that remain active in today's industry. In both industries, the phase of industry formation was preceded by strongly state-controlled technology transfer processes. However, in particular in the PV sector, the state-owned enterprises involved during this phase of technology transfer are no longer relevant for China's current PV industry. Hence, this early phase of technology transfer is not discussed in detail.

The empirical analysis followed a case study approach, drawing on mixed data sources, as suggested by Eisenhardt (1989). Firstly, we reviewed the existing literature on technology transfer in the wind and PV industries and screened business reports of relevant companies and news reports for information on technology transfer. Secondly, we conducted a total of 27 interviews with experts in China and Germany (which was a main source of technology transfer to China in both industries). The interviews were conducted in the fall of 2014 with experts from industry as well as with researchers of relevant expertise. An interview guideline was developed with different questions depending on the respective expertise, which allowed for setting different focuses in the interviews. Based on the interview results, a second review of existing empirical data and literature was conducted to ensure a triangulation of all findings and update relevant information.

4. Development trajectories in the wind power and solar PV industries

Before presenting the empirical data on technology transfer in section 5, the following section provides an overview of the overall development trajectories in the wind and PV sectors both globally and in China. Based on findings from existing literature, it highlights key differences between the two sectors.

4.1. Diverging development trajectories in the global wind power and solar PV sectors

There is now strong evidence for the fact that wind power and solar PV differ with regard to the role that home markets play for innovation and the localization of industries (Huenteler et al., 2016). Two recent, analogous econometric studies analyzed the effect of deployment policies on domestic and foreign innovation in wind power and solar PV. Dechezleprêtre and Glachant (2014) find that domestic wind power deployment policies had an effect on innovation 28 times stronger than foreign ones. In contrast, Peters et al. (2012) clearly find that foreign-based demand-pull policies are at least as effective as domestic demand-pull policies in driving patenting in PV cells and modules. In other words, cell and module manufacturers have not been more responsive to demand-pull measures in their home country than elsewhere.

A similar picture emerges from studies analyzing the effect of deployment policies on the competitive success of domestic firms. On the one hand, comparative studies of wind power in different countries find that domestic deployment policies correlate well with industrial competitiveness.[6] Lewis and Wiser (2007) conclude from a review of global wind power industry development that domestic deployment policies are "a *pre-requisite* to achieving successful localization" (p. 1855; italics added). Recent quantitative studies of the PV industry, on the other hand, find that domestic market size is not a good predictor of international competitiveness (Algieri et al., 2011; ICTSD, 2010). Recent reports by policy think tanks that explicitly compare deployment policy outcomes in the solar PV and wind power industries arrive at the same conclusions (Barua et al., 2012; Huberty and Zachmann, 2011). Using trade data, Huberty and Zachmann (2011) find a correlation between domestic deployment and international competitiveness in wind power, but no such relationship in solar PV. They arrive at the conclusion that using domestic demand as an industrial policy "may work for wind turbines, but we find no evidence that it works for solar cells" (p. 1). Barua et al. (2012) conclude from a multi-country case study that "domestic deployment is key to building … domestic industries" in wind power, whereas in PV "a large domestic manufacturing industry and significant domestic deployment do not necessarily go hand-in-hand" (p. 2–3).[7] The differing role of geographical proximity is reflected in processes of catching up of emerging economies in the two industries. In wind power, catching up almost always involves significant support for a domestic market and often required protectionist actions by governments (Lewis, 2007, 2012). The cases of China, Taiwan, and Malaysia, in contrast, which emerged as hubs of PV cell and module production without supporting a significant domestic market, show that countries can reach international competitiveness in PV manufacturing without supporting local demand (Cao and Groba, 2013; Liu and Goldstein, 2012). A more detailed comparison of development trajectories in the wind and solar PV sectors can be found in Hughes and Quitzow (2017).

4.2. Wind power and solar PV in China

China's wind power sector is one of the often-cited success stories of low-carbon energy development in emerging economies (Dai and Xue, 2014; Lewis, 2013). Cumulative investments in the sector have risen 100-fold between 2005 and 2014, and China now leads the world in wind power installations, with 115 GW at the end of 2014 (NEA, 2015). The creation of a domestic wind industry and the accumulation of indigenous technological capacities has been a central aim of the government ever since it started investing in domestic wind turbine manufacturing in the mid-1990s (Lewis, 2013 p. 43), but it was only after the surge in capacity investment in 2005 that China became a hub for wind turbine manufacturing (Lewis, 2013; Ru et al., 2012). In 2005, China had only a few small-scale turbine manufacturers and was strongly relying on foreign companies. After 2007 the large Chinese manufacturers had accumulated sufficient experience to be able to satisfy the increasing demand on the local market. The share of foreign companies in Chinese wind energy installations dropped from 75 percent in 2004 to only 12 percent in 2010 (Gosens and Lu, 2013). By 2011 four manufacturers – Goldwind, Sinovel, United Power and Mingyang – were already among the world's top 10 wind turbine manufacturers with a total share of 26,7 percent of the world market and hence continued growing in the following years (Zhou et al., 2012).

However, the growing share of the Chinese manufacturers in the overall production capacity is to a large extent based on their strong position in the national market where they have reached a share of more than 90 percent. Observers have pointed out that China's wind manufacturers, though dominant in China, have not acquired the technological capabilities needed to meet international quality standards and hence to successfully compete on more mature markets in OECD countries (Gosens and Lu, 2014; Schmitz and Lema, 2015). Consequently Chinese firms only account for a small share of global wind turbine exports, most of which has gone to other developing countries, rather than into mature markets in Europe and the United States (UNEP, 2014; Cao and Groba, 2013). Lema et al. (2013) have pointed out that Chinese firms compete mainly on price, continuing to lag behind major international competitors in terms of reliability and design skills.

The evolution of the Chinese PV industry stand in stark contrast to these developments, especially regarding the role of the home market. While the Chinese wind industry developed based on the domestic market, the Chinese PV sector became the global manufacturing leader without a significant home market (Zhang et al., 2013). Instead, Fu and Zhang (2011) have highlighted the importance of investments in domestic R&D capabilities, which have enabled Chinese firms to rapidly absorb and commercially exploit foreign PV technologies. China's share of global production grew at an impressive rate, increasing from less than 2 percent in 2003 to 35 percent in 2007 and 58 percent in 2013 (de la Tour et al., 2011; IEA-PVPS, 2014). Until around 2005, the industry was mainly focused on cell and module production. After 2005, firms started to move further upstream into wafers and ingots. Foreign demand was the main driver of the Chinese PV industry in the formative phase of development with more than 95 percent of the modules being exported, mainly to Europe and North America. Due to this dependence, the financial crisis and the cutback on policy support for solar-based generation in the target markets had a strong negative impact on Chinese manufacturers. This was further reinforced by the anti-dumping investigations, which started in the US and Europe in the year 2011 (Zhang et al., 2013). The decreasing

[6] The market leaders of the four largest markets in 2010 – China, the US, India, and Germany, were all domestic companies (BTM, 2011).

[7] In 2011, the top five wind markets (according to cumulative installed capacity) were home to 9 of the top 10 turbine suppliers, whereas in PV the top 5 countries were home to only three.

Table 3
Examples of key mechanisms of international knowledge transfer in the Chinese wind energy industry.

Mechanism	Examples
Design licensing	Goldwind: Vensys (2003) Sinovel: Fuhrländer (2005), Windtec (2006)
Joint Ventures	Xian Weide: Nordex (1997) Yituo: Made (1997)
Foreign subsidiaries	Vestas (2005) GE (2006)
M&A	Goldwind: Vensys (2008) XEMC: Darwind (2009)
Joint development involving technology suppliers/design firms	Sinovel: Windtec (2007) United Power: Aerodyn (2007)

Source: Lewis (2013); Gosens and Lu (2013); selected company reports.

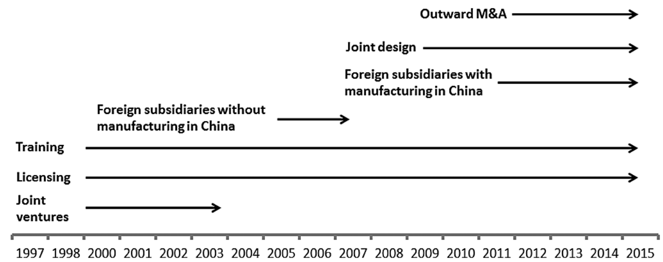

Fig. 2. Evolution of key international technology transfer mechanisms in the wind energy industry over time.

demand for Chinese PV modules led to large overcapacities, and from 2009 onwards the Chinese government implemented a series of policy measures to stimulate local demand for solar PV. Consequently, Chinese PV firms also started venturing into the segments of system integration, installation, and project development, as they began serving the domestic market (Zhang et al., 2013; Quitzow, 2015). Despite the growth of the domestic market, China still exported approximately half of its production in 2013 and remains the dominant international supplier of PV cells and modules (IEA-PVPS, 2014).

5. Modes of technology transfer in the wind and PV sectors

The differing trajectories of industry development in China's wind and PV sectors are reflected in corresponding differences in the use of transfer mechanisms both across the two sectors and over time. The following section presents the results of the data collected on transfer mechanisms in both sectors and describes their evolution from an initial formative phase to the following growth phase.

5.1. Technology transfer in China's wind energy sector

In the wind energy sector, knowledge transfer mechanisms involving both a large *scope of tacit knowledge transfer* (i.e. intra-firm transfer mechanisms) and those focused on product-related knowledge transfer (i.e. licensing agreements and joint design with specialized design firms) were dominant. Both types of transfer mechanisms have evolved over time, mainly reflecting the increasing sophistication of the Chinese wind energy industry as well as evolving domestic content requirements. The overall focus on these two types of transfer mechanisms remains stable over time (see Table 3 and Fig. 2 for an overview).

In the formative, pre-industrial phase of wind energy development (lasting until approximately 2000), technology transfer mainly took place via government-orchestrated technology transfer agreements. These took the form of government-backed licensing agreements and joint ventures. A notable example of the former are two government-funded licensing agreements involving Goldwind as the recipient firm and German Jacobs (later purchased by RE Power) and Danish Bonus (later purchased by Siemens) as the suppliers of technology (Gosens and Lu, 2013; Lewis, 2007). Major joint ventures were arranged between Spanish Made and Yituo, Denmark's NEG Micon and Goutou and Germany's Nordex and Xi'an Aero Engine Corporation, (Gosens and Lu, 2013; Lewis, 2013). Both types of arrangements were accompanied by training for Chinese staff to facilitate the transfer of needed manufacturing know-how. This represented a key element of the "Ride the Wind" program, launched in 1997 with the aim of progressively increasing the local content in China's wind energy sector (Gosens and Lu, 2013).

In the following phase of early market formation, lasting until approximately 2005, government-backed joint ventures were replaced by fully domestic firms operating with private licensing agreements, and a number of foreign subsidiaries were established. Major Chinese wind turbine producers, like Sinovel, Dongfang, Yunda/Windey and Goldwind, had licensing agreements with mainly Danish and German technology suppliers (Chen et al., 2014; Lema and Lema, 2013). Similar strategies were followed by a number of Chinese component suppliers (Chen et al., 2014). Goldwind, China's largest wind turbine producer, had licensing agreements with the German RE Power and Vensys (Gosens and Lu, 2013). In addition, it ran an extensive training program for staff to acquire and update their skills abroad and acquired skills by hiring personnel previously employed by Chinese subsidiaries of foreign wind turbine producers (Lewis, 2007).

Major foreign firms with subsidiaries in China during this period included Vestas (Denmark), Gamesa (Spain), General Electric (USA), and Suzlon (India). Despite increasing pressure to localize production, none of these firms had established production facilities in China before 2006, so that turbines were imported from the country of origin. Also Nordex, which had produced turbines locally in its joint venture with Xi'an Aero Engine Corporation, transitioned to a fully foreign-owned subsidiary in 2004. Similarly, NEG Micon ended its cooperation with Goutou after being purchased by Vestas. The merger of NEG Micon's and Vestas' Chinese operations in 2004 was accompanied by a significant number of layoffs, enabling a transfer of these human resources to domestic firms. In addition, cooperation between these foreign subsidiaries and local component suppliers is likely to have involved a degree of knowledge transfer (Lewis, 2013).

With the passing of the Renewable Energy Law in 2005, China's market and industry entered a new phase of accelerated growth, during which the domestic industry rapidly matured and increased its market share. This went hand in hand with new forms of technology transfer. Foreign firms under pressure to localize production began establishing manufacturing lines, while a number of domestic firms initiated joint development projects with foreign partners. Cooperations between Chinese manufacturers and European design firms were established. In addition, a number of players made acquisitions of foreign manufacturers and design firms (Lema et al., 2013). Goldwind, for instance, took over Vensys in 2008 (Lewis, 2013; Gosens and Lu, 2013). A number of other firms have followed since (Lema et al., 2013). A number of these purchases have been in the field of project development, aimed at creating foreign markets for Chinese wind turbines, while others were made to acquire foreign technology and know-how (Lema et al., 2013; Tan et al., 2013).

Table 4
Examples of key international technology transfer mechanisms in the PV industry.

Mechanism	Examples
Turnkey production facilities	Centrotherm (buyers not disclosed)
Trade in production equipment	Talesun: Rena, Baccini; Trina: Centrotherm
Foreign-educated entrepreneurs	Suntech: Dr. Zhengrong Shi (CEO); Canadian Solar: Dr. Shawn Qu (CEO)
Inter-firm human resources transfer	Trina: Pierre Verlinden (Chief Scientist); Yingli: Dengyuan Song (Chief Technology Officer)
Joint research and development with international research centers	Yingli: ECN (Netherlands); Suntech: UNSW; Trina: Australian National University

Source: Quitzow (2015); Zhang and White (2016); interviews and selected company reports.

5.2. Technology transfer in China's solar PV sector

Technology transfer in China's solar PV sector has taken a very different form than in the wind energy sector. It has revolved around two major channels of transfer that played only a minor role in the wind energy sector – trade in production equipment and the return of foreign-trained Chinese professionals to China. At later stages of industry formation, this was complemented by joint research and development with foreign research institutes (see Table 4 and Fig. 3 for an overview), rather than privately-owned design firms. The transfer of knowledge from other manufacturers in the form of design license agreements played only a very minor role. The limited licensing that did occur was focused on the licensing of production process steps. Similarly, foreign-direct investment and outward M&A[8] have played a relatively minor role as a mechanism of technology transfer. In sum, technology transfer in the PV sector has been dominated by mechanisms, enabling the transfer of process-related knowledge and with a more limited *scope of tacit knowledge transfer.*

Similar to the wind energy sector, the very early stage of development was dominated by government-orchestrated technology transfer. In the 1970s and 1980s, the government facilitated the import of production lines from the US by four state-owned enterprises: Kaifeng, Qinhuangdao Huamei, Ningbo, and Yunnan Semiconductor. It also organized a joint venture involving the US firm Corona (Zhang and White, 2016). While able to function as counterparts to an emerging domestic R&D sector at a number of Chinese universities, these firms and the product-specific know-how they may have acquired no longer play a significant role in the market today (Marigo, 2007).

A second phase of development began in the late 1990s. In response to European market developments as well as a number of rural electrification programs in China, a number of Chinese entrepreneurs created a set of privately-owned module manufacturing firms in the late 1990s. The major firms founded during this period were Yingli, Suntech, Canadian Solar and Trina. Some with professional experience in the US or Australian PV sector, these entrepreneurs imported production equipment from the US and Europe (Marigo, 2007). These pioneer firms also

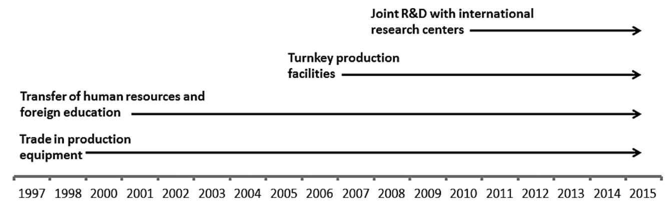

Fig. 3. Evolution of key mechanisms of international technology transfer in the Chinese PV industry over time.

collaborated with German certification bodies to improve the quality of their products. In a few exceptional cases, leading German PV suppliers even supported this process (Quitzow, 2015). This allowed these manufacturers to sell Chinese modules under the German manufacturers' brand name on the German supply-constrained market (Hug and Schachinger, 2006).

As the sector matured internationally, turn-key production facilities became available on the international market. Beginning in 2006, this further reduced the technological barrier to entry for China's second wave of PV firms. These firms often did this with little or no expertise in the PV sector, building merely on their general manufacturing know-how and the support and training offered by the turn-key suppliers. In addition, a larger number of foreign-trained Chinese and non-Chinese professionals joined major PV firms, occupying important positions in the realm of technology development and marketing. Examples include the Chief Technology Officers who joined companies, such as Sunergy, Solarfun and JA Solar, between 2005 and 2007 (Zhang and White, 2016). First-tier producers, like Trina and Yingli, also engaged in cooperation with foreign research institutes, most importantly the School of Photovoltaic and Renewable Energy Engineering at the University of New South Wales (UNSW) in Australia. Early on, this was primarily focused on introducing know-how and processes developed at UNSW to those firms. As the sector continued to advance, these cooperation agreements began focusing on the development of new cell concepts and processes in joint development programs. Examples include the development of Yingli's flagship Panda-series solar cells, which were developed in cooperation with ECN in the Netherlands. At this advanced stage, a small number of licensing agreements focused mainly on process steps were also signed between PV manufacturers and international research centers (Quitzow, 2015).

6. Synthesis and discussion of results

Based on the detailed description of technology transfer mechanisms in the previous section, this section provides a brief synthesis and discussion of the main results of the paper, linking technology-related patterns to the different development trajectories observed in China's wind and solar PV sectors. It then briefly discusses other possible explanations for the differing outcomes.

6.1. Technology transfer patterns, industry localization and catching up

As the results of the comparison show, technology transfer in both the wind power industry and the solar PV sector does indeed conform to the predicted patterns (see Fig. 4 for a stylized comparison of the main technology transfer mechanisms in the wind energy and solar photovoltaics industry). Chinese firms in the wind power industry have relied on transfer mechanisms with heavy involvement of supplier firms over prolonged periods of time. This has enabled the transfer of a high degree of product-specific tacit

[8] It should be noted that processes of industry consolidation in the solar photovoltaics sector beginning with the financial crisis in 2008/2009 have also included a series of merges and acquisitions involving Chinese firms. Generally, these have been seen as decisions aimed at capturing market share, promoting vertical integration and increasing the global scope of firms and building up non-Chinese manufacturing capacity to avoid trade barriers. Technology transfer has not figured as a prominent motivation. See for instance "Mergers between PV Companies Driven by International Integration and Expansion Strategies", *Energy Trend*, 25.7.2015. Accessed on 13.7.2016 at http://pv.energytrend.com/price/20150725-9170.html.

knowledge. In the PV industry, transfer mechanisms have mainly facilitated the transfer of process-related knowledge and the *scope of tacit knowledge transfer* has been comparatively lower.

A key channel for technology transfer in the PV sector has been the international trade in production equipment. This equipment has been produced and sold by independent equipment providers, especially from the US, Germany, Switzerland and to a lesser degree Japan, rather than manufacturers of PV modules or cells (Hughes and Quitzow, 2017). While an important number of these equipment suppliers are based in large markets like Germany, they are not directly involved in the production of PV modules or systems. Hence tacit knowledge transfer facilitated by these suppliers was limited to process-related aspects. Product-specific knowledge held by solar PV manufactures has not played a significant role in enabling the build-up of capabilities in China's PV industry. Tacit knowledge has also been transferred via human resource transfers and in cooperation with international research institutes and certifiers. Compared to transfer mechanisms utilized in the wind energy sector, these are far more limited in *scope*.

In the wind power industry intra-firm mechanisms have remained the dominant modes of transfer, albeit with important changes over time. While joint ventures were the dominant form of transfer in the early stage of Chinese industry development, this has given way to the creation of direct subsidiaries by foreign producers and purchases of design licenses in the subsequent stage of industry formation and, later, outward M&A activities by Chinese firms (i.e. the acquisition of a number of mainly European technology suppliers and design firms). Product and design-specific knowledge, provided by other turbine producers and specialized design firms in the form of joint ventures and joint development projects, has been central to transfer processes and remains so over time. Moreover, the use of outward M&A for the purchase of other manufacturers and design firms at later stages in the industrial development process indicates that Chinese firms, still lacking significant sales in international markets, are seeking to access product-specific knowledge developed via user-producer interactions in those markets.

6.2. Alternative explanations

Below we discuss a number of alternative explanations for the observed geographical patterns of industry location in the wind power and solar PV industries, building on the central factors highlighted in Porter's diamond model (Porter, 1990). While these

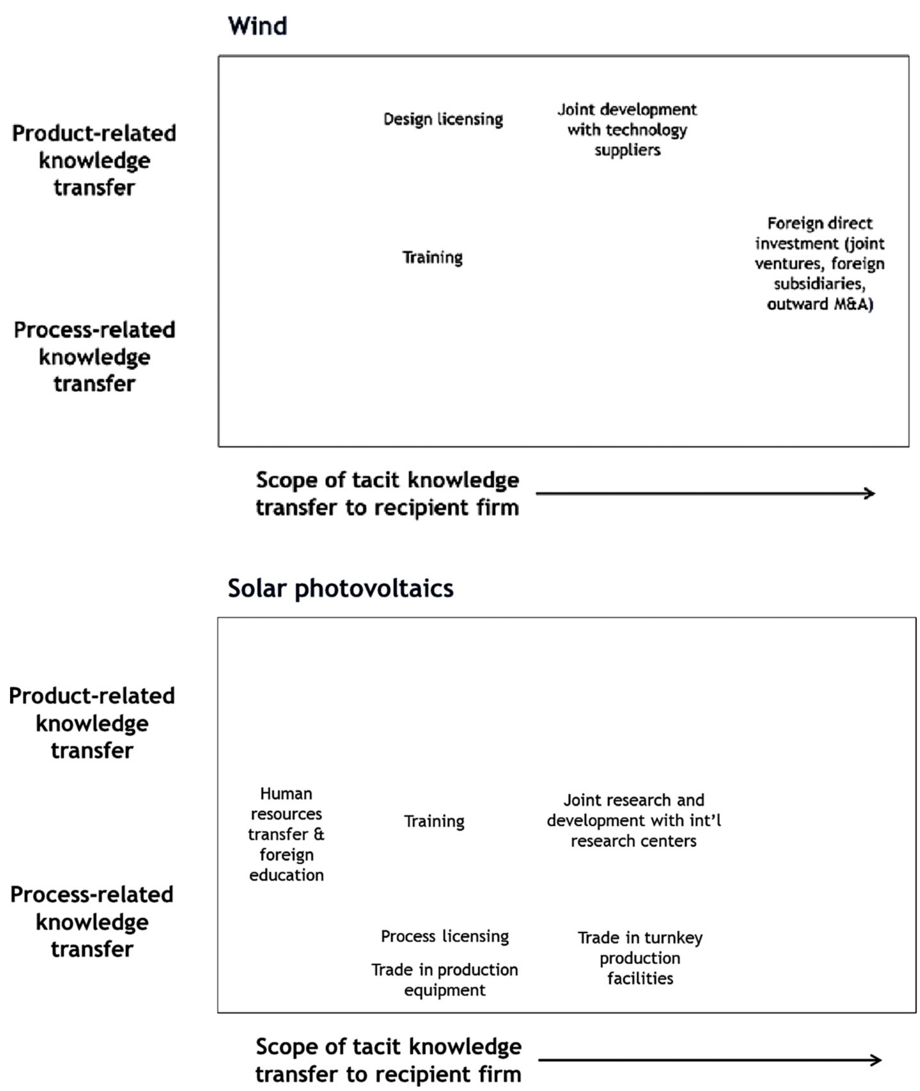

Fig. 4. Stylized comparison of the main international technology transfer mechanisms in the wind energy and solar photovoltaics industries.

factors contributed to the observed divergence between China's solar and wind industries, we argue that they complement rather than replace technology-specific factors as explanation for the observed divergence in technological trajectories.

6.2.1. Input factor costs

Firstly, it might be argued that factor conditions in China are more favorable for competition in the PV sector than in the wind sector. Key advantages that have been cited in this regard are an abundance of low-cost, semi-skilled labor as well as relatively easy access to capital for investment in the export-oriented manufacturing sector. Given the relatively higher importance of these two variables in the PV sector, this may offer one explanation of the competitive success of China's PV sector firms. This advantage is further enhanced by the high modularity of PV systems and relatively low shipping costs for PV modules and cells, which provides a stronger case for exploiting factor conditions in China than in the wind sector (Peters et al., 2012). However, labor costs only represent a relatively small fraction of the cost of a PV module, so that this can represent at best a partial explanation of Chinese competitive success in the PV sector. The relatively minor importance of country-specific input factors in explaining China's price advantage in solar PV manufacturing is confirmed by a recent assessment of what drives regional trends in the sector (Goodrich et al., 2013).

6.2.2. Domestic competitive environment

The intensity of domestic competition is considered another key factor influencing competitiveness of national industries in Porter's diamond model. We argue that this is not likely to represent an important factor for explaining the differing outcomes in the wind and PV sectors. The absence of a significant market for PV systems in China prior to 2009, on the one hand, and fierce competition in the wind energy sector, on the other, would suggest that domestic market conditions were in fact more favorable for the competitive success of Chinese wind energy firms. Firm strategy and structure might appear to offer a more plausible explanation, as the PV sector is dominated by privately-owned firms while China's wind energy sector is largely controlled by state-owned firms. Among the large producers only Goldwind, albeit the most successful Chinese wind turbine manufacturer, is now partially privately-owned. Nevertheless, it lags far behind all the major Chinese module producers in terms of its share of global exports.

6.2.3. Related industries

The existence of related industries and the corresponding supplier structures represents a further success factor in building a strong system of innovation and production. This idea is closely related to the concept of absorptive capacity, which proposes that the ability of firms to absorb and utilize knowledge depends in part on their prior knowledge in related fields as well as more generic organizational capabilities for learning.

This line of argument is supported by a recent study, which finds a link between the strength of the semiconductor industry and manufacturing success in the solar PV industry, albeit without considering China in the sample (Choi and Diaz Anadon, 2014). Building on these findings, it might be argued that Chinese success in the PV sector stems from the existence of relatively strong related industries. China's strength in electronics manufacturing coupled with substantial investments in the build-up of knowledge in the field of semiconductors might represent two such enabling factors for the PV industry. However, China has lagged behind other countries in Asia in the semiconductor industry, including Taiwan, Korea, Japan and Malaysia, but overtook these countries very quickly in the solar PV industry. Moreover, China's wind turbine manufacturers have also built on existing capabilities in heavy industry and manufacturing of electric generators (Lewis, 2012).

In sum, these alternative explanations raise a number of valid points. Nevertheless, they offer at best partial explanations of the diverging development trajectories observed in China's wind and solar PV sectors. We argue, that these explanatory variables need to be complemented with technology-specific variables to offer a more complete picture of industrial localization and international competitiveness in the two sectors.

7. Conclusions and policy implications

Developing countries increasingly adopt policies to promote low-carbon energy technologies with the hope to attract technology transfer from abroad and, eventually becoming global manufacturing hubs. Experience from the wind industry, e.g., the successes of the early-movers Denmark, Germany, Spain, and India in the 1980s and 1990s, had suggested that a strong and stable market support scheme was the pre-condition for building industrial leadership in the low-carbon energy field. This heuristic is now being called into question by the rapid emergence of manufacturing hubs that developed to serve export markets rather than domestic markets, i.e. in the solar PV industry.

China epitomizes the differences between the two technologies. While the country just recently started developing a national market for solar power, it has taken the lead in global PV manufacturing and dominates exports to all major markets. In contrast, China's wind industry has almost exclusively relied on the domestic market to build local manufacturing capabilities and struggles to export into mature markets in Europe and the United States. This paper sought to explore the reasons for these differences, using a comparative analysis of China's catching up processes in wind and solar energy. Our results suggest that the differences can be traced back to differences in the nature of the two technologies, as manifested in the distinctly different modes of international technology transfer. These have led to differing outcomes in terms of industry localization and international competitiveness. Alternative explanations, like differences in input factor costs, the domestic competitive environment, and existing related industries across the two sectors, do not offer a sufficient basis for explaining the divergence in development trajectories.

These findings suggest that the competitive advantage that China has developed in PV manufacturing may also be more vulnerable than the competitive advantage that European and American firms still enjoy in the wind power industry. Current advantages may be largely related to the larger scale of production combined with a broader enabling environment for low-cost manufacturing rather than more lasting, technology-based advantages. While European or American firms are unlikely to compete with Chinese firms on this basis, this may offer opportunities for firms in other emerging countries, including India, as China continues to advance economically and begins to lose its factor cost advantage. Others have argued that China's capabilities in scaling-up manufacturing and translating new technologies into cost competitive commercial products represent a unique competitive advantage (Nahm and Steinfeld, 2014). Our findings would suggest that these capabilities are relevant mainly in the field of mass-produced goods. Moreover, they may lose in importance at more advanced stages of the technology life-cycle, as processes become increasingly standardized across the industry and factor costs gain a stronger influence on total cost.

For the wind power industry, it seems to imply that the geography of production will remain more geographically dispersed, not only due to logistical challenges but due to the nature of innovation and technological change and the strong importance of user-producer interactions. At the same time, it indicates that the development of a local industry is unlikely to occur in the absence of a strong home market. This suggests the persistence and further consolidation of a number of relatively stable regional production hubs.

In addition, our research results offer more general insights for policy makers considering the promotion of future emerging environmental technology sectors. The findings offer a novel framework for distinguishing between different types of sectors, linking these differences to the dynamics of innovation and international competition. This in turn raises important questions on the nature of potential first-mover advantages to be derived from ambitious market support for emerging technology sectors. The rapid process of technology transfer in the area of mass-produced goods implies a different set of challenges from the inertia of complex assembled products. Specifically, industrial policy targeting first-mover advantages in export markets are likely to be more stable in complex assembled products, while late movers have better chances to catch-up in mass produced goods if they can successfully exploit economies of scale.

In addition, investments in a domestic market are key to building up industrial capabilities in complex assembled products and should be coupled with the promotion of intra-firm technology transfer mechanisms. In other words, policies promoting cooperation between foreign and domestic firms to serve the domestic market are likely to contribute to the process of catching up. In the area of mass produced goods, policies might focus on stimulating investment and entrepreneurship in the sector, while offering particular incentives to citizens active in the industry abroad. Moreover, incentives for international cooperation in research and development are likely to offer important benefits to the local industrial sector. That said, these technology specific considerations only represent one of several success factors. Hence, the specific design and ambition of industry promotion efforts should also build on other important variables, such as input factors, the existence of related industries and the size of the home market.

Acknowledgements

We thank Tobias Schmidt and Joern Hoppmann from ETH Zurich for discussions that informed this research. Elements of the research were supported by the Germany Ministry of Education and Research (BMBF) via its funding to the Institute for Advanced Sustainability Studies under Grant No. 01US0902 as well as the German Academic Exchange Service and Zonta International, which supported part of the field work. Further elements of this research were conducted as part of the activities of SCCER CREST (Swiss Competence Center for Energy Research), which is financially supported by the Swiss Commission for Technology and Innovation (CTI) under Grant No. KTI.1155000154.

References

Abernathy, W.J., Utterback, J., 1988. Innovation over time and in historical contexte. In: Tushman, M., Moore, W. (Eds.), Readings in the Management of Innovation. Harper Collins Publishers, New York City, pp. 25–36.
Algieri, B., Aquino, A., Succurro, M., 2011. Going "green": trade specialisation dynamics in the solar photovoltaic sector. Energy Policy 39, 7275–7283.
Anderson, P., Tushman, M.L., 1990. Technological discontinuities and dominant designs: a cyclical model of technological change. Adm. Sci. Q. 35, 604–633.
Baranson, J., 1970. Technology transfer through the international firm. Am. Econ. Rev. 60, 435–440.
Barua, P., Tawney, L., Weischer, L., 2012. Delivering on the Clean Energy Economy: the Role of Policy in Developing Successful Domestic Solar and Wind Industries. World Resources Institute (WRI) and Open Climate Network (OCN) Working Paper.
Beise, M., Rennings, K., 2005. Lead markets and regulation: a framework for analyzing the international diffusion of environmental innovations. Ecol. Econ. 52, 5–17. http://dx.doi.org/10.1016/j.ecolecon.2004.06.007.
Bell, M., 1990. Continuing Industrialisation, Climate Change and International Technology Transfer. A Report Prepared in Collaboration with the Resource Policy Group, Oslo, Norway. Science Policy Research Unit, University of Sussex, Brighton, UK.
Bell, M., 2010. Innovation Capabilities and Directions of Development. STEPS Centre Working Paper 33.
Bell, M., 2012. International technology transfer, innovation capabilities and sustainable directions of development. In: Ockwell, D., Mallett, A. (Eds.), Low-Carbon Technology Transfer: from Rhetoric to Reality. Routledge, New York City, pp. 20–47.
Bell, M., Figueiredo, P., 2012. Innovation capability building and learning mechanisms in latecomer firms: recent empirical contributions and implications for research. Can. J. Dev. 33, 14–40.
Bell, M., Pavitt, K., 1992. Accumulating technological capability in developing-countries. World Bank Econ. Rev. 257–281.
BTM, 2011. World Market Update 2010. Ringkøbing, Denmark.
Cao, J., Groba, F., 2013. Chinese Renewable Energy Technology Exports: the Role of Policy, Innovation and Markets. DIW Discussion Paper 1263.
Chen, Y., Rong, K., Xue, L., Luo, L., 2014. Evolution of collaborative innovation network in China's wind turbine manufacturing industry. Int. J. Technol. Manag. 65, 262–299.
Choi, H., Diaz Anadon, L., 2014. The role of the complementary sector and its relationship with network formation and government policies in emerging sectors: the case of solar photovoltaics between 2001 and 2009. Technol. Forecast. Soc. Change 82, 80–94.
Cimoli, M., Dosi, G., Stiglitz, J.E., 2009. Industrial Policy and Development: the Political Economy of Capabilities Accumulation. Oxford University Press, Oxford, UK. http://dx.doi.org/10.1093/acprof.
Coase, R., 1937. The nature of the firm. Economica 4, 386–405.
Dai, Y., Xue, L., 2014. China's policy initiatives for the development of wind energy technology. Clim. Policy 15, 30–57. http://dx.doi.org/10.1080/14693062.2014.863549.
Davies, A., 1997. The life cycle of a complex product system. Int. J. Innov. Manag. 1, 229–256.
de la Tour, A., Glachant, M., Ménière, Y., 2011. Innovation and international technology transfer: the case of the Chinese photovoltaic industry. Energy Policy 39, 761–770.
Dechezleprêtre, A., Glachant, M., 2014. Does foreign environmental policy influence domestic innovation? Evidence from the wind industry. Environ. Resour. Econ. 58, 391–413.
Eisenhardt, K., 1989. Building theories from case study research. Acad. Manag. Rev. 14, 532–550.
European Commission, 2010. Member States Competitiveness Performance and Policies. European Commission, SEC, Brussels (2010) 1272 final.
Fu, X., Zhang, J., 2011. Technology transfer, indigenous innovation and leapfrogging in green technology: the solar-PV industry in China and India. J. Chin. Econ. Bus. Stud. 9, 329–347.
Goodrich, A.C., Powell, D.M., James, T.L., Woodhouse, M., Buonassisi, T., 2013. Assessing the drivers of regional trends in solar photovoltaic manufacturing. Energy Environ. Sci. 6, 2811–2821. http://dx.doi.org/10.1039/c3ee40701b.
Gosens, J., Lu, Y., 2013. From lagging to leading? Technological innovation systems in emerging economies and the case of Chinese wind power. Energy Policy 60, 234–250.
Gosens, J., Lu, Y., 2014. Prospects for global market expansion of China's wind turbine manufacturing industry. Energy Policy 1–18. http://dx.doi.org/10.1016/j.enpol.2013.12.055.
Gosens, J., Lu, Y., Coenen, L., 2015. The role of transnational dimensions in emerging economy 'Technological Innovation Systems' for clean-tech. J. Clean. Prod. 86, 378–388.
Hakanson, L., Nobel, R., 2000. Technology characteristics and reverse technology transfer. Manag. Int. Rev. 1, 29–48.
Hansen, U.E., Ockwell, D., 2014. Learning and technological capability building in emerging economies: the case of the biomass power equipment industry in Malaysia. Technovation 34, 617–630. http://dx.doi.org/10.1016/j.technovation.2014.07.003.
Hobday, M., 2000. The project-based organisation: an ideal form for managing complex products and systems? Res. policy 29, 871–893.
Huberty, M., Zachmann, G., 2011. Green Exports and the Global Product Space: Prospects for EU Industrial Policy. Bruegel Working Paper 7.
Huenteler, J., Schmidt, T.S., Ossenbrink, J., Hoffmann, V.H., 2016. Technology life-cycles in the energy sector — technological characteristics and the role of deployment for innovation. Technol. Forecast. Soc. Change 104, 102–121.
Hug, R., Schachinger, M., 2006. Chinese solar modules penetrating the German market. SolarServer (Online) 10. November 2006.
Hughes, L., Quitzow, R., 2017. Low-carbon technologies, national innovation systems, and global production networks: the state of play. In: Goldthau, A., Keating, M., Kuzemko, C. (Eds.), Handbook of International Political Economy of Energy and Natural Resources. Edward Elgar.
ICTSD, 2010. Technology Mapping of the Renewable Energy, Buildings, and Transport Sectors: Policy Drivers and International Trade Aspects. International Center for Trade and Sustainable Development (ICTSD), Châtelaine.
IEA, 2015. Energy Technology Perspectives 2015. International Energy Agency (IEA), Paris, France.
IEA-PVPS, 2014. Trends 2014 in Photovoltaic Applications: Survey Report of Selected

IEA Countries between 1992 and 2013. Report IEA-PVPS T1-25:2014.
Jänicke, M., Jacob, K., 2004. Lead markets for environmental innovations: a new role for the nation state. Glob. Environ. Polit. 4, 29–47.
Lema, A., Lema, R., 2013. Technology transfer in the clean development mechanism: insights from wind power. Glob. Environ. Change 23, 301–313. http://dx.doi.org/10.1016/j.gloenvcha.2012.10.010.
Lema, R., Berger, A., Schmitz, H., 2013. China's impact on the global wind power industry. J. Curr. Chin. Aff. 42, 37–69.
Lema, R., Lema, A., 2012. Technology transfer? The rise of China and India in green technology sectors. Innov. Dev. 2, 23–44.
Lewis, J., 2012. Green innovation in China: China's Wind Power Industry and the Global Transition to a Low-Carbon Economy. Columbia University Press, New York, NY.
Lewis, J., 2013. Green Innovation in China: China's Wind Power Industry and the Global Transition to a Low-Carbon Economy. Columbia University Press, New York.
Lewis, J., Wiser, R., 2007. Fostering a renewable energy technology industry: an international comparison of wind industry policy support mechanisms. Energy Policy 35, 1844–1857.
Lewis, J.I., 2007. Technology acquisition and innovation in the developing world: wind turbine development in China and India. Stud. Comp. Int. Dev. 42, 208–232. http://dx.doi.org/10.1007/s12116-007-9012-6.
Lin, X., Tao, S., 2012. Transnational entrepreneurs: characteristics, drivers, and success factors. J. Int. Entrepreneursh. 10, 50–69. http://dx.doi.org/10.1007/s10843-011-0082-1.
Liu, J., Goldstein, D., 2012. Understanding China's renewable energy technology exports. Energy Policy 52, 417–428. http://dx.doi.org/10.1016/j.enpol.2012.09.054.
Magnusson, T., Tell, F., Watson, J., 2005. From CoPS to mass production? Capabilities and innovation in power generation equipment manufacturing. Ind. Corp. Change 14, 1–26. http://dx.doi.org/10.1093/icc/dth042.
Marigo, N., 2007. The Chinese silicon photovoltaic industry and market: a critical review of trends and outlook. Prog. Photovolt. Res. Appl. 15, 143–162.
Miller, R., Hobday, M., Leroux-Demers, T., Olleros, X., 1995. Innovation in complex systems industries: the case of flight simulation. Ind. Corp. Change 4, 363–400. http://dx.doi.org/10.1093/icc/4.2.363.
Morrison, A., Pietrobelli, C., Rabellotti, R., 2008. Global value chains and technological capabilities: a framework to study learning and innovation in developing countries. Oxf. Dev. Stud. 36, 39–58. http://dx.doi.org/10.1080/13600810701848144.
Nahm, J., Steinfeld, E., 2014. Scale-up nation: China's specialization in innovative manufacturing. World Dev. 54, 288–300.
NEA, 2015. Wind Power Industry Monitoring. National Energy Agency (NEA), Beijing, China, p. 2014 available online at: http://www.nea.gov.cn/2015-02/12/c_133989991.htm.
Ockwell, D., Sagar, A., de Coninck, H., 2014. Collaborative research and development (R&D) for climate technology transfer and uptake in developing countries: towards a needs driven approach. Clim. Change 131, 401–415. http://dx.doi.org/10.1007/s10584-014-1123-2.
Pegels, A., Lütkenhorst, W., 2014. Is Germany's energy transition a case of successful green industrial policy? Contrasting wind and solar PV. Energy Policy 74, 522–534.
Peters, M., Schneider, M., Griesshaber, T., Hoffmann, V., 2012. The impact of technology-push and demand-pull policies on technical change. Does the locus of policies matter? Res. Policy 41, 1296–1308.
Pizer, W., Popp, D., 2008. Endogenizing technological change: matching empirical evidence to modeling needs. Energy Econ. 30, 2754–2770. http://dx.doi.org/10.1016/j.eneco.2008.02.006.
Porter, M., 1990. The Competitive Advantage of Nations. Free Press, New York.
Porter, M., van der Linde, C., 1995. Toward a new conception of the environment-competitiveness relationship. J. Econ. Perspect. 9, 97–118.
Quitzow, R., 2015. Dynamics of a policy-driven market: the Co-evolution of technological innovation systems for solar photovoltaics in China and Germany. Environ. Innov. Soc. Trans. 17, 126–148.
Quitzow, R., Walz, R., Köhler, J., Rennings, K., 2014. The concept of "lead markets" revisited: contribution to environmental innovation theory. Environ. Innov. Soc. Trans. 10, 4–19.
Reddy, N.M., Zhao, L., 1990. International technology transfer: a review. Res. Policy 19, 285–307.
REN21, 2016. Renewables 2016: Global Status Report. REN 21, Secretariat, Paris.
Ru, P., Zhi, Q., Zhang, F., Zhong, X., Li, J., Su, J., 2012. Behind the development of technology: the transition of innovation modes in China's wind turbine manufacturing industry. Energy Policy 1–12. http://dx.doi.org/10.1016/j.enpol.2011.12.025.
Schmidt, T., Huenteler, J., 2016. Anticipating industry localization effects of clean technology deployment policies in developing countries. Glob. Environ. Change 38, 8–20.
Schmitz, H., Lema, R., 2015. The global green economy. Competition or cooperation between Europe and China? In: Fagerberg, J., Laestadius, S., Martin, B.R. (Eds.), The Triple Challenge for Europe: Economic Development, Climate Change, and Governance. Oxford Scholarship Online.
Stock, G.N., Tatikonda, M.V., 2000. A typology of project-level technology transfer processes. J. Oper. Manag. 18, 719–737.
Tan, X., Zhao, Y., Polycarp, C., Bai, J., 2013. China's Overseas Investments in the Wind and Solar Industries: Trends and Drivers. World Resources Institute, Washington DC.
Tsang, E., 1997. Choice of international technology transfer mode: a resource-based view. Manag. Int. Rev. 2, 151–168.
United Nations Environment Programme (UNEP), 2014. South-south Trade in Renewable Energy: a Trade Flow Analysis of Selected Environmental Goods.
Utterback, J.M., Abernathy, W.J., 1975. A dynamic model of process and product innovation. Omega 3, 639–656. http://dx.doi.org/10.1016/0305-0483(75)90068-7.
Vernon, R., 1966. International investment and international trade in the product cycle. Q. Rev. Econ. 88, 190–207.
Williamson, O.E., 1979. Transaction-cost economics: the governance of contractual relationships. J. Law Econ. Oct. 233–261.
World Intellectual Property Organization, 2015. Successful Technology Licensing. World Intellectual Property Organization, Geneva.
Zhang, S., Andrews-Speed, P., Zhao, X., He, Y., 2013. Interactions between renewable energy policy and renewable energy industrial policy: a critical analysis of China's policy approach to renewable energies. Energy Policy 62, 342–353. http://dx.doi.org/10.1016/j.enpol.2013.07.063.
Zhang, W., White, S., 2016. Overcoming the liability of newness: Entrepreneurial action and the emergence of China's private solar photovoltaic firms industry. Res. Policy 34, 894–913.
Zhou, Y., Zhang, B., Zou, J., Bi, J., Wang, K., 2012. Joint R&D in low-carbon technology development in China: a case study of the wind-turbine manufacturing industry. Energy Policy 1–9. http://dx.doi.org/10.1016/j.enpol.2012.03.037.

Rainer Quitzow is a Senior Research Associate at the Institute for Advanced Sustainability Studies and Senior Lecturer in Innovation Economics at the Technische Universität Berlin. He holds a PhD from the Department of Political and Social Sciences of the Freie Universität Berlin. His research focuses on sustainable innovation and industrial policy and governance of energy transition processes. In particular, he has focused on the internationalization of emerging renewable energy industries and the changing role of emerging economies in this context. Before his career as a researcher, Rainer Quitzow worked at the World Bank in Washington, DC where he conducted governance and policy impact analysis for the preparation of development programs in Latin America and Africa.

Joern Huenteler is a Young Professional in the World Bank's Energy & Extractives Global Practice. Previous to joining the World Bank, he was a postdoctoral research fellow in the Energy Technology Innovation Policy (ETIP) research group at the John F. Kennedy School of Government at Harvard University. Joern holds a Ph.D. from the Department of Management, Technology, and Economics at ETH Zurich (Switzerland). In his doctoral dissertation, "Creating Markets for Energy Innovations: Case Studies on Policy Design and Impact," he examined how technology characteristics affect the impact of technology policies in the energy sector, with a particular focus on wind power and solar PV.

Hanna Asmussen currently works as an Associate at The Boston Consulting Group (BCG). Prior to joining BCG, she worked as a Research Fellow at the Chair for Energy and Resource Management at the Technische Universität Berlin. Her research focused on new business models in the energy sector in the context of digitalization, innovation management and new markets for renewable energy, as well as technology transfer in domestic and foreign energy markets. She holds a Master of Science in Industrial Engineering from the Technische Universität Berlin.