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The Co-evolution of Policy, Market and Industry in the Solar Energy Sector

A Dynamic Analysis of Technological Innovation Systems for Solar Photovoltaics in Germany and China

Rainer Quitzow

FFU-Report 06-2013

ffu
Forschungszentrum für Umweltpolitik
Freie Universität Berlin
Fachbereich Politik- und Sozialwissenschaften
Otto-Suhr-Institut für Politikwissenschaft

Publisher

Freie Universität Berlin
Forschungszentrum für Umweltpolitik
Ihnestraße 22
14195 Berlin
Web: www.fu-berlin.de/ffu

ISSN 1612-3026
FFU-Rep 06-2013

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I would like to thank Stefan Werland, Robert Brandt (both FFU) and Lars Waldmann (Agora Energiewende) for providing me with helpful comments based on a previous version of the report.

This report represents a working paper (Nr. 13) prepared in the context of the research project „Lead Market Strategien: First Mover, Early Follower, Late Follower" (http://kooperationen.zew.de/en/lead-markets/home.html) funded by the German Federal Ministry of Education and Research (BMBF) within its program „Wirtschaftswissenschaften für Nachhaltigkeit (WIN 2), which is part of its framework program "Research for Sustainable Development (FONA).

LEAD MARKET

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Author

Rainer Quitzow
rainer.quitzow@fu-berlin.de

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Abstract

Based on a system of innovation (SI) perspective, this paper provides a dynamic analysis of innovation and industrial development in the emerging global solar energy sector. It focuses on developments in China and Germany within the context of an evolving international technological innovation system (TIS) for solar photovoltaics. The TIS approach is the most suitable for analyzing innovation systems in emergent technology fields, as it explicitly captures the dynamics of change in the system (Jacobsson & Bergek 2011). However, to date, the approach has been applied to analyze national TIS, largely ignoring international influences (Coenen et al. 2012).

To fill this gap in the literature, the paper adapts and applies the TIS framework for the analysis of a co-evolving TIS. This is different from a purely international perspective, as manifested in the sectoral system of innovation (SSI) approach. The SSI approach may be appropriate for the analysis of more established innovation systems, where structures, actors and institutions are more stable (Coenen & Díaz López 2010). An emergent global TIS, however, remains highly susceptible to (policy) developments occurring in individual countries. To capture these dynamics, the concept of a multi-level TIS is proposed. This acknowledges that a global TIS is composed of a number of sub-systems (i.e. TIS) at the national and sub-national levels, which retain a certain degree of autonomy. At the same time, actors and networks are frequently not limited to a single geographic scale, as has been acknowledged in relational approaches to economic geography (Bathelt & Gluckler 2003; Yeung 2005). They may entertain linkages across multiple scales, often drawing on a physical presence in different localities. Such linkages allow developments in national (or sub-national) TIS to exert influences upon each other.

The paper draws on this adapted version of the TIS concept to frame the empirical analysis of an evolving global TIS in solar photovoltaics. Building on a slightly expanded version of the system functions outlined by Bergek et al. (2008), the paper then traces the dynamic inter-linkages between Germany and China, as they have represented the most important drivers of change during the most dynamic period of TIS development. It sheds new light on the process of industry development and technological change in the emergent TIS for solar photovoltaics and highlights how different system functions have been provided throughout this process (considering third countries where appropriate) and how they have shifted geographically as the international TIS has matured.

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1 Introduction

This paper provides a dynamic analysis of innovation and industrial development in the emerging global solar energy sector. It focuses on the development of crystalline silicon-based photovoltaic (PV) technologies in the period from 2004 to 2010. It describes how policy, market and industry dynamics in Germany and China have co-evolved and reinforced each other, thus enabling the dynamic market growth and industry expansion witnessed during the period.

To do so, the paper builds on and adapts the technological innovation system (TIS) framework and the related system functions approach (Bergek, Jacobsson, Carlsson, Lindmark, & Rickne, 2008; Hekkert, Suurs, Negro, Kuhlmann, & Smits, 2007). It is argued that the existing TIS framework may be suitable for understanding early stages in the development of a national TIS. However, it does not sufficiently account for the inter-linkages between different TIS, which gain in importance as the TIS matures and which have played a key role in driving the dynamic growth of the PV sector over the past decade. The study, therefore, proposes an expanded TIS framework for analyzing the dynamics of co-evolution between multiple country-level TIS. This allows the framework to capture the key role played by the dynamically increasing inter-linkages and feedbacks between initially largely separate TIS. Given the crucial importance of national policy in the development of the TIS for PV-based solar energy, it is argued that the proposed framework remains the most appropriate approach to understanding development in this policy-driven sector for the time being. Other approaches, such as the sectoral system of innovation (Malerba, 2006) or the global value chain approach (Pietrobelli & Rabellotti, 2011), which provide a truly international perspective on innovation and industrial development, do not sufficiently account for relevant country-specific dynamics.

As indicated, the analysis focuses on Germany and China, the key drivers of TIS development during the period under consideration. Where appropriate, key influences from third countries, such as the US, Australia, Japan, Spain and Italy, are also mentioned. However, in an effort to limit the scope of the paper, no detailed account of developments in these countries is provided. A truly comprehensive analysis of the emergent global TIS for solar PV would also require an in-depth treatment of these third countries. Nevertheless, the chosen approach highlights not only the most important empirical phenomena, but it is also able to conceptually capture most if not all the relevant processes driving the emergence of a global TIS.

2 Theoretical Discussion and Analytical Framework

2.1 Theoretical discussion

In the innovation system literature, the TIS framework and the related system functions approach proposed by Bergek et al. (2008) has emerged as the most suitable for analyzing the dynamics of innovation in emergent technology fields (Coenen, Benneworth, & Truffer, 2012; Coenen & Díaz López, 2010). One of the key distinguishing features of the system function approach is its ability to capture the *dynamic evolution* of an innovation system. Among other things, it has been applied to analyze the development of renewable energy technologies in Germany (Jacobsson and Bergek, 2004).

According to Bergek et al. (2008), a TIS refers to "a socio-technical system focused on the development, diffusion and use of a particular *technology*" (p.408) (emphasis added by the author). This may be distinguished from other system of innovation approaches, which focus on innovation in a particular sector (Malerba, 2006), country (Nelson, 1993) or region (Asheim & Gertler, 2006). Based on this technology-based delineation of the innovation system, Bergek et al (2008) have developed an analytical approach, which defines seven key processes, or "functions," with a "direct and immediate impact" (p.409) on the dynamics of TIS development (i.e. the development, diffusion and use of a chosen technology). These seven "system functions" are considered the most important drivers of development and change in the TIS and serve as a heuristic device for analyzing the dynamics of TIS development. Each system function represents a synthesis of theoretical concepts and key findings from the innovation system literature as well as work from related fields, including political science, sociology, and organization theory (a short summary of each of the seven system functions is provided in the box on the following page).Finally, the functions are interlinked and may be mutually reinforcing. Hence, positive feedback loops within the TIS may set in motion a process of "cumulative causation" (Jacobsson and Bergek, 2004, p. 823), thus enabling a period of particularly dynamic development of the TIS.

The system functions approach has been applied in a long list of empirical case studies, mainly on emergent TIS at the national and regional level. These studies have shown that it provides a useful analytical framework for analyzing TIS development in early stages of system formation, when the relevant dynamics are largely (if not entirely) confined to national boundaries. However, in more advanced stages of system formation, inter-linkages with TIS in other countries gain in importance. In this context, it no longer suffices to analyze the TIS in an individual country, but it becomes necessary to understand the dynamic interaction between multiple TIS. Although, in principle, a TIS spans geographic boundaries (Carlsson & Stankiewicz, 1991; Hekkert et al., 2007), in the past most studies have not considered cross-country interactions or other international influences in their treatment of a country-specific TIS (Coenen et al., 2012). Multi-country studies have largely taken a comparative approach without exploring the dynamic inter-linkages across countries. The few studies with a truly international focus on the other hand have largely abstracted from the national-level and have focused attention on the activities of key firms within an international context (see for example Köhler et al., 2012).[1]

[1] The resulting studies have important similarities with the sectoral innovation system approach.

Box: The seven system functions (Bergek et al. 2008)

Knowledge development and diffusion refers to the evolution of the knowledge base underlying the TIS, how this knowledge is transferred to new actors and how it is utilized for promoting innovation and technological change.

Influence on the direction of search refers to pressures and incentives to invest in the development of particular technologies and which provide guidance for actors engaged in technology development and innovation within the TIS.

Entrepreneurial experimentation refers to risk-taking by individuals and firms resulting in certain types of entrepreneurial ventures and the development of experiments, which support TIS development by enabling a social learning process and addressing unmet needs within the TIS.

Market formation refers to the evolving customer demand for the related technology, both in terms of its size and the specific requirements requested by the developing customer base.

Legitimation refers to the process of building legitimacy for a given technology among stakeholders who have the ability to support or constrain the development of the TIS as well as the broader public in so far as it represents an influencing factor for TIS development.

Resource mobilization refers to the process of mobilizing different types of resources, which are important for the development of the TIS, most importantly financial and human resources.

Development of positive externalities refers to the development of external economies resulting from system development and which enhance the ability of actors in the system to support the remaining system functions by lowering barriers of entry, providing easier access to needed resources or inputs, reducing uncertainty, etc.

This paper argues that a pure international focus may be an appropriate approach in certain well established technology fields, where national-level dynamics have lost considerably in importance. However, in more advanced yet still formative stages of a global TIS, national-level systems retain a considerable degree of autonomy. This is particularly true in markets for environmental technologies, where market formation is heavily dependent on national-level policy choices rather than broader market trends (Jänicke & Lindemann, 2010). Simultaneously, it has been shown that the diffusion of environmental policies may lead to the development of similar, policy-driven markets as the related technology gains in maturity (Jänicke & Jacob, 2004). In tandem with the emergence of an increasing number of country-level TIS, cross-country linkages gain in importance, leading to dynamic interactions and feedbacks between different innovation systems.

Bergek and Jacobsson (2003) acknowledge the importance of considering different phases of industry evolution when analyzing the functional dynamics of a TIS. They identify two key phases and point out the different roles played by various functions in this context. The first phase is characterized by experimentation with frequent entries and exits of firms and a relatively large variety of competing technological alternatives. This is followed by a growth phase, in which firm entries as well as technological variety are reduced, industry consolidation takes place and diffusion and firm expansion take center stage. The proposed framework addresses the latter of the two phases of TIS development, highlighting the importance of cross-country linkages during this phase. In fact, it is argued that developments in this growth phase cannot be understood without an analysis of the increasing transnational linkages in the system and the resulting process of value chain segmentation, which accompanies this second phase of industry evolution.

The lack of such a spatial perspective has been identified as an important weakness in the current TIS literature (Coenen et al., 2012). In their spatial critique of the TIS framework, Coenen et al., (2012) point out the need to consider different geographical contexts and scales when analyzing the structures and dynamics of a particular TIS. To fill this gap in the literature, a number of studies have emerged, which have focused particular attention on the transnational linkages within emerging TIS. Using social network analysis as a tool, Binz, Truffer, & Coenen, (2013) have demonstrated not only that transnational linkages are relevant at different stages of TIS development. They have also shown that the spatial configuration as manifested in the network of national and transnational linkages change quite rapidly as the TIS evolves. In addition studies have emerged, which analyze the role of transnational linkages in the development of a particular country-level TIS (Binz, Truffer, Li, Shi, & Lu, 2012). The proposed study goes a step further by providing a dynamic analysis of a global TIS, albeit through the lens of two key countries (i.e. China and Germany). It highlights the importance of transnational interactions and mutually reinforcing feedbacks between China and Germany as key drivers of global TIS development.

In doing so, it also goes beyond the broader literature on the international dimensions of industrial development and technological change. Past studies in this area have primarily focused on the firm level, i.e. the international investment behavior of primarily multinational firms. Vernon's product lifecycle hypothesis, which focused primarily on the behavior of US-based firms, represented the first attempt to link the dynamics of industrial innovation and product lifecycles to concurrent changes in the location of production. He hypothesized in the 1960s that US firms were pioneers in the development of innovations, which were labor-saving and which responded to the "high-income wants" of US customers. Moreover, as products gained maturity and developed into global products, these firms were likely to shift production centers to low-cost locations (Vernon, 1966). By the late-1970s, he had revised his hypothesis in light of the increasingly global outlook of (multinational) firms. He acknowledged that firms with a global production network may not only shift production to low-cost locations earlier in the product lifecycle, but they might also develop innovations tailored to the particular needs of other countries than the US. Nevertheless, his premise that innovations were likely to be initially produced in a high-income target market before production was shifted to a lower cost location remained intact (Vernon, 1979).

The product lifecycle hypothesis has since been broadened to cover multinational firms more generally and adapted to account for the increasingly global nature of production networks. Based on Vernon's hypothesis, the concept of a "lead market" has been developed to identify markets for the development and introduction of particular innovation designs (Bartlett & Ghoshal, 1990; Beise, 2004; Meyer-Krahmer & Reger, 1999). Initially, the related literature remained focused on firm-level behavior. The country-specific characteristics of these lead markets were used to explain the decisions of multinationals regarding the location of R&D facilities.

Beise (2004) took this discussion a step further by abstracting from the firm-level and developing a set of country-level factors – or "lead market advantages" - for understanding the international success (i.e. diffusion) of certain technological innovations. The underlying assumption has remained, however, that innovations emerge in certain (industrialized) countries, which is followed by their international diffusion. The approach assumes that innovations emerge and establish themselves first in a particular lead market without significant interaction occurring with other markets. It contends that national or regional markets bring forth competing innovation designs before one of the country-specific designs establishes itself as a globally dominant design. In other words, the framework acknowledges competition but not the dynamic inter-linkages and feedbacks between country-level innovation systems.

The following case study on solar energy will demonstrate that this linear model of innovation (step 1) followed by diffusion (step 2) does not do justice to the dynamic process of internationalization during the growth phase of this emergent TIS. Rather the picture that emerges is one of increasingly interlinked and mutually supportive TIS. Although the role of a lead market remains relevant for stimulating the transition from the formative to the growth phase, the subsequent international dynamics of TIS development are decidedly more complex than assumed by Beise and other scholars in the field. The diffusion of the particular innovation, i.e. the gradual formation of an international market, may not progress in tandem with the spatial reconfiguration of industry. Instead, demand- and supply side dynamics diverge to a considerable degree, and TIS development is characterized by a dynamic process of co-evolution in which different countries fulfill different and evolving functions within an emerging global TIS. Moreover, as this study of the solar PV sector in Germany and China will demonstrate, emerging economies are not primarily recipients or mere adapters of foreign technology as the discourse of catching-up or latecomer industrialization might suggest (Fu, Pietrobelli, & Soete, 2011; Watson, Sauter, & Centre, 2011). Rather the study suggests that China has in fact played a key role in driving overall TIS development.

2.2 A co-evolutionary framework for TIS development

To capture these dynamics, the concept of a global multi-level TIS is proposed. This acknowledges that a global TIS is composed of a number of sub-systems at the national and sub-national levels, which retain a certain degree of autonomy. In fact, in an emergent and policy-driven TIS, institutional changes at the national-level have important impact on TIS development. As acknowledged in relational approaches to economic geography (Bathelt & Gluckler, 2003; Yeung, 2005), however, actors and networks are frequently not limited to a single geographic scale. They may entertain linkages across multiple scales, often drawing on a physical presence in different localities. Such linkages represent the inter-connections between different sub-systems within a multi-level TIS and allow developments in national (or sub-national) TIS to exert influences upon each other. They play an important role in the development of a global TIS, increasing in strength, number and complexity during the growth phase of a TIS.

In other words, the multi-level TIS concept rests on the following conceptual adaptations or clarifications of the TIS concept. It rejects the idea that an emergent, global TIS can be described independently from country-specific framework conditions and dynamics. At the same time, it challenges the idea that TIS dynamics during the growth phase of an industry can be adequately considered at the level of a single country. Rather it is essential to consider developments in multiple countries and how these co-evolve.

To do so, it is necessary to focus attention on the linkages that enable such cross-country interactions. It does not suffice to acknowledge the existence of cross-national networks, but it requires an acknowledgment of how these networks are configured and how interactions within these networks influence overall TIS development. The paper offers a basic analytical framework further outlined below for describing the most important linkages between Germany and China as well as other key countries. In addition, it highlights the fact that as transnational linkages increase, dynamic feedbacks across countries also grown in importance. Due to the continuing importance of policy, domestic actors and institutions retain significant influence on national TIS development. However, increasingly the interventions by domestic actors are also shaped by important developments abroad.

Finally, the paper introduces a conceptual adaptation to the seven system functions, as they have been proposed by Bergek et al. (2008). It proposes an eighth system function, which is labeled as “development of scale economies and cost reduction”. This function highlights the crucial role that cost reduction plays in enabling the diffusion of a technology and hence the growth of the related TIS. Cost reduction may result both from core technological advances, process innovations as well as the increasing scale of production. Arguably, this function is partly overlapping with other system functions, like the development of positive externalities, knowledge development or resource mobilization. The author, however, takes the position that overlaps and inter-dependencies across system functions are in fact inherent to the framework. Notably, the development of external economies is both supported by the remaining functions and reinforces them.

In other words, the system functions do not represent mutually exclusive analytical categories derived from a consistent theoretical basis. Rather, as indicated above, they function as a heuristic device for better understanding TIS dynamics. In this context, it is considered legitimate and useful to add this important system function. As the following analysis of the TIS for solar photovoltaics demonstrates, the changing geographical pattern in the development of scale economies and cost-reduction plays a key role in understanding the overall dynamics of TIS development.

2.3 Scheme of analysis and structure of the paper

In the remainder of the paper, these new and adapted concepts are applied to frame the empirical analysis of an evolving global TIS in solar photovoltaics. In doing so, it focuses on developments in Germany and China from 2004 to 2010, as these countries have represented the most important drivers of change during the most dynamic period of TIS development. Germany has represented the lead market for solar photovoltaics during this dynamic growth phase, accounting for more than 50 percent of the worlds installed capacity until 2010. Moreover, it remains the most important producer of production equipment, inverters and a number of components. China, on the other hand, has risen to the largest supplier of solar photovoltaic cells and modules, having captured more than 50 percent of these markets.

The paper begins with a review of system functions at the national level in both Germany and China in the period between 1999 and 2003. Building on this introductory section, the main part of the empirical analysis traces the changing functional dynamics of the TIS in Germany and China during the period of 2004 to 2010. It shows how these dynamics have affected overall TIS development as well as the important geographical shift of the main production center to China. The analysis will first treat developments in Germany and China independently, alluding to foreign drivers of system functions where necessary. Following this, an overview and systematization of the most important transnational linkages is provided. The paper closes with a description of the key feedbacks and inter-dependencies between the TIS development in Germany and China, enabled by these linkages and which have shaped developments in the two countries as well as the global TIS.

In this way, the paper is able to trace how a process of co-evolution involving these two countries has shaped the growth and geographic reconfiguration of a global, multi-level TIS in solar photovoltaics. Ideally, the analysis would also include an in-depth treatment of other key countries, which have played an important role in TIS development, such as Italy, Spain, the US, Taiwan and Japan. Since this is beyond the scope of the paper, it focuses on Germany and China, considering important developments in third countries where appropriate. Although this cannot do justice to the full complexity of global TIS development, it provides a sufficient empirical basis for understanding the core dynamics of growth and internalization in the TIS for solar photovoltaics, while sketching out a framework for analyzing the suggested co-evolutionary dynamics of change.

3 Setting the scene: functional dynamics of the TIS for solar photovoltaic technology in China and Germany from 1999 to 2003

The following section provides a snapshot of the Germany’s and China’s TIS for solar PV in 2003. It outlines the most important developments within the eight system functions, while introducing key actors, networks and institutions.

3.1 Germany

3.1.1 Legitimation

The legitimation of renewable energies in general took an important boost with the emergence of the first federal government with participation from the Green Party in 1998 (Fuchs & Wassermann, 2012). These favorable political conditions represented an important backdrop against which the solar energy sector was able to take important positive developments during the period. During its first term, the government took the decision to phase-out nuclear energy, while reducing the country's CO2 emissions, so that ambitious renewable energy targets became inevitable (Mautz & Byzio, 2005). By 2010, the government wanted to achieve a share of at least 12,5 percent electricity from renewable sources (Government of Germany, 2002, p. 97). A further boost came with the transfer of the renewable energy portfolio to the Green Party-led Ministry of Environment after the 2002 elections (Bruns, Ohlhorst, Wenzel, & Köppel, 2011, p. 205). Moreover, with the Green Party's electoral victory in 1998, Hans-Josef Fell, one of the key protagonists in Germany's grassroots solar energy scene, became a member of the German parliament, able to influence further developments at the federal level (Mautz & Byzio, 2005, p.79) and act as a policy entrepreneur in support of the sector (Mintrom & Vergari, 1996). Finally, in terms of state-level policy, Nordrhein-Westfalen represented the frontrunner with is program for renewable energy and energy efficiency managed by its state energy agency (Fuchs & Wassermann, 2012; Mautz & Byzio, 2005).

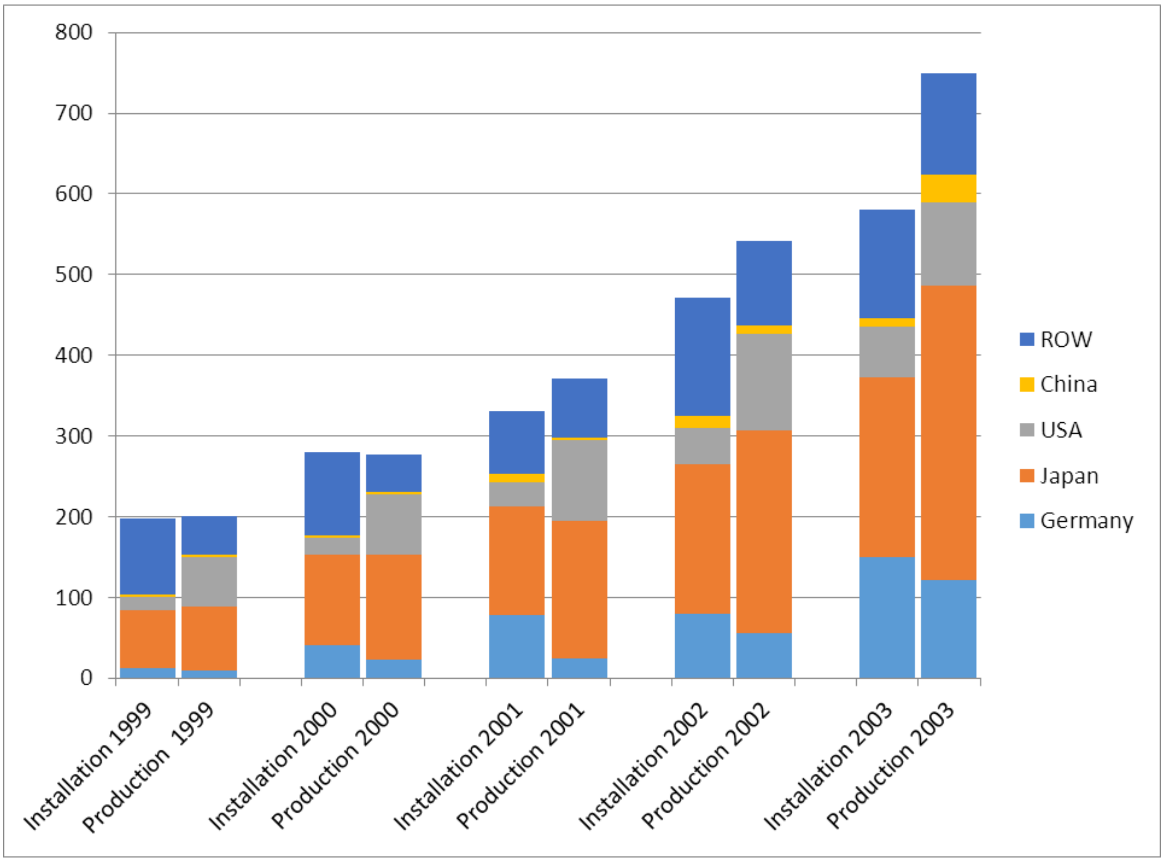
The growing solar energy sector also led to the creation of the Federal Solar Industry Association (Bundesverband Solarindustrie, BSi), which consolidated the activities of several existing industry groups (Bruns, Ohlhorst, Wenzel, & Köppel, 2011, p. 203). With employment reaching 10,000 to 12,000 in the German solar energy sector (IEA-PVPS, 2004, p. 18), this new organization added to the growing strength of existing lobbying organizations, including the German Society for Solar Energy (Deutsche Gesellschaft für Solarenergie, DGS), the Association for Solar Energy (Solarenergie-Förderverein, SFV) and the German-led EUROSOLAR as well as hundreds of local solar initiatives (Drücke, Nurr, & Stryi-Hipp, 2004).

Another factor which allegedly helped in garnering political support for the sector was the threat from major PV suppliers Siemens and Angewandte Solarenergie GmbH (ASE, later RWE Schott and Schott) in the mid-1990s to discontinue production lines in Germany and concentrate their activities in the more promising US market (Fuchs & Wassermann, 2012, p. 235; Ristau, 1998). At the same time, these negotiations represented an expression of remaining reservations among politicians, mainly due to the high costs of solar energy compared to wind power. The reservations also found expression in the renewable energy law (EEG) passed in 2000, which limited the solar feed-in tariff to an additional 350 MW of installed capacity.

3.1.2 Market formation

Despite these reservations, the period from 1999 to 2003 represented a preliminary growth phase of the German TIS for solar PV (see Figure 1). The key driver of market growth was the government-funded 100,000-roof program, which was complemented by a feed-in tariff of DM 0,99 (approximately €0,50) per kWh starting in 2000. The former represented a capital subsidy in the form of a soft loan program operated by KfW, the German state-owned development bank. This program ran from 1999 to 2003 until the cap of 350 MW of additional installed capacity had been reached. During this period, it enabled the dynamic development of the German market for privately-owned (i.e. non-commercial), grid-connected rooftop PV systems, which received the most favorable financing conditions under the program (Bruns et al., 2011, pp. 197-199; KfW, 2004, p.45). Additional market support during this period came from a number of federal states, most importantly Nordrhein-Westfalen with its REN Program (Program for the Rational Use of Energy and Use of Inexhaustible Energy Sources) as well as a growing number of municipal governments who had introduced cost-covering feed-in tariffs during this period (Bruns et al., 2011; Mautz & Byzio, 2005). As a result of these programs, Germany's cumulative installed capacity had reached more than 400 MW by the end of 2003 (Federal Ministry of the Environment, 2012).

Figure 1: Global Annual Photovoltaic Installations and Production by Country from 2000 to 2003 (in MW)



Source: Earth Policy Institute Database. Available at: http://www.earth-policy.org/data_center/

3.1.3 Entrepreneurial experimentation

The growing small-size, rooftop market was primarily being supplied with cells and modules produced by the solar divisions or subsidiaries of well-established multinational firms from Japan (Kyocera, Sharp), the US/Europe (BP Solar, Siemens/Shell Solar), and the German firm ASE (later RWE Schott and Schott), a subsidiary of RWE, one of Germany's four large energy companies. These large firms accounted for about two thirds of sales throughout the program's lifetime (KfW, 2004, p. 49). In addition, the market enabled the growth of a number of solar manufacturing start-ups, which had entered the market during the mid- to late-1990s, including firms like Q-Cells, Solon, Solarfabrik, Conergy, Solarwatt, ErSol, Solara, to name a few. A handful of firms were also founded during the early 2000s. Most importantly SolarWorld, which had functioned as an installer and distributor during the 1990s, entered the manufacturing business with the acquisition of production lines from a number of existing firms, including Bayer Solar. Moreover, Wacker Chemie, an established producer of polysilicon, increased its production for the PV industry (Räuber, 2005, p. 163-164). Finally, by 2003, most of today's major German PV equipment suppliers had entered the market. Most of them were established firms with experience in adjacent or related markets like semiconductors, glass manufacturing and wet chemistry.

With these old and new players, Germany had substantial production capacity along the entire value chain. By 2003, Germany had replaced the US as second largest producer of cells and modules, accounting for over 80 MW and 110MW of annual production (IEA_PVPS, 2003, 2002). Nevertheless, in 2003 Japan still accounted for over 50 percent of global production of cells and modules, and more than half of Germany's demand was being met by foreign-produced products (KfW, 2004, p.49).

3.1.4 Resource mobilization

As indicated above, resource mobilization on the demand side was primarily enabled by the KfW loan program and was dominated by small scale investments from private households. Towards the end of the program, not only commercial investors (26%) but also investment vehicles created by private households for tax purposes (13%) increased their share of investments (KfW, 2004, p. 43). The latter included local initiatives aimed at establishing community-owned solar energy plants (Mautz & Byzio, 2005, p. 81-82).

On the supply side, the boom of the "New Economy" during the 1990s helped facilitate access to capital from private investors. While a number of IPOs were launched during this period, including SolarWorld, Sunways and Solarfabrik, the bulk of external funding came from private sources (Jennings, Margolis, & Bartlett, 2008, p. 6). Combined with rising corporate profits, this enabled steady investment growth, reaching an annual volume of €159 million in 2003 (Ruhl, Lütter, & Schmidt, 2008, p. 12). During this period, investments in German solar firms dominated the global industry, accounting for 77%, 87% and 38% of global investments in the years 2001 to 2003[2]. Investments in production lines were frequently financed with subsidies mainly financed by *Länder* (German federal States) governments. Nordrhein-Westfalen, Bavaria as well as a number of East German states emerged as facilitators of the growing number of production facilities (Brachert, Hornych, & Franz, 2013, p. 8; Ristau, 1998, p. 57-66). For example, the firm Q-Cells, founded in Thalheim, Sachsen-Anhalt in 1999, financed approximately one third of its investments with EU structural funds and subsidies from the government of Sachsen-Anhalt (Nölting, 2009, p.44). Other examples are Berlin's Solon, which received €6 million in public start-up funding, and ASE (later Schott), which received public funding from Länder-governments in Baden-Württemberg (€10 million) and Bavaria (€20 million) as well as the Ministry of Education and Research (€12 million for two projects) (Ristau, 1998, p. 64)[3].

3.1.5 Development of scale economies and cost reduction

As outlined above, up to 2003 the German market was still dominated by large, international players operating in an oligopolistic market. Hence, the dynamics of cost reduction within the German market have to be viewed through this international lens. As data from the 100,000-rooftop program show (see Table 1), both module and overall system prices declined during this period. However, module prices declined less rapidly and actually increased by approximately 10 percent in 2001, thus departing from the international trend and causing an overall increase in system prices of about 6 percent for the year[4].

This is likely a result of the important boost in demand without a corresponding development of local distribution channels or domestic supply. This was corrected from 2002, which is reflected in particular in the rapid reductions in installation charges. Despite an improved balance between domestic supply and demand (see Figure 1 above), module prices in Germany remained fairly stable compared to the 1990s (see Figure 2), when more significant cost reductions could be achieved by Japanese and US producers. Investments in the German solar industry were relatively fragmented during this period with little potential for capturing economies of scale. Although Germany had the largest number of firms, ASE/RWE Schott remained the only firm with more than 20 MW of production capacity (until 2002). This compares to three firms in the US and five firms in Japan, including Sharp with more than 100 MW of production capacity (IEA-PVPS, 2002). In 2003, Q-Cells became the second firm with a cell production capacity of more than 20 MW in Germany (IEA-PVPS, 2003).

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[2] Percentages are based on author's own calculations based on data from Ruhl et al. (2008) and Jennings et al. (2008).

[3] This includes a slight correction of the information in Ristau (1998), where he writes that €10 million was supplied by the government of Nordrhein-Westfalen for a factory in Gelsenkirchen. According to a former employee, this represents a factual error. Rather €10 million was supplied by the government of Baden-Württemberg for a factory in Heilbronn.

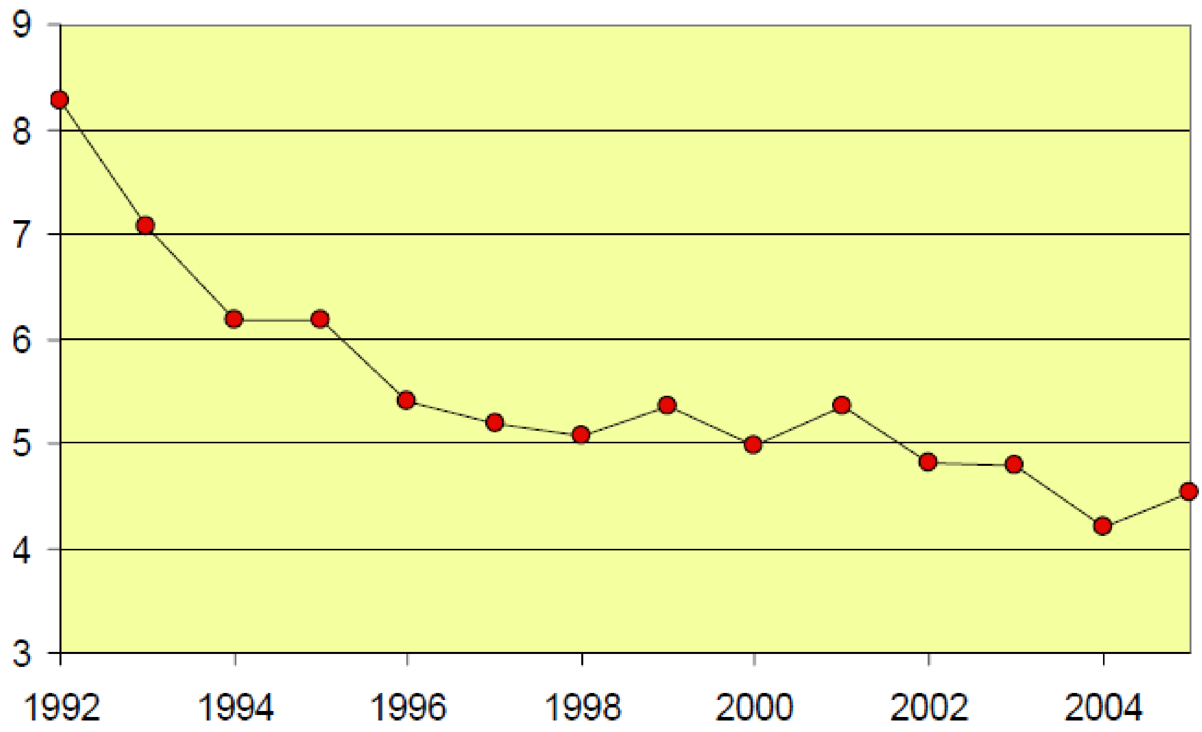
[4] Authors calculations based on KfW (2004, p. 48).

Table 1: Average costs for commercially-owned PV systems from 1999 to 2003 in € per kWp (only system up to 10kWp

Year	Average Size (KWp)	Module price (percent change)	Inverter price (percent change)	Installation (percent change)	Other components (percent change)	Total Cost
1999	3,1	4758	831	693	602	6884
2000	3,8	4499 (- 5%)	641 (- 22%)	484 (-30%)	509 (-15%)	6133 (-11)
2001	4,2	4939 (+10%)	630 (-2%)	474 (-2%)	479 (-6%)	6522 (+6%)
2002	4,9	4413 (-11)	564 (-10%)	373 (-21%)	429 (-10%)	5779 (-11%)
2003	5,7	3816 (- 14)	527 (-7%)	303 (-19%)	330 (-23%)	5021 (-13%)

Source: KfW (2004, p. 48)

Figure 2: Average module prices in Germany from 1992 to 2004 in € per Wp



Source: Kruck & Eltrop, (2004, p. 27)

3.1.6 Knowledge development and diffusion

In terms of research and development, Germany had also developed substantial capacity by the early 2000s. Most of the major German solar research institutes had been founded. These included institutes focused mainly or exclusively on solar energy research, such as the Fraunhofer Institute for Solar Energy Systems (ISE), the Leibniz Institute for Solar Energy Research in Hameln and the Centre for Solar Energy and Hydrogen Research Baden-Württemberg (ZSW), as well as institutes with important activities on photovoltaics within a broader research agenda, including the Bavarian Centre for Applied Energy Research, the Hahn-Meitner Institute in Berlin, the Leibniz Institute for Crystal Growth (IKZ), the Institute of Technical Thermodynamics of the German Aerospace Centre, the Forschungszentrum Jühlich, among others. Moreover, since 1990, the research community was organized in the Research Association for Solar Energy (FVS, renamed Research Association Renewable Energy in 2009), allowing for coordination not only among the research community but also with the industry and policy makers. In terms of public R&D spending, Germany ranked third behind Japan and the US for most of the 1990s (Räuber, 2005, p.152). Correspondingly, Germany consistently took third place in international patent registrations[5].

3.1.7 Influence on the direction of search

During this first growth phase, two key factors influencing the direction of search in the sector can be identified. On the demand side, the governmental 100,000 roof program became the major driver of market growth, so that its funding guidelines became a crucial determinant of market developments. As indicated above, the program prioritized privately-owned, rooftop systems, which accounted for the vast majority of installations during the program's funding period.

In the sphere of technology development, public R&D funding remained the central driver, supplying more than twice as much funding compared to private actors[6]. The government's 4th Energy Research Program (1996-2005) supplied funding to the PV sector via the Ministry of Environment and the Ministry of Education and Research. While the former pursued a balanced approach focused on cost reduction in silicon-based PV, system integration and development of thin film technologies, the latter exclusively financed the development of thin film technologies (Federal Ministry of Economy and Labor, 2005). In terms of funding, approximately 47 percent of overall funding went to the development of silicon-based technologies, 40 percent to thin film and other alternative PV technologies, while the remaining funds supported system integration (Prognos, Fraunhofer ISE, IE, IWR, & WindGuard, 2007).

3.1.8 Positive externalities

During this early period, a key positive externality was generated by policy experiments at the local level. The proliferation of local cost-covering feed-in tariffs provided the needed experience to convince policy makers at the federal level of the viability of such a scheme. Moreover, it demonstrated how a scheme differentiated by type of technology could work and enabled policy makers to respond rapidly with the amendment of the Renewable Energy Act when the 100,000 roof program expired (Mautz & Byzio, 2005, p. 79). Within the in-

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[5] Based on patent data provided by the Fraunhofer Institute for System and Innovation Research.

[6] Based on company data in Ruhl et al. (2008, p. 20) and data on public spending in IEA PVPS(1999, 2000, 2001, 2002, 2003). Given the fact that firms may include public R&D subsidies in their company figures on R&D spending, the ration be skewed even more strongly towards public R&D funding.

dustry, a key step forward was the emergence of equipment suppliers with divisions dedicated exclusively to the PV sector, significantly lowering the barriers to entry in the sector. Previously, newly founded firms had been highly dependent on accessing the expertise of established international players like Siemens/Shell, BP Solar and others[7]. Finally, the increasing number of system integrators as well as the first commercially oriented financing schemes emerged, paving the way for rapid market growth from 2004 (Mautz & Byzio, 2005).

3.2 China

3.2.1 Legitimation

In China, the government's endorsement of renewable energy in general and solar energy in particular was still comparatively weak in the period up to 2003. In principle the potential role of solar energy had been acknowledged, however primarily as an option for promoting rural electrification in remote areas. In 1996, the government launched the New and Renewable Energy Development Program (1996-2010) (World Bank, 1999), and following from this a number of rural electrification programs were launched. Important support for these initiatives came from the international level. The Brightness Program, aimed to supply 23 million people with renewable energy by 2010, was part of an international initiative launched at the World Solar Peak Conference in Zimbabwe in 1996 (NREL, 2004a). Other important support came from programs sponsored by the German development agencies, the World Bank's China Renewable Energy Development Program (CREDP) (World Bank, 1999)and the UNDP's Capacity Building for the Rapid Commercialization of Renewable Energy, which facilitated the creation of China's Renewable Energy Industries Association (CREIA) in 2000 (UN, 2007). Renewable energies gained further legitimacy when the State Economic and Trade Commission (SETC) proposed its Tenth Five-Year Plan for Sustainable Development. This included the Tenth Five-Year Plan for New and Renewable Energy Commercialization Development (2001-2005) with the goal to increase the production capacity for solar cells to 53 MW (NREL, 2004b). Despite these targets, however, the government did not consider solar PV a mature technology with potential for large scale commercialization (Martin, 2011, p. 27). In other words, while a number of foundations for boosting the legitimacy of the PV sector in China had been laid, it remained a niche technology without any strategic relevance for the central government.

3.2.2 Market formation

Rural electrification programs represented the main source of demand for solar PV systems in China up to about 2007. The first major deployment program was the Brightness Program, which began piloting in 1996 and was finally launched in 1999, followed by the

[7] Based on interviews with industry experts.

Township Electrification Program or Song Dian Dao Xiang (2001-2004). These government-financed programs were based on a competitive bidding process, where system providers competed for tenders to install off-grid systems in unelectrified villages. The focus was on solar home systems, village PV systems and a small number of hybrid PV-wind systems (Ku, Lew, & Ma, 2003; NREL, 2004a, 2004b; Seng, 2009). Another scheme supported by the World Bank-financed CREDP provided a subsidy of $1,50 to $2 per Watt to accredited PV system companies, which enabled a market for solar home systems in remote rural areas (World Bank, 1999). These three major programs were complemented by a number of rural electrification projects funded by bilateral donor agencies, most of which came online from 2001 (Shyu, 2010).

As a result of these various programs, the country's cumulative installed capacity increased from 19MW in 2000 to 52 MW in 2003 (Honghua, Dou, Sicheng, & Fang, 2012, p.7). The vast majority of installations were in the area of off-grid applications (96 percent), mainly rural applications (51 percent) and applications in the telecommunications sector (Sicheng, 2006). In terms of global market share, these developments remained insignificant, representing well below 1 percent of global installed capacity. For the country's pioneering firms, however, it represented a key learning opportunity. Until 2003, Yingli, Suntech and Trina generated the majority of their revenue from domestic sales. In fact, until 2002, Trina and Suntech still depended exclusively on domestic demand.[8]

3.2.3 Entrepreneurial experimentation

With growing domestic and international demand, Chinese production of solar modules and cells began increasing from the low levels of the late 1990s. Between 1999 and 2003, production grew from approximately 2,5MW to an estimated 35MW (Li, 2004, p.78). This compares to 20 MW in India and more than 110 MW in Germany (IEA-PVPS, 2003). Simultaneously, the company mix began to shift. The first wave of companies, created in the 70s and 80s, had been exclusively state-owned and focused exclusively on the small domestic market with entire production lines imported from the US (Marigo, 2007, p. 146). This was followed by a second wave of state-owned firms, which emerged at the local level to supply modules and systems to regional deployment programs within the scheme of the Brightness Program (Zhang & White, 2012, p. 11).

Finally, in the late 1990s to early 2000s, a first group of privately-held enterprises emerged, including both domestic companies and a number of ventures with foreign participation, such as Canadian Solar Inc. (CSI) (Canada), Kyocera-Tianjin and Hebei Ningjin Songgong Semiconductor (both Japan). The most important entrants were Trina (1997), Yingli (1998), Suntech (2001) and CSI (2001).While these new companies profited from early sales in the government-sponsored rural electrification programs (Zhang & White, 2012,

[8] Based on company annual reports. No exact sales data is available for Yingli prior to 2004.

p. 36), their commercial orientation soon led them to target the booming European market. In terms of their entry, they all pursued unique trajectories. Trina began as a system integrator for the Brightness Program, and CSI began producing solar batteries for the automobile sector. Suntech and Yingli both entered the business as module producers. However, Yingli had begun pursuing a strategy of vertical integration by 2002, while Suntech focused on adding further module production facilities.

While key production equipment was still imported mainly from Europe and the US, companies began sourcing components domestically as well (Davila, Foster, & Jia, 2009; Marigo, 2007). The ability to source auxiliary equipment locally, while striking a cost-effective balance between automation and the use of the relatively abundant supply of skilled labor was viewed as one of the main sources of competitive advantages by these pioneering firms (Davila et al., 2009; Suntech Power Holdings, 2005). Despite these dynamic changes in the country's solar industry, until 2003 domestic demand in the form of the various rural electrification programs actually outstripped supply. As a result, international players, including Siemens, Astropower, Sharp, Kyocera, Shell and BP Solar received accreditation as suppliers to the government-sponsored deployment programs and retained an important share of the market (Ku et al., 2003).

3.2.4 Resource mobilization

On the demand side, the largest share of funding for domestic market development came from the central government. This was complemented with funds from provincial governments in the Western part of the country as well as international donors. In addition, the World Bank's CREDP, which accounted for approximately 1,7MW of installed capacity by 2003 (Bhattacharyya & Ohiare, 2012, p. 682), was able to mobilize funds from firms and households. With only a partial subsidy, users were obliged to invest their own funds to purchase systems under the scheme.

On the supply-side, investments in manufacturing capacity were fully government or donor-funded until the late 1990s and had the character of demonstration projects (Li, 2004).The new generation of firms entering the industry at the turn of the century represented commercial ventures. Their emergence coincided with the transition from a centrally-controlled system of financing new technology-based ventures to an increasingly decentralized and more commercially-driven system of capital provision. In this evolving system, an increasing number of local government-, university- and corporate-backed venture capital funds collaborate with local governments and state-owned enterprises to facilitate the funding of promising start-up companies (White, Gao, & Zhang, 2005). Following this pattern, the early ventures in the PV industry, such as Yingli and Suntech, financed their companies with a combination of their private wealth and funding from state-owned VCs and local SOEs. Suntech's founder, Dr. Zhengrong Shi, for instance, is known to have approached a series of local governments until he received support from the Wuxi government in Jiangsu province in securing US$6 million in initial investment for his firm. Contributing US$400,000 of his own funds as well as 14 patents that he owned, Dr. Shi received a 25 percent stake and the position of CEO (Batson, 2006; Davila et al., 2009; Marukawa, 2012). Yingli's founder, Liansheng Miao, provided an initial investment of $600,000 before convincing a local industrial park operator, Baoding District Industrial Development Zone, to enter the venture as an equity investor (Zhang & White, 2012, p. 15).

3.2.5 Cost reduction and development of scale economies

According to reports on Suntech's firm history, developing a low-cost approach for module manufacturing had always been the declared goal of the firm's founder. In Dr. Shi's initial business plan in 2001, he had proposed to bring the cost per Watt down from $5 to $3 per Watt (Davila et al., 2009; Knight, 2011). With the help of Suntech's "flexible China-based, low-cost manufacturing model" (Suntech Power Holdings, 2005, p. 2), he allegedly achieved this goal by 2003 (Batson, 2006). After establishing a first 10MW production line 2002, the firm had quickly expanded its capacity to a total of 25 MW by December 2003. This second production line was less reliant on ready to use European equipment and integrated a number of lower cost, domestic components as well as used machinery purchased from Italy and Japan. Moreover, in an effort to leverage the availability of low-cost Chinese labor, the firm established a "semi-automated manufacturing model" (Batson, 2006; Davila et al., 2009; Suntech Power Holdings, 2005). In addition, the firm made efforts to reduce material costs by developing a process for utilizing lower grade silicon wafers. While less detailed information is available on Yingli's activities during this time, it pursued a similar strategy based on a "balanced combination of advanced automated manufacturing equipment and low-cost skilled labor" (Yingli Green Energy Holding, 2007, p. 111).

3.2.6 Knowledge development and diffusion

Knowledge development in the field of solar energy has been supported by the Chinese government since the late 1950s, albeit at a relatively limited scale. By the 1970s, first ventures into the development of manufacturing capacities were made. By 2001, approximately 30 institutes and universities were involved in R&D related to the PV sector. Public R&D funding has increased slowly but steadily, reaching an estimated US$2,4 million during the 9th Five-Year Plan (1996-2000) and US$5,2-6,2 million during the 10th Five-Year Plan (2001-2005).The focus of this public R&D support has mainly been on materials and the manufacturing process (Marigo, 2007, p 146-147). Moreover, since 2000, these activities have increasingly addressed specific bottlenecks in the development of China's PV value chain. Most notably, this has included activities to develop technological capacities in the production of equipment for the PV industry (Yang et al., 2003, p. 704) as well as a focused effort in the field of purified silicon production (de la Tour, Glachant, & Ménière, 2011; Fischer, 2012).

While these efforts may have supported the development of China's overall technological capacities in the sector, by themselves they were not sufficient to jump-start the dynamic industrial development since 2000. More important was the acquisition of key expertise from abroad, which occurred via two important channels. The first mechanism was the return of experienced, foreign-trained Chinese professionals (de la Tour et al., 2011, p. 764-765). Suntech's Dr. Shi is the most well-known example of this process. Before founding Suntech in 2001, he had acquired his PhD at the world renowned School of Photovoltaic and Renewable Engineering at the University of New South Wales (Australia) and spent almost 10 years as director of research at the Australian PV company Pacific Solar (Knight, 2011). Similarly, Dr. Shawn Qu, the founder and CEO of CSI, holds a PhD in material science from a Canadian university and gained extensive experience working on PV-related technologies in Canada. A second important channel was the import of equipment from suppliers in Europe and the US along with the engineering services to enable their efficient use. Under the able leadership of their foreign-trained executives, this enabled these early manufacturing firms to integrate the latest production equipment into their PV manufacturing lines. Additional support came from a number of German solar manufacturers who helped in bringing production processes up to European standards[9].

3.2.7 Influence on the direction of search

During this early period of industrial development, Chinese actors were mainly focused on establishing their first lines of production and attaining international standards of quality and efficiency, while reducing costs. China's rural electrification programs served as a learning ground for some of these early players, including Trina, Yingli and Suntech (Zhang & White, 2012, p. 36). However, the target market was the growing German market. Correspondingly, important aims of these companies in the early years were to obtain international quality certifications and develop international marketing channels (Davila et al., 2009; Yingli Green Energy Holding, 2007).

3.2.8 Development of positive externalities

During the period to 2003, the Chinese pioneer firms played a key role in developing positive externalities, from which the second wave of firms would reap the benefits in the following years. As Zhang & White (2012) have argued, these early movers played an essential role in overcoming the industry's "liability of newness" in China. They established firms in the solar PV sector as recognized high-technology enterprises and demonstrated the ability to compete with more established international players. Most importantly, this provided the basis for accessing funding and other forms of support from local governments. Other benefits included greater ease in attracting well-trained returnees and international industry experts (Zhang & White, 2012, p. 35) and easier access to equipment from European and US suppliers who began to establish distribution channels during this period.

[9] Based on interviews with industry experts.

4 The growth phase: the functional dynamics of the TIS for solar photovoltaic technology in China and Germany from 2004 to 2010

In the following section, the further development of the German and Chinese TIS from 2004 to 2010 is described in detail. Developments in both countries are described separately, while alluding to emerging transnational linkages between the two countries as well as key third countries, in so far as they support one of the eight system functions.

4.1.1 Legitimation

With the conclusion of the 100,000-roof program in 2003, the solar energy sector in Germany had built up significant momentum. Second only to Japan in terms of both market and industrial capacity, the sector had developed significant political weight. Correspondingly, sustaining the emergent solar industry played a central role in justifying the increase of the feed-in tariff for solar energy in late 2003 (Deutscher Bundestag, 2003, p. 1).

The subsequent growth of the solar industry added to the further professionalization of its lobbying organization. In 2006, another merger took place between the BSi and the Unternehmensvereinigung Solarwirtschaft (UVS), yielding the industry's current Bundesverband Solarwirtschaft (BSW) (Bruns et al., 2011, p. 204). By 2007, the BSW staff had reached 25 employees, and by 2009 the association represented a total of 750 companies in the solar industry[10]. Moreover, the activities of the BSW and its umbrella organization, the Bundesverband Erneuerbare Energien, received increasing support from the government. The associations launched joint campaigns with the Federal Ministry of the Environment, such as the solar energy week and a campaign promoting renewable energies. The latter led to the creation of an agency for the promotion of renewable energy (*Agentur für Erneuerbare Energien*) in 2008. In addition, in 2007, the German association of equipment producers created a section focused on the PV sector.

From 2009, support for the renewable sector weakened at the federal level, due to the election of a conservative government. Although no fundamental changes to the renewable energy law were made, the decision to increase the lifetime of the country's nuclear power plants in 2010 was widely perceived as a negative sign for the continued expansion of renewable energies. This threat was short lived, however. After the nuclear meltdown in Japan in 2011, the government not only reversed this decision in light of widespread public pressure, but the conservative political parties were also forced to accept the inevitability of Germany's so-called *Energiewende* (energy transition), establishing a firm national consensus in this regard (Ethics Commission for a Safe Energy Supply, 2011; Tenbrock & Vorholz, 2011).

[10] Based on http://www.solarwirtschaft.de/ueber-uns/historie.html.

Finally, with module producers beginning to cluster in the former East Germany, governments in Thüringen, Sachsen and Sachsen-Anhalt emerged as additional supporters of the industry. The visibility of the regional cluster was further strengthened with the creation of a cluster initiative entitled "Solar Valley Mitteldeutschland" in 2008, receiving support from the Federal Ministry of Education and Research (BMBF) as well as the respective *Länder* governments[11]. The importance of the Länder-governments in sustaining support for the solar energy industry has gained particular visibility from 2010, when the conservative government launched attempts to first reduce the PV feed-in tariff and then make more fundamental changes to the renewable energy law. In both cases, drastic changes were prevented by Länder-governments represented in the country's upper chamber, the *Bundesrat* (Bauchmüller, 2012; Bundesrat, 2010).

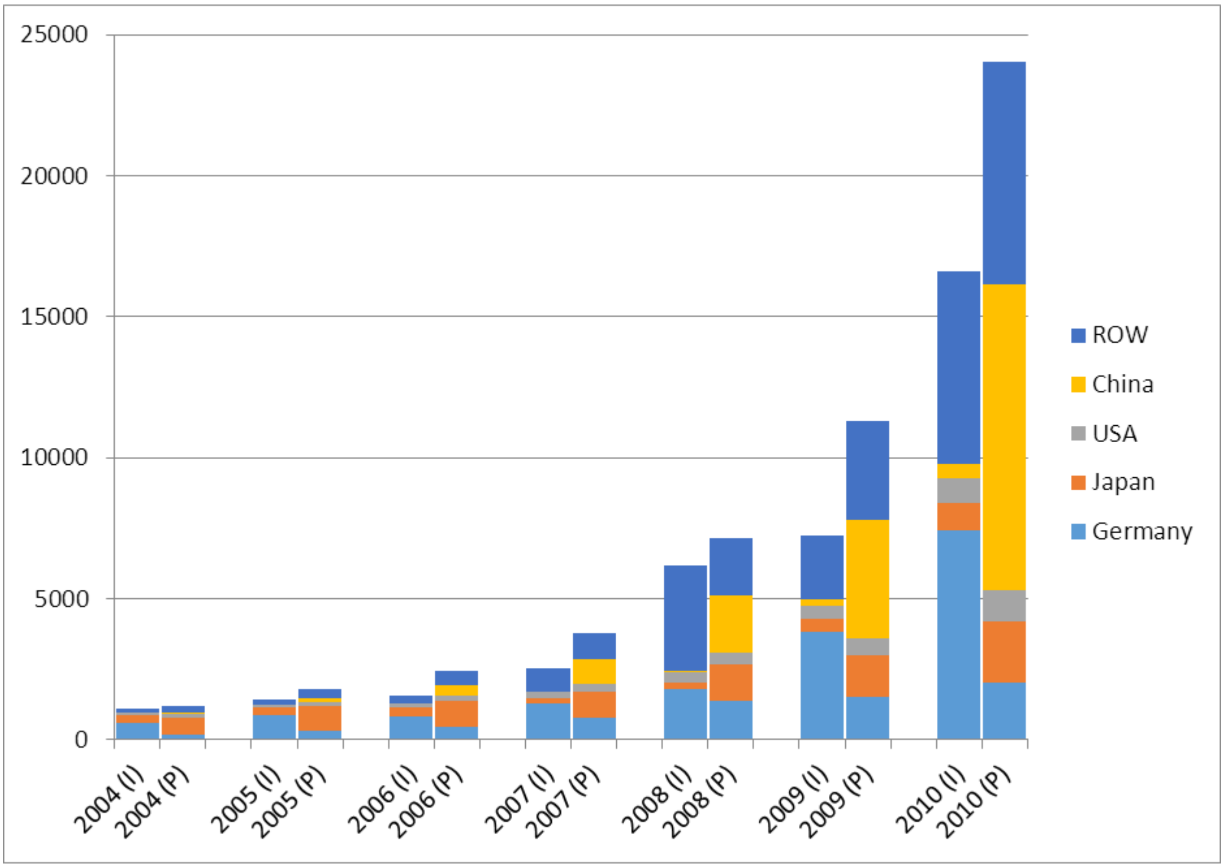
4.1.2 Market formation

After revisions to the solar feed-in tariff were confirmed by the Bundestag in December 2003, market growth in Germany took off in 2004 (see Figure 3). The feed-in tariff had been increased to a maximum of 57,4 cents per kWh for small rooftop systems of up to 30KW, while ground-mounted installations received 45,6 cents per kWh. Although these rates were subject to an automatic annual reduction of the feed-in tariff by 5 percent, the law no longer included any cap or other limit to the feed-in tariff, providing additional investment security to project developers. The result was a quadrupling of annual installed capacity in 2004 to 670 MW, making Germany the world's largest market for solar energy systems. In 2005, the market grew by additional 40 percent, yielding 951 MW of installed capacity (Federal Ministry of the Environment, 2012, p. 21). At the same time, a trend towards progressively larger PV systems reemerged with MW-scale systems accounting for approximately 15 percent of the market in 2004 and 2005 (Chrometzka, 2011). In 2004, the first 5 MW solar park, the world's largest at the time, was constructed (IEA-PVPS, 2004, p.9).

In 2006, the market slowed down slightly (Federal Ministry of the Environment, 2012, p. 21), due to supply shortages and rising module prices. However, by 2007, these price increases could be compensated by rising efficiencies in the balance of systems. This enabled overall system prices to decline in Germany, so that the market grew by a further 50 percent in 2007 and 2008 with the share of MW-plants increasing to over 20 percent of total installations in 2009. In 2009, with module prices suddenly declining sharply, the market grew by over 100 percent, reaching more than 4 GW of annual installed capacity. Despite various *ad hoc* measures to reduce the feed-in tariff , this trend continued in 2010 with over 7 GW of installed capacity that year (Federal Ministry of the Environment, 2012; Fraunhofer ISE, 2012).

[11] See http://www.solarvalley.org.

Figure 3: Global Annual PV Installations and Production Capacity by country from 2004 to 2010 in MWp



Source: Earth Policy Institute Database. Available at: http://www.earth-policy.org/data_center/

4.1.3 Entrepreneurial experimentation

In Germany, the market boom from 2004 to 2010 was primarily shaped by a small number of leading PV manufacturers, while the number of new entrants in the field of crystalline silicon-bases PV declined compared to the late 1990s and early 2000s. In addition, the sector was characterized by a dynamic development of German solar equipment suppliers. The overall sector was characterized by a high investment ratio, ranging from 14 to 25 percent[12]. Nevertheless, German investments in production capacity lagged behind the dynamic market developments described in the previous section, and domestic firms have consistently supplied less than 50 percent of German demand (EuPD, 2009).

On the manufacturing side, the most ambitious firms were Q-Cells and SolarWorld. Both invested heavily during these years, though pursuing very different strategies. Q-Cells placed its major focus on rapidly expanding capacity in its core business of producing silicon-based solar cells, while investing heavily in new technologies via investments in joint ventures and start-up companies. In 2007 and 2008, these investments made Q-Cells the

[12] Author’s own calculations based on Lütter et al. (2009, p. 11 - 12).

world's largest producer of solar cells with an annual capacity of 516MW and an export ratio of 60 percent, rising to 760MW and 70 percent in 2008 (IEA-PVPS, 2007, 2008). With the development of a facility in Malaysia, total cell production capacity had reached more than 1,2 GW by 2010[13].

SolarWorld, on the other hand, pursued a strategy focused on capacity expansion and vertical integration in the production and distribution of silicon-based solar modules. With its origins as a distributor of PV systems, the company had always maintained a presence in the downstream segment. This was further expanded with the acquisition of a 29 percent stake in the project developer Solarparc AG in 2006. Simultaneously, manufacturing capacity was progressively expanded mainly via acquisitions and across all steps of the supply chain. Moreover, the firm's initial emphasis on wafer production was reduced, as the relative share of cell and module production increased. By 2010, Solar World's wafer and module production capacity had reached almost 1 GW, while cells lagged slightly behind with 775 MW. This expansion strategy went hand in hand with the development of a second center of production in the US, which was acquired via the purchase of Shell Solar in 2006. Thereafter, about two thirds of total cell and module production and about a quarter of wafer production were situated in the US[14].

In addition to these two heavyweights, around 10 to 15 module producers progressively increased their capacity during this period, while expanding their activities in the downstream segments of the value chain. The largest of these was Solon with 412 MW (2010) followed by handful of producers with 200 to 250 MW production capacity. Companies with significant cell manufacturing capacities included Schott Solar (former RWE Schott), Sunways, ErSol and manufacturing newcomer Conergy. The latter had established its first fully integrated manufacturing line in 2007. Among these, Schott Solar and Conergy were the only vertically integrated companies until Germany's industrial heavyweight Bosch entered the sector in 2008. With the acquisition of ErSol (merged with wafer producer ASI Industries in 2006) and module supplier Aleo Solar, Bosch established itself as the third major German manufacturer.

In tandem with this expansion of manufacturing capacity, the German equipment suppliers also made important investments during this period. A number of equipment suppliers made entries into the PV sector, while a number of existing suppliers invested heavily in the expansion of their PV activities. The larger firms established divisions or even separate subsidiaries dedicated exclusively to the solar sector. By 2006, the three largest suppliers, Centrotherm, Roth und Rau and the Schmid Group, had developed offerings for turnkey production lines. To establish and further develop these offerings, these firms invested

[13] Data on production capacity is based on company annual reports.

[14] All information on SolarWorld is based on company annual reports.

heavily in firm acquisitions to obtain needed technological competences and increase the share of components produced in-house. Moreover, equipment offerings, in particular in the turnkey segment, went hand in hand with engineering and training services to support clients in putting new equipment and production lines into operation. Initially, these clients were primarily European manufacturers, however, as early as 2007 Asian manufacturers represented roughly half of total turnover, a figure which had risen to about 67 percent by 2011 (Wessendorf, 2012). In the turnkey segment, Asian manufacturers have represented an even larger share of demand[15].

4.1.4 Resource mobilization

On the demand side, the revised solar feed-in tariff provided the basis for an investment boom in solar PV installations. Investments in PV systems rose progressively from €1,5 billion in 2004. This was followed by a doubling of annual investment in 2005 and again in 2008, reaching an annual expenditure of €6,2 billion. In 2009, investments reached €9,6 billion and then peaked at €19,5 billion in 2010 before dropping back to €15 billion the following year (Federal Ministry of the Environment, 2005, 2006a, 2009a, 2010a, 2011a). As these numbers show, investments in installations in Germany appear to have been largely unaffected by the turbulence of the global financial crisis.

Partly, this may be a result of the fact that KfW has continued to provide low-interest loans for the financing of solar energy systems. Evaluations of the KfW renewable portfolio, which were conducted for the years 2007 to 2011, indicate that from 2007 to 2010 KfW provided finance for 40 to 50 percent of all PV systems installed in Germany during that period. Depending on the program, loans were capped at €50,000, €500,000, €1 million or €10 million. In the years 2009 and 2010, a special program in response to the financial crisis even offered loans of up to €25 million, thus helping to bridge potential financing gaps (Bickel & Kelm, 2010; Bickel et al., 2008; Bickel, Kelm, & Edler, 2009, 2011, 2012). Additional finance was provided by Germany's rural development bank (*Landwirtschaftliche Rentenbank*). In the peak years of 2009 and 2010, it provided farmers with loans for financing PV systems of €993 million and just under €1,2 billion, respectively (Landwirtschaftliche Rentenbank, 2011, p. 36). This amounts to approximately 10 and 6 percent of total investment in new installations in the respective years[16].

In addition, local banks and Sparkassen became important providers of capital for the large number of smaller, privately owned systems. As system sizes began to increase, project-based, non-recourse financing models became increasingly important. Due to the existing experiences with wind energy projects, acquiring the needed debt financing was not a sig-

[15] Based on interviews with industry experts.

[16] Author's own calculations based on Landwirtschaftliche Rentenbank (2011) and Federal Ministry of the Environment (2010, 2011).

nificant challenge. Important lenders included the State-owned HSH Nordbank and Nord LB as well as the Commerzbank, all with significant experience in the wind sector. In addition, the Southern-based Bayern LB and LBBW played an important role, due to their proximity to many of the projects[17].

Despite the increasing share of larger projects, equity for the majority of projects still came from individuals and farmers, accounting for 39 and 21 percent of installed capacity in 2010 (Solarpraxis, 2012, p. 28). Equity for the larger projects initially came primarily from project developers themselves. Additionally, the first local solar energy cooperatives emerged between 2003 and 2007 and increased rapidly from 2008. By 2010, an estimated 150 to 200 solar energy cooperatives existed in Germany, mainly located in the former West German states. The majority of these cooperatives were initiated by existing cooperative banks and mobilized investments in either a portfolio of rooftop systems or smaller ground-mounted solar energy parks (Holstenkamp & Ulbrich, 2010).

Finally, by 2008, closed solar funds, which collect equity capital from private investors, emerged as a significant source of private capital for larger solar projects. In this model, investors become partners in a company (typically in the form of a GmbH&Co KG), which functions as a special purpose vehicle (SPV) for one or several solar projects. In 2008, closed solar funds accounted for €68 million in equity, jumping to €477 million and €605 million in 2009 and 2010, respectively[18]. On the one hand, this dynamic development was as a result of the time lag between the decline in module prices and the reduction of feed-in tariffs, which made solar projects particularly attractive financial investments in 2009 and 2010. On the other hand, it represented an important indicator for the increasing maturity of the sector, enabling project developers to provide fund managers and investors with the needed securities to attract capital from individual private investors to off-balance sheet, project-based investments.

On the supply side, annual investments more than doubled in the years 2004 to 2006, amounting to €294 million, €668 million and €1,3 billion. From 2007, investment growth slowed down both in relative and in absolute terms. In 2007 and 2008, the totals were €1,866 and €2,183 billion respectively (Lütter, Uhlemann, Ammon, Otto, & Lohr, 2009, p. 12). At the same time, Germany's share of global investment decreased during this period. By 2007, Germany only accounted for 15 percent of total global investments, compared to a high of almost 90 percent in 2002. Moreover, the period before 2005 had been dominated by private investments. In 2005, public equity activity in the sector exploded globally, accounting for approximately three quarters of total investment in the sector (Jennings et al., 2008).That year Q-Cells launched the largest German IPO to date, raising €240 million.

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[17] Based on interviews with industry experts.

[18] Based on data available on the website of the German Association of Closed Funds (*Verband Geschlossene Fonds*): http://www.vgf-online.de/statistik.html

Other major IPOs included Centrosolar (€49 million, initially via Regulated Unofficial Market in Frankfurt), Conergy in 2006 (€100 million), and Aleo Solar (€38,5 million) in 2007. Among the equipment suppliers, Centrotherm Photovoltaics (€134 million) launched the largest IPO in 2007[19].

Only the three major players Q-Cells, Solar World and Conergy followed up with major capital injections. Q-Cells relied heavily on the public equity, raising approximately €1 billion by issuing shares and convertible bonds from 2005 to 2010. SolarWorld only raised approximately €250 million in equity, but issued over €1,3 billion in debt over the same period. Finally, Conergy raised more than €700 million in equity and over €600 million in debt[20]. In addition, German industrial heavyweight Bosch entered the PV sector in 2008, investing around €2 billion up to 2011. This included more than €1 billion for the acquisition of Ersol in 2008 and Aleo Solar for more than €100 million in 2009 (Brück, 2012; Werner, 2012).

In addition to these market-driven funding mechanisms, German solar companies continued to benefit from public investment subsidies. In a number of East German regions, companies could receive cash grants from regional development funds of up to 30 to 50 percent of total investment costs, depending on the size of the company (Grau, Huo, & Neuhoff, 2012, p. 27-30). These investment subsidies represented an important incentive for companies to develop facilities in the Eastern part of the country supporting a significant concentration of manufacturing companies in the States of Sachsen, Sachsen-Anhalt and Thüringen (Brachert et al., 2013, p. 8). SolarWorld, for instance, recorded an average of €64 million in investment grants in its balance sheet during the period 2005 to 2010[21].

Although the financial crisis affected the solar sector less severely than other industries, it did lead to constraints in accessing fresh financial capital, which led to a stagnation of global investments in 2009 (UNEP, 2012, p. 15). In Germany, the most tangible impact was the cancellation of Schott Solar's IPO, which had been scheduled for September 2008 and was expected to raise more than half a billion Euros[22]. Q-Cells on the other hand raised €220 million in debt in 2008 and floated convertible bonds worth €250 million in 2009, indicating their resilience to the turbulence in the capital markets. Conergy raised €400 million in equity in 2008, and SolarWorld raised €75 and €85 million in debt in 2008 and 2009, respectively[23].

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[19] Based on company annual reports.

[20] Based on company annual reports.

[21] Based on company annual reports.

[22] *Handelsblatt,* "Schott sagt Börsengang ab," October 8, 2008. Accessed on September 11, 2013 at: http://www.handelsblatt.com/finanzen/aktien/neuemissionen/verschiebung-auf-unbestimmte-zeit-schott-solar-sagt-boersengang-ab/3032902.html

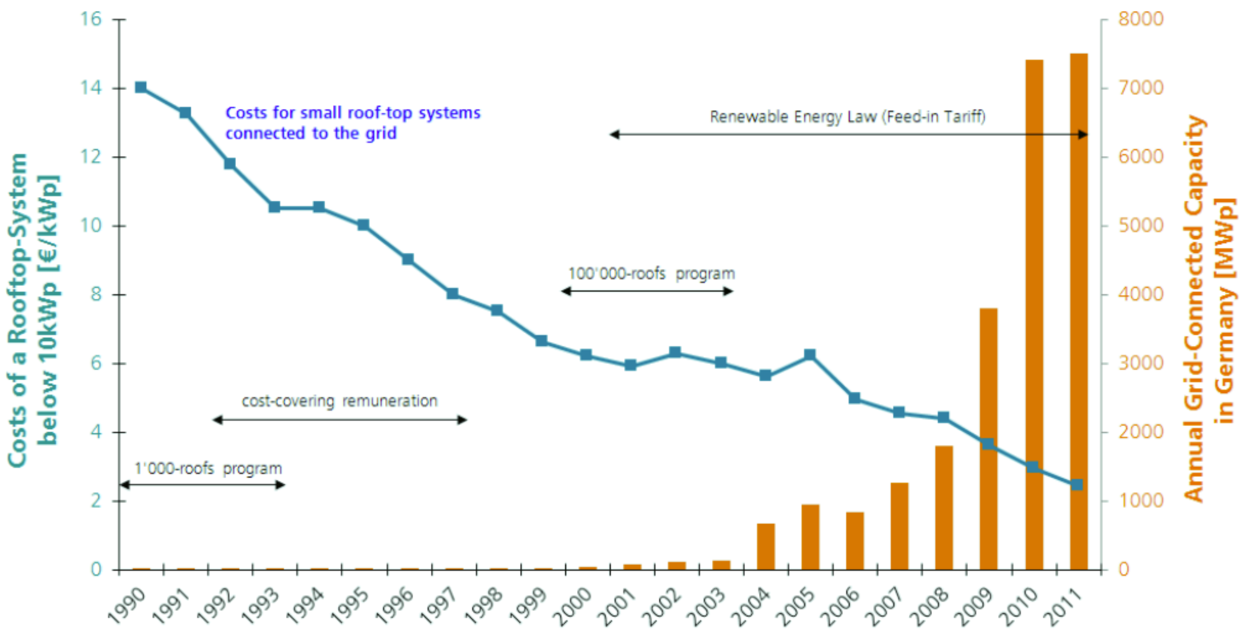
[23] Based on company annual reports.

4.1.5 Development of scale economies and cost reduction

Rapid market development in Germany was accompanied by important reductions in system prices. After a short increase in 2005 following the introduction of the new feed-in tariff, prices declined step by step (see Figure 4). By 2008 German systems were well below averages in Japan and other major Western PV markets (IEA-PVPS, 2008, p. 28). Even Chinese system prices remained above average prices for utility-scale plants in the German market. Only in the rest of Asia were prices slightly lower (see Figure 5). An analysis of cost drivers in the US and Germany attributes Germany's price advantage to the size and stability of the German market and the benefits related to this, such as lower market risks and greater competition among installers (Seel, Barbose, & Wiser, 2013).

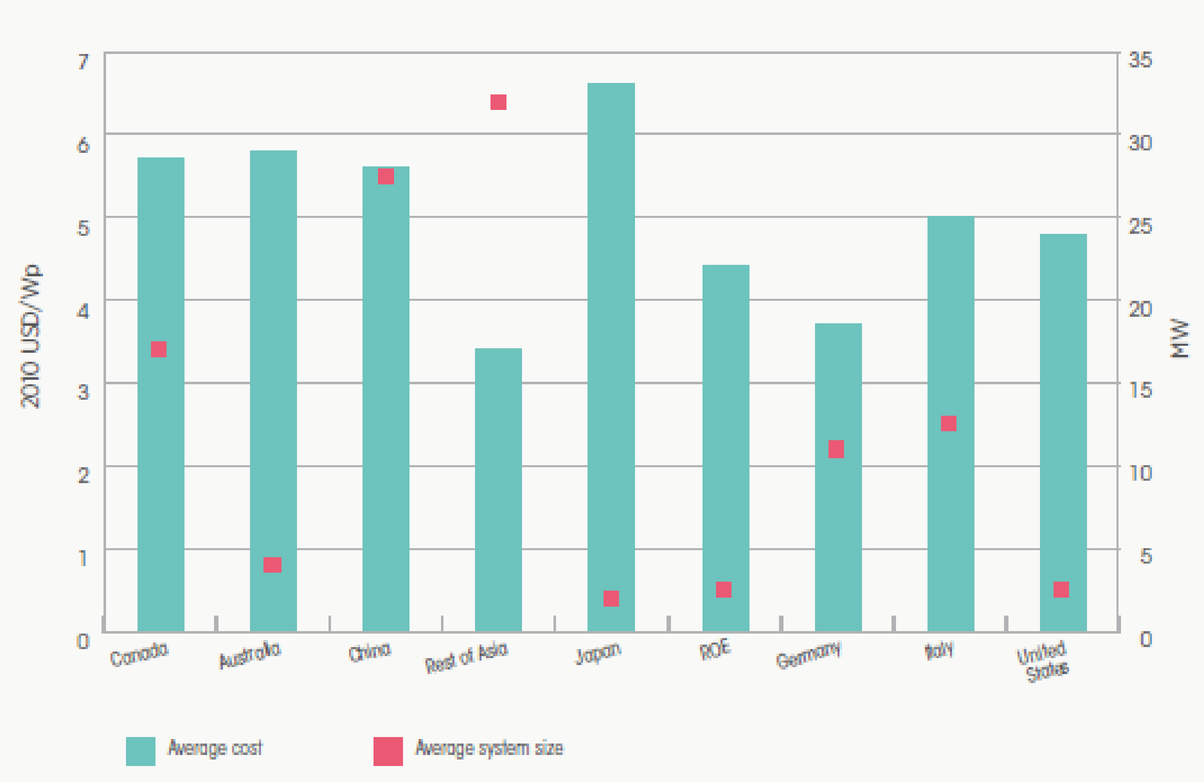
Declines in system prices have come in spite of rising module prices up to 2008, caused by supply-side constraints. A key bottleneck was the shortage in polysilicon, the main raw material needed for the production of silicon-based solar cells. With less than ten major producers, high capital intensity and response times of up to 3 years, this segment of the supply chain did not keep pace with the rapid market growth triggered by Germany's feed-in tariff. As a result, prices for silicon sky-rocketed, reaching an average price of more than $100 per kg (Willeke & Räuber, 2012, p.33-35) and spot market prices of more than $450 per kg by 2008 (US Department of Energy, 2011, p. 36). This impacted not only the cost of module production but also the willingness of cell and module producers to expand production. As Q-Cells states in its 2005 annual report, "Our policy is to only expand our production capacity when we have access to the corresponding raw materials..." (Q-Cells, 2006, p. 21).

Figure 4: Annual installation of grid-connected PV capacity and development of prices for rooftop-systems below 10kWp in Germany



Source: Fraunhofer ISE (2012)

Figure 5: Average prices and sizes of utility-scale solar power plants



Source: IRENA (2012, p. 27)

To secure a stable supply of polysilicon, manufacturers entered long-term supply agreements with silicon producers. In some cases, this involved substantial pre-payments to help silicon producers expand production. Panel makers were thus forced to shoulder not only part of the investment risk but a significant portion of the financing costs. In addition, wafer producers PV Crystalox and Solar World both invested in their own production of polysilicon. To mitigate the rise in silicon prices German manufacturers also pursued efforts to reduce the use of silicon in cell production and to develop methods for recycling the material from waste generated in the production process. Q-Cells, for instance, reduced wafer thickness by almost 50 percent between 2003 and 2007, enabling the firm to keep material costs stable. Solar World, on the other hand, was able to source 20 percent of its silicon from recycled materials produced by its subsidiary Solar Material. Despite these efforts, many producers slowed down the expansion of production capacity, so that the supply of solar modules in Germany continued to lag behind the growth in domestic and European demand. Especially smaller producers, such as Centrosolar, were constrained by the needed capital to secure the required silicon. As an alternative, a number of producers, including Q-Cells, Schott and Sunways, invested in the production of thin film solar modules[24].

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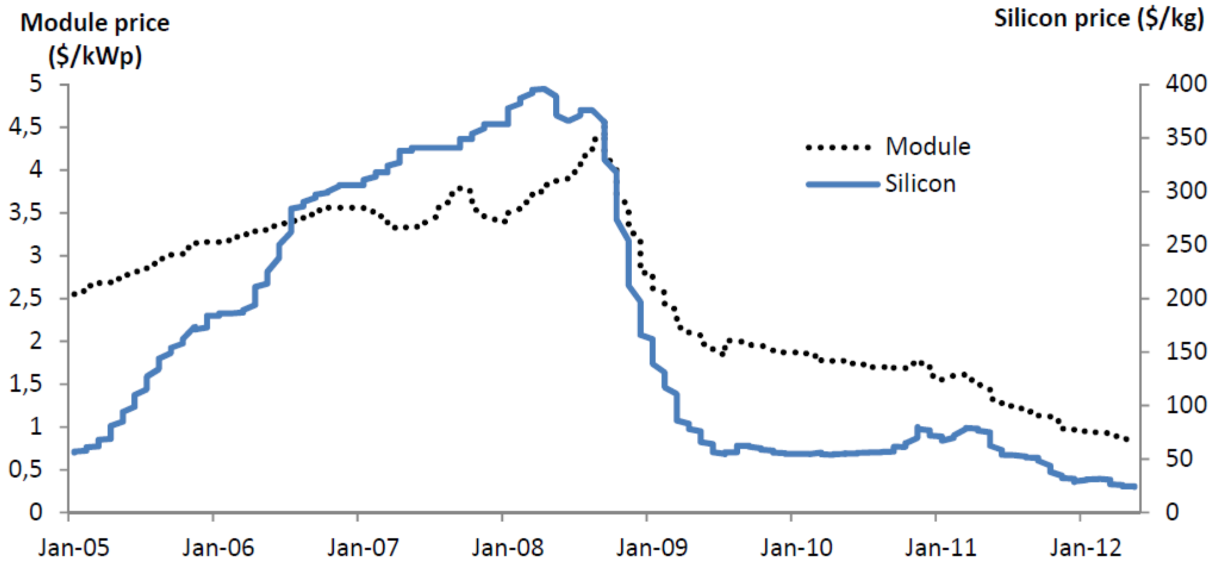
[24] Information in this paragraph is based on the annual reports of the mentioned companies.

Towards the end of 2008, increased silicon production started easing the supply bottleneck. Increased availability of the raw material not only caused prices for polysilicon to fall from its high in early 2008 to approximately $50 per kg by mid-2009, it also enabled producers to utilize idle production capacity and boost their output. The simultaneous collapse of the Spanish market and reductions in the German feed-in tariff helped module prices to fall from a high of close to €4 per W in mid-2008 to slightly over €2 per W for European-made modules by the end of 2009 (US Department of Energy, 2011, p. 60) (see also Figure 6).

Figure 6: Silicon and PV module prices from 2005 to 2012



Source: de la Tour & Glachant (2013)

These price reductions were partially underpinned by industry-wide economies of scale and real reductions in the cost of production. As specialized suppliers invested in scaling-up their production for the growing PV industry, this brought down prices for equipment and components[25]. Additionally, some of the larger German manufacturers tried to reduce costs by investing in production capacity in Asian countries. In 2007, Q-Cells and Solar World began to develop facilities in Malaysia and Korea, respectively. Additionally, Schott Solar had begun operating a production facility in the Czech Republic as early as 2004. From 2008 the largest German manufacturers invested in further production capacity in an effort to exploit internal economies of scale. As mentioned above, by 2010, Bosch, Q-Cells and Solar World had all reached over 1 GW of capacity[26].

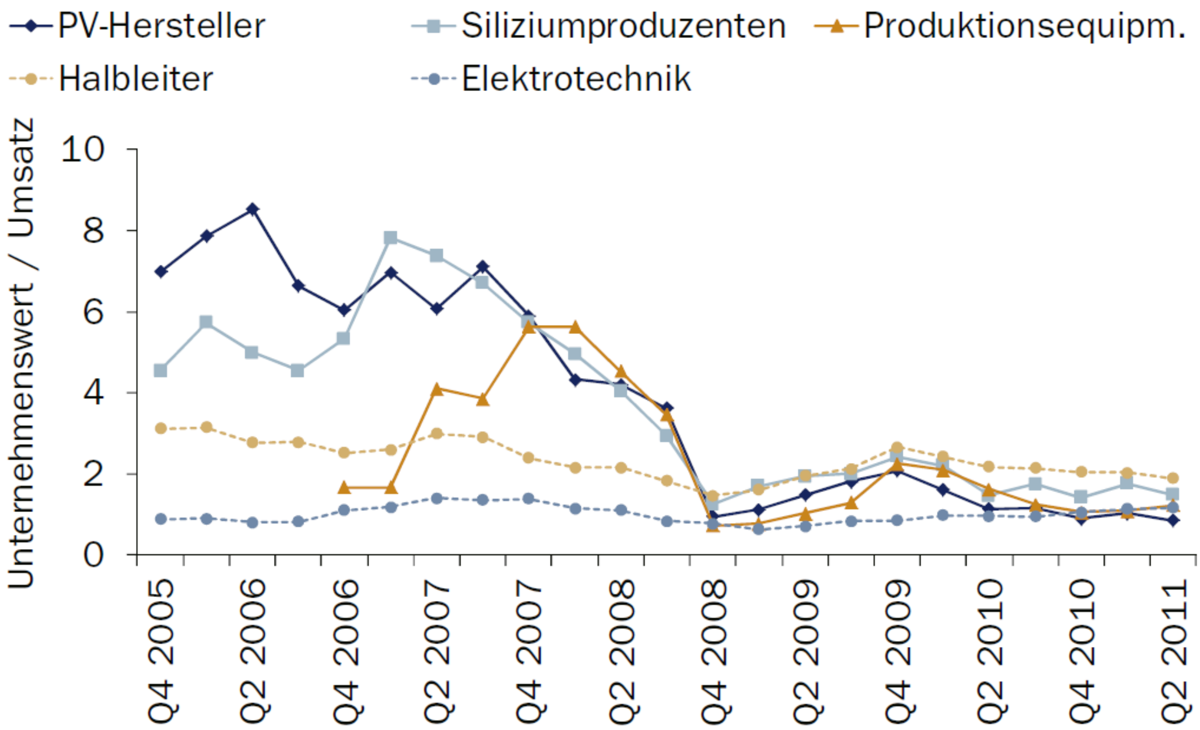
According to estimates in Kirkegaard, Hanemann, Weischer, & Miller (2010, p. 49), technological advances coupled with increasing economies of scale had brought module produc-

[25] Based on interviews with industry experts.

[26] Based on annual reports of the mentioned companies.

tion costs to approximately €1,35 per Watt by 2010, though no distinction is made across countries or firm types. The related assumptions are based on state of the art equipment and cell concepts as well as a polysilicon price of $60 per kg, which only partly reflected the cost structures of German manufacturers at the time. Among other things, manufacturers remained locked into wafer or polysilicon supply agreements with significantly higher prices. Hence, a significant portion of the price reduction had to be compensated by narrowing profit margins, resulting in the relative decline of stock valuation to turnover shown in Figure 7.

Figure 7: Stock valuation relative to turnover



Source: Fawer & Magyar (2011)

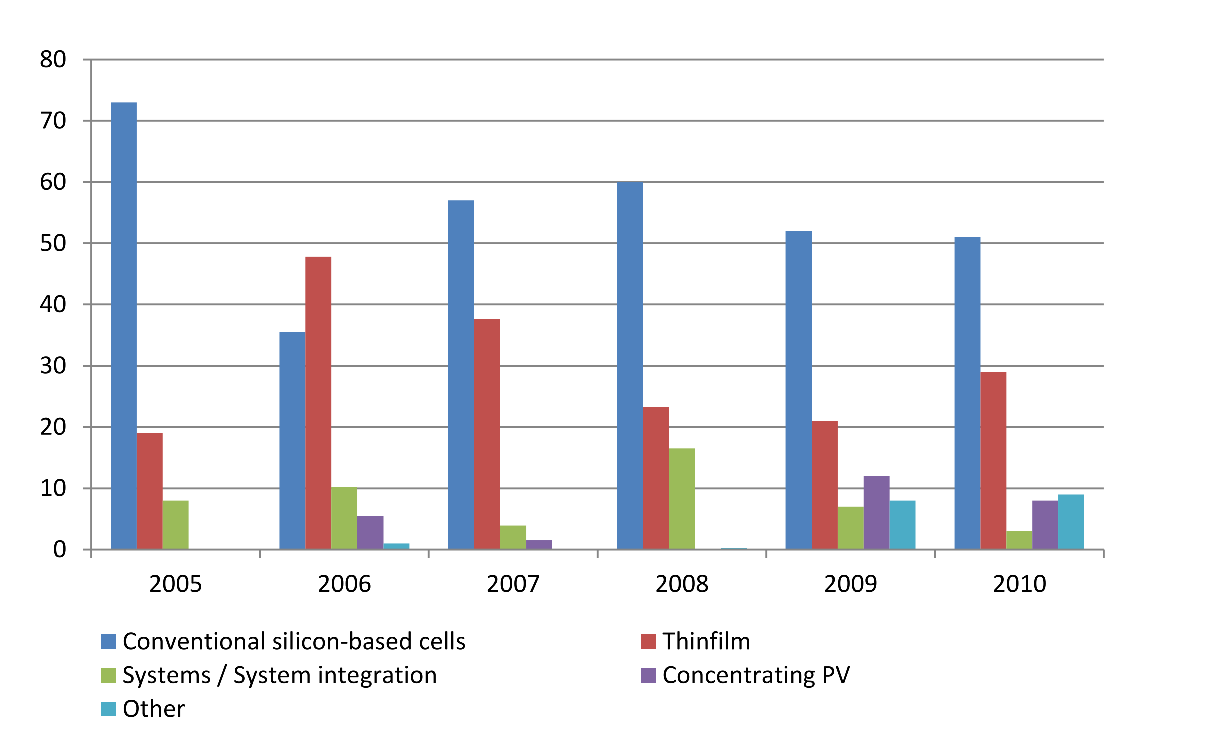
4.1.6 Knowledge development and diffusion

The period of 2004 to 2010 was characterized by important increases in the investments in research and development in Germany. This was driven both by increased government funding and increased funding from Germany's booming solar energy industry. Government expenditures in R&D almost doubled from 2004 to 2005 to €32,3 million. In the following years, the annual R&D budget remained relatively stable, ranging from €31 million to €43 million between 2006 and 2010. With that the PV sector received more public R&D investments than any other renewable energy technology in Germany over that period (Federal Ministry of the Environment, 2011b, p. 11). Only the US government invested more than Germany during this period (Willeke & Räuber, 2012, p. 10).

R&D focused on traditional silicon-based solar cells received slightly over 50 percent of the total funding for the period 2005 to 2010. Over the same period, thin film technologies received approximately 28 percent of funding with a particular boost in 2006 (48%) and 2007

(38%)[27] (see also Figure 8). In particular in the field of traditional solar cells, the research scene was dominated by the Fraunhofer ISE. Among the active projects in the year 2007 (including projects initiated in the preceding years), over 40 percent of funding was allocated to projects individually implemented by the institute and an additional 8 to 9 percent to projects with its participation, bringing the total to more than 50 percent. The ISFH remained a distant second accounting for 13 percent of funds allocated to research on silicon-based solar cells (only single partner projects)[28].

Figure 8: Distribution of public R&D funding, % of total (2005 - 2010)



Source: Federal Ministry of the Environment (2006b, 2007, 2008, 2009b, 2010b, 2011b)

In addition to the relatively stable flow of public R&D funding, private R&D investments increased in response to the rapidly increasing industry turnover. Having roughly matched public expenditures in 2004 and 2005, private R&D investments reached €65 million in 2006, thus surpassing public expenditures for the first time. R&D expenditures continued to grow thereafter amounting to €163 million or more than five times the public budget by 2008 (BSW & Solarpraxis, 2009, p. 31). Despite these important increases in absolute expenditures, the share of R&D relative to industry turnover decreased from approximately 2,8 percent in 2003 to figures ranging from approximately 1,5 to slightly over 2 percent[29].

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[27] Based on Federal Ministry of the Environment (2006b, 2007, 2008, 2009b, 2010b, 2011b).

[28] Based on Projektträger Jülich (2008).

[29] Author's own calculations based on data from BSW & Solarpraxis (2009, p. 31) and Lütter et al. (2009, p. 11).

Given the fact that corporate R&D expenditures may also include funds acquired from public sources, the real share of private R&D funding may be even lower than these figures suggest. SolarWorld for instance states in its annual reports that more than one third of its R&D investments in the years 2005 to 2007 were grant financed.

A particular strength of the German R&D landscape has been the close collaboration between manufacturers and equipment suppliers (Nussbaumer, Biro, Haverkamp, & Bothe, 2007). Moreover, the German PV industry, in particular in East Germany, is characterized by a high network density. In other words, the number of cooperative relationships is relatively high compared to other industrial sectors in Germany, which also implies a relatively rapid diffusion of knowledge throughout the German solar industry (Brachert et al., 2013; Hornych & Brachert, 2010). These cooperative relationships were supported by a number of collaborative R&D projects funded by the Federal Ministry of the Environment as well as the State governments of Baden-Württemberg and Niedersachsen (Nussbaumer et al., 2007). In addition, the Federal Ministry of Education and Research supported a cluster initiative known as "SolarValley Mitteldeutschland" in the Eastern States of Sachsen, Sachsen-Anhalt and Thüringen with a total of €150 million over the period 2008 to 2013 (Aulich & Frey, 2009).

4.1.7 Influence on the direction of search

In accordance with a tradition dating back to the year 1987, policy makers and a selected group of key stakeholders from industry and the research community discussed the strategic direction of public R&D programs at the biannual "Glottertaler Gespräche" near Freiburg (Bruns et al., 2011, p. 172). In 2005, the participants of these discussions developed a roadmap to help identify key focus areas for research. From 2007, the Strategic Research Agenda developed by the European PV-technology platform served as the main reference point (Federal Ministry of the Environment, 2008, p. 14-15). According to the research agenda developed in 2005, twin goals of public R&D funding should be enhancing the competitiveness of solar energy vis-à-vis conventional energy and securing Germany's technological leadership in the PV sector (Federal Ministry of the Environment, 2006b, p. 12). To do so, R&D funding should focus on reducing the cost of silicon-based PV cells and modules, the further development of thin film technologies and system integration, a focus which was broadly maintained following the discussions in 2007 and 2009 (Federal Ministry of the Environment, 2008, 2010b). In addition, the strategists agreed that funding should encourage collaboration between research institutes and industry and focus on medium- to long term projects, averaging approximately five years (Federal Ministry of the Environment, 2010b, p. 19). Despite the goal of promoting collaborative R&D, projects involving cooperation between firms and research institutes only accounted for about one third of the funding volume. Approximately 10 percent of total funding went to projects, which involved both suppliers and manufacturers[30].

In addition to this public-private dialogue, a key influence on the direction of search resulted from the silicon shortage mentioned above. From 2004 to 2008, producers placed particular emphasis on reducing wafer thickness and developing other ways to reduce the amount of silicon needed in the production process. Furthermore, it stimulated investments in the development of thin film technologies, which require only limited or no silicon[31].

4.1.8 Development of positive externalities

Rapid market growth and industry development in Germany had important implications both domestically and internationally. Most importantly, the success of the German feed-in tariff inspired countries like Spain, Italy and the Czech Republic to invest in similar demand-side subsidy schemes, thus triggering an unprecedented market boom. Moreover, the German market became a learning ground for established commercial players to enter the solar energy sector, ranging from investment banks and pension funds to specialized equipment producers. The scale and profitability of the German market combined with its stable policy and institutional framework offered a strong foundation for these firms to become acquainted with the new industry before venturing into new, less predictable markets (Fulton & Mellquist, 2011).

In addition, important cluster dynamics developed in East Germany where the accessibility of investment subsidies combined with high quality infrastructure and the availability of qualified personnel made greenfield investments very attractive. As indicated by Brachert et al. (2013), dense network ties enabled knowledge to diffuse within the industry. Even more importantly, Germany's traditional strength in equipment production enabled important synergies between manufacturers and suppliers (Nussbaumer et al., 2007). Combined with Germany's strong export orientation, the resulting technological advances became readily available to firms around the globe. A case in point is the focus among German suppliers on the development of turnkey production lines, mainly intended for the development of production capacity abroad (Heup & Rentzing, 2009).

4.2 China

4.2.1 Legitimation

Starting at a relatively low level, the legitimation of the Chinese solar energy industry made a number of advances both in China and internationally during the growth period of

[30] Based on review of projects listed in Projektträger Jülich (2008).

[31] Based on interviews with industry experts and company annual reports.

2004 to 2010. Domestically, the Renewable Energy Law, which went into effect on January 1, 2006, represented an important milestone for the broader renewable energy sector. Among other things, it called for targets and a corresponding plan for the promotion of renewable energy development. In the Medium and Long-Term Development Plan for Renewable Energy, which followed in 2007, the solar energy targets remained very modest, however, aiming only at 300 MW of cumulative installed capacity by 2010. This compared to 5 GW of targeted wind power capacity and 4 GW biomass-based energy generation capacity (Schuman & Lin, 2012, p.92).

At the international level, Chinese firms also began the period with a modest reputation. Quality concerns and the lack of a certification infrastructure supplied producers with only weak legitimacy on the international market. An important boost in legitimacy came as a result of the supply shortages that emerged in Europe in response to the boom in demand. This mismatch between supply and demand facilitated growing sales of Chinese modules and cells in the German and other European market. Supply, distribution and licensing agreements with German brand name firms enabled Chinese pioneer firms to overcome initial customer hesitation and establish themselves as legitimate competitors in the German market (Hug & Schachinger, 2006). In fact, in 2005, Suntech entered a licensing agreement for the OEM production of solar modules for its main German competitor, SolarWorld The German firm became its largest single customer the following year. Other major customers in 2005 and 2006 were IBC Solar and Conergy (Suntech Power Holdings, 2005, 2007). While in 2005 Trina Solar still sold the majority of its products to smaller system integrators in Germany, by 2006 it had secured agreements with Conergy and Phönix Sonnenstrom AG (now Phoenix Solar AG) (Hug & Schachinger, 2006). Finally, in 2008, Q-Cells entered into an OEM agreement with SolarFun for the manufacturing of modules with its cells, which it then used in its emerging systems business (SolarFun Annual Report, 2009, p. 85).

Another important avenue enabling Chinese manufacturers to establish their legitimacy in Germany and other international markets was via the certifications offered by major certification bodies. Of key importance for the German market have been TÜV Rheinland, the VDE Institut as well as its partner Fraunhofer ISE. While initially panels also entered the market without certifications, major producers began to acquire the relevant certifications by 2006. In certain cases, German manufacturers also helped acquire certifications for modules produced for them by Chinese firms under OEM agreements (Hug & Schachinger, 2006).

These inroads in the German market not only boosted the reputation of Chinese solar products internationally, it also built momentum for developments in China. With Chinese producers gaining prominence abroad, their clout also grew at home. In 2006, Suntech received the high profile contract for supplying modules for a rooftop installation on Beijing's Olympic Stadium[32]. In 2010, in the run up to the launch of China's 12th Five Year Plan, the State Council proclaimed the solar PV industry as a "strategic emerging industry" for China (Ahrens, 2013, p. 5; Zhang & White, 2012, p. 3). Subsequently, the Plan, launched in early 2011, included a target for 5 GW of installed capacity by 2015. In addition, in 2009 Jiangsu province announced a target of 240 MW by 2011 (Wong, 2009).

4.2.2 Market formation

The dynamics of domestic market formation in China largely mirrored the growing legitimacy of the industry. Market growth before 2010 was minimal relative to the rapidly expanding markets in Europe. At the end of 2009, cumulative installed capacity stood at only 300 MW (Honghua et al., 2012, p.7). From 2004, all major producers, therefore, generated the vast majority of their sales overseas, most importantly in Germany. Canadian Solar, Yingli and Trina all sold over 60 percent of their modules in Germany between 2004 and 2006, while Suntech went from over 70 percent in 2004 to an average of 46 percent for the period[33]. While Germany remained the single largest market for these four companies through 2011, starting in 2006 the Spanish and from 2009 the Italian and Czech markets became other important destinations for Chinese module exports. In fact, at its peak in 2008, the Spanish market represented the largest single destination of Chinese solar products (Kirkegaard et al., 2010, p.54).

The following year, as the Spanish market imploded, the Chinese government commitment to developing a domestic market increased markedly. At the central level, the Ministry of Housing and Urban-Rural Development initiated a national subsidy program for building-integrated PV (BIPV), while the Ministry of Finance and the National Development and Reform Commission (NDRC) launched the Golden Sun Program. Both programs were based on a capital-subsidy scheme, offering subsidies of RMB 15 to RMB 20 per Watt and between 50 to 70 percent of investment costs, respectively. By mid-2010, the government had approved 640MW of projects under the Golden Sun program, amounting to approximately RMB 20 billion in subsidies. In parallel, using feed-in tariff-type scheme, a first large-scale project was awarded by the National Energy Administration based on a competitive bidding process (Martinot, 2010, p.290). Based on the same scheme, a further 280 MW were auctioned in 2010 (Huo & Zhang, 2012, p.41) (see overview of Chinese market growth and demand-side policies in Figure 9).

Moreover, at the provincial level, the governments of Jiangsu and Zheijang provinces, where an important share of the Chinese solar PV industry is based, initiated the country's first feed-in tariff schemes for solar PV in 2009. In Jiangsu, a feed-in tariff was introduced

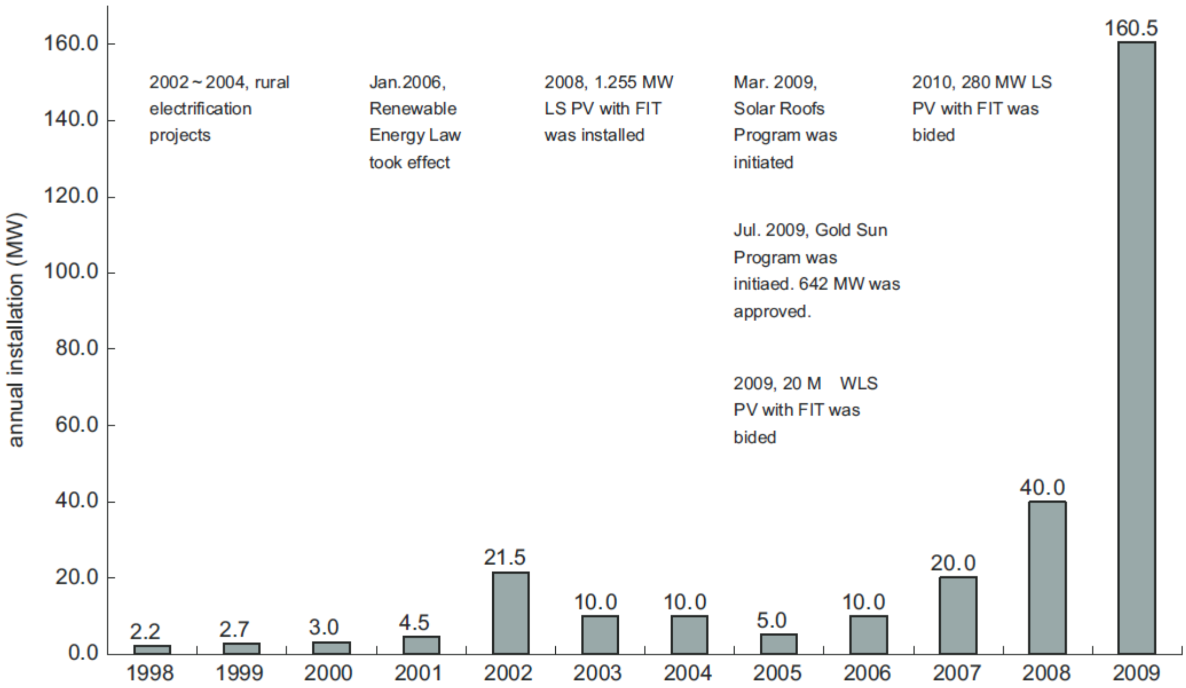
[32] Suntech Power Holdings, "Suntech Power Chosen to Provide Solar Energy System for Beijing Olympics", April 17, 2006. Accessed on September 11, 2013 at: http://ir.suntech-power.com/phoenix.zhtml?c=192654&p=irol-newsArticle&ID=843121&highlight=

[33] Based company annual reports.

for different types of PV applications ranging from RMB 2.10 to RMB 4.30 per kWh, while the Zheijang government offered a premium of RMB 0.70 for electricity generated from PV systems over the average price of coal-based power (Martinot, 2010, p. 290). The governments in Shandong and Qinhai followed suit, launching feed-in tariff schemes in 2010 and 2011, respectively (Green Prospects Asia, 2011; Viljoen, 2010).

As a result of these measures, the Chinese market grew by over 200 percent in 2010 and 500 percent in 2011, adding 0,5 GW and 2,5 GW of new capacity, respectively. With this China still lagged far behind the record numbers achieved in Germany with over 7 GW in both years as well as the explosive growth recorded in Italy, which recorded a total of more than 10 GW in 2010 and 2011. Nonetheless, this allowed China to increase its installed capacity from 8th (2009) to 7th (2010) and finally to the 4th largest globally in 2011 (IEA-PVPS, 2012).

Figure 9: Chinese market growth and key demand-side policies



Source: Huo & Zhang (2012, p. 42)

4.2.3 Entrepreneurial experimentation

From 2004, China's solar PV industry saw a surge of new entrants, while the pioneer firms invested aggressively in the rapid increase of their production capacity. As pointed out by Zhang & White (2012), the focus of activities shifted from exploration of new possibilities and the development of organizational legitimacy to the exploitation of demonstrated opportunities in the market. Among the pioneers, Trina, Yingli and Canadian Solar pursued strategies focused on vertical integration coupled with rapid expansion of productive capacity. Beginning with module production before or by 2004, they expanded their manufacturing activities progressively upstream thereafter, moving to the production of cells, wafers, ingots, and, in the case of Yingli, even the production of purified silicon. Suntech, on the other hand, expanded its capacity for the production of cells and modules even more rapidly, but refrained from moving up the value chain[34]. As a result, it was able to establish itself as the largest manufacturer of solar cells by 2010 (REN21, 2011, p. 41).

In parallel to the investments of the pioneers, a large number of new companies entered the industry at different points of the value chain and with different levels of investments. Among the major ventures, three waves of entries can be identified, each characterized by an increasing capital intensity and initial investment volume. The first approach largely mimicked Suntech's model with its focus on the production of modules and cells for export to Germany and other European countries. The only representative of this approach in the list of the top-ten, foreign-listed firms was Solarfun, founded in 2004. Immediately following this, JA Solar and Sunergy entered the sector with a larger initial investment and a focus, at least initially, on the production of solar cells. These were intended for processing mainly by domestic module producers. In 2005 and 2006, a third group, consisting of ReneSola, Jinko and LDK Solar, began with the production of silicon wafers, also mainly intended for processing by domestic manufacturers. Especially the third group of companies followed up with ambitious vertical integration strategies. ReneSola and LDK Solar invested heavily in their core activity of wafer manufacturing, while integrating upstream and downstream with investments in the production of polysilicon, cells and modules. Jinko pursued a strategy of downstream integration, investing in a balanced set of wafer, cell and module production capacity. JA Solar and Sunergy, from the previous wave, initially maintained their focus on cell production. Only in 2010, did they add module production, mainly in an effort to boost their direct presence in foreign markets. Like Solarfun, they did not invest substantial resources in upstream segments of the supply chain, however[35].

These vertical integration strategies were enabled in part by the parallel emergence of a large number of second- and third tier manufacturing companies[36], a number of which were acquired by the larger players. In addition, a growing network of suppliers to the PV industry began to develop during this period. These included a growing number of increasingly specialized equipment suppliers as well as a number of established companies, such as GCL-Poly, which invested significant resources in the development of polysilicon production. Finally, with the initiation of the bidding process for large scale solar energy installations, a range of State-owned enterprises entered the sector as project developers. In a number of instances, they partnered with the country's large manufacturing firms, supply-

[34] Based on company annual reports.

[35] Based on company annual reports.

[36] In 2011, it was estimated that there were more than 330 Chinese module producers and more than 60 cell and wafer producers (Honghua et al., 2012).

ing needed project financing. In 2010, State-owned firms won 70 percent of the bids launched by the National Energy Administration (Schwartz, 2010).

4.2.4 Resource mobilization

The key focus of this system function during the period 2004 to 2010 was the mobilization of financial resources to enable a rapid scaling-up of manufacturing capacity. This process went hand in hand with a transition from the mobilization of domestic finance to strategies targeting international capital markets, culminating in the launching of initial public offerings in New York and London. Suntech began this wave of solar IPOs in 2005, raising $400 million for the company on the New York Stock Exchange (NYSE). Approximately one year later, the pioneers Trina and Canadian Solar as well as early followers, Solarfun and ReneSola, followed with IPOs on NYSE, NASDAQ and the London Stock Exchange. The process continued in 2007 with Yingli, LDK Solar, JA Solar and Sunergy and came to a close with ReneSola's second IPO in 2008 and Jinko's IPO in 2010. The proceeds ranged from a modest $50 million raised at ReneSola's first IPO in London to a record $469 million raised by LDK Solar on NYSE (Zhang & White, 2012, p. 52-53) (see Table 2 and Table 3 for an overview). The total revenues from these eleven IPOs represented over $2 billion in public equity, amounting to more than half of total investment in 2005, 2007 and 2008 and close to 50 percent in the years 2006 and 2009[37].

In the run up to these IPOs, the companies raised debt and equity from both foreign and domestic sources. Bank borrowing was mainly domestic and involved China's "big four" State-owned commercial banks as well as a number of second tier commercial banks. In many cases, loans were guaranteed by local State-owned companies with stakes in the various companies. In Yingli's case for example, the local state-owned company, Baoding Tianwei Baobian, which held a 51 percent stake during the years prior to the IPO, functioned as an important facilitator for accessing bank lending. At this stage, the so-called policy banks, such as China Development Bank, played no major role in providing finance to the sector[38].

Simultaneously, private equity financing had evolved significantly. Initially, investments had come from the company founders and mainly local government-backed investment funds. In the run-up to the various IPOs, this was supplemented by important investments from a variety of international players. International investors ranged from smaller VC and equity funds, based mainly in Hong Kong and the US, to major international investment banks, like Deutsche Bank, JP Morgan, HSBC and Goldman Sachs. The latter contributed a significant portion of the pre-IPO equity to Suntech, Canadian Solar and Yingli (Zhang & White, 2012, p. 52-53) (see overview of key funding sources and IPOs in Table 2).

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[37] Estimates based on data from Bloomberg New Energy Finance Investment Database.

[38] Based on company annual reports.

Table 2: Main sources of funding of the four Chinese pioneer firms

	Suntech	Trina	Canadian Solar	Yingli
Major sources of equity funding (including convertible debt) before IPO	Founder, Several local State-owned enterprises and investment companies, Chinese and UK-based VC and private equity funds, Goldman Sachs	Founder, Multiple Chinese and Hong Kong-based VC and private equity funds partly held by founder and other company directors, Swiss and US-based VC and private equity funds	Founder, HSBC, JAFCO (Japan)	Founder, Local State-owned enterprise, Chinese VC and private equity, Deutsche Bank, JP Morgan, various US investment banks
Total of major pre-IPO equity funding	$96 million	$40 million	$12 million	$229 million
Major pre-IPO bank lenders	Industrial and Commercial Bank of China and others	n.a.	Industrial and Commercial Bank of China, China Everbright Bank, Royal Bank of Canada	Agricultural Bank of China, Chinese Construction Bank, Bank of China, China Everbright Bank, China CITIC Bank
Pre—IPO short-term borrowings	$46 million	$34 million	$14 million	$28 million
Pre-IPO assets (property, plant, equipment)	$13 million	$25 million	$1 million	$72 million*
Year and location of IPO	2005 / NYSE	2006 / NYSE	2006 / NASDAQ	2007 / NYSE
IPO revenue	$400 million	$98 million	$115 million	$391 million

Source: Zhang & White (2012, p. 52-53) and company annual reports.

Table 3: IPOs of major post-2004 entrants

	ReneSola	Solarfun	LDK Solar	JA Solar	Sunergy	Jinko
Year and location of IPO	2006 / LSE 2008 / NYSE	2006 / NASDAQ	2007 / NYSE	2007 / NASDAQ	2007 / NASDAQ	2010 / NYSE
IPO revenue	$50 million $130 million	$150 million	$469 million	$225 million	$94 million	$100 million

Source: Zhang & White (2012, p. 52-53)

Complementing these commercial sources of finance, Chinese firms could also rely on a number of subsidy and investment support schemes. These subsidies are primarily offered by local and provincial governments in an effort to promote high-technology industrial firms. They are embedded in the broader Chinese paradigm of economic development and innovation, based on fierce regional competition (Gu & Lundvall, 2006; Xu, 2011). While the central government offers broad targets and guidelines, it delegates risk-taking and experimentation to lower levels of government. Within this framework, local governments have been characterized as "entrepreneurial" or "developmental" working with promising entrepreneurs and investors directly or indirectly to promote successful ventures within their jurisdiction[39] (Baum & Shevchenko, 1999; Blecher & Shue, 2001).

Table 4: Examples of investment support measures offered to PV sector by local governments

Refund of loan interest	(Huaian) Refund equal to 50% of the real interest of loans only in the year when most equipment was bought, if the initial investment is more than €50 million. (Jinzhou) Any new PV plant before 2012 will get a refund equal to 100% of the interest of loans, calculated according to the national basic interest rate in that period.
Refund of electricity consumption fees	(Huaian) Refunds equal to ¥0.05/kWh or ¥0.1/kWh in the first year of production, depending on manufacturing capacity.
Refund of land transfer fee	(Huaian and Jinzhou) Refund of the residual land transfer fee, if the initial investment in PV manufacturing is more than €50 million.
Refund of corporate income tax	(Huaian) New plants can be refunded 100% of residual corporate income tax from the first to the second year, and 50% from the third to the eighth year.
Refund of value added tax payment	(Huaian) New PV plants can receive 50% of the residual VAT payment from the first to the second year, and 25% from the third to the fifth year. (Jinzhou) New PV plants can receive 100% of the residual VAT payment from the first to the third year, and 50% from the fourth to the sixth year.

Source: Grau et al. (2012, p.32)

39 In other, less favorable cases these authors have applied the labels "predatory" or "clientelist".

In this effort to attract investment and promote entrepreneurship, local governments not only help arrange financing but typically also offer companies - whether foreign or locally-owned - access to low-cost energy and land, tax breaks as well as different forms of investment grants (Haley & Haley, 2013a). Initially, these were available as generic subsidies for high-technology firms, but from a 2009 a number of provinces began to introduce schemes aimed specifically at the PV-sector (Grau et al., 2012). Table 4 provides an overview of the incentives offered by Huaian in Jiangsu province in 2009. In addition to these local-level benefits, officially recognized high-technology firms and foreign-invested enterprises are also entitled to a number of reductions in central government taxes. Newly established high-technology firms receive a 2-year tax holiday followed by 3 years of taxation at 12,5 percent. Thereafter, high-technology firms are taxed at the preferential rate of 15 percent[40]. Finally, foreign invested companies and R&D institutions may receive exemptions from import or value-added taxes when purchasing specialized instruments and equipment (Huo & Zhang, 2012, p. 42-43).

Most of the major solar energy firms note the receipt of investment or R&D grants in their annual reports starting in 2005 or 2006. Up to the year 2007, the recorded annual subsidies ranged – with the exception of LDK Solar - from under $100,000 to slightly over $2 million. From 2008 to 2009, the spread had widened significantly. While a number of companies reported no subsidies or subsidy levels of under €200,000, the majority of companies received annual subsidies of several million dollars. By 2010, a number of companies had reached over $10 million in government grants and subsidies. Particularly high levels of subsidies are outlined in the annual reports filed by LDK Solar, which offers a detailed breakdown of the various sources. As early as 2007, LDK Solar received over $3 million in investment support and more than €3 million in electricity subsidies. Thereafter, electricity subsidies grew in tandem with production volumes and reached $33 million or approximately 20 percent of the company’s total electricity costs in 2010. Investment grants peaked in 2009 at $26 million. Finally, the company was exempted from a number of payments for acquired land use rights[41] (see overview of subsidies received by LDK Solar in Table 5).

Table 5: Overview of subsidies received by LDK Solar (in million $)

	2006	2007	2008	2009	2010
Electricity subsidies	0,8	3,1	4,7	4,8	33,3
Investment or R&D grants	1,5	3,6	1,9	31,5	5,6
Subsidies on land use rights				0,8	1,3

Source: LDK Solar annual reports

[40] This reflects the tax policy as amended in 2008 (Deloitte, 2013). In previous years, similar 2+3 arrangements were in force.

[41] Based on company annual reports.

Starting in 2008, these investment support measures were complemented by the provision of major loan facilities by the China Development Bank. According to an agreement announced on December 23rd, 2008, the China Development Bank would provide loans of up to $70 million for the expansion of the Yingli's cell manufacturing capacity by 100 MW[42]. More substantial support was offered from 2010 with multi-billion dollar loan agreements extended to LDK Solar ($8.9 billion), Suntech ($7.3 billion), Yingli ($5.9 billion) Trina and JA Solar ($4.4 billion each) (see overview of loans and credit agreements from State-owned banks to Chinese solar firms in Table 6). Due to their relatively high interest rates, these credit lines are frequently not drawn down by the firms. However, they function as de facto repayment guarantees for commercial lenders (Sanderson & Forsythe, 2013). As a result, Chinese firms were largely unaffected by the global financial crisis and could even increase their borrowing during the height of the crisis.

Table 6: Loans and credit agreements involving Chinese banks to Chinese solar companies since January 2010

Company	Amount ($M)	Banks
China Sunergy	160	China Development Bank
Daqo New Energy	154	Bank of China
Hanwa SolarOne	1,000	Bank of China
Hanwa SolarOne	885	Bank of Shanghai
JA Solar	4,400	China Development Bank
Jinko Solar	7,600	Bank of China
LDK Solar	8,900	China Development Bank
Suntech	7,330	China Development Bank
Trina Solar	4,400	China Development Bank
Yingli Green Energy	179	China Citic Bank, Bank of China
Yingli Green Energy	5,300	China Development Bank
Yingli Green Energy	144	Bank of Communications
Yingli Green Energy	257	Bank of Communications
Total	40,709	

Source: Mercom Capital Group[43]

[42] Yingli Green Energy, "Yingli Green Energy Subsidiary Signs Eight-Year US$70 million Loan Agreement with China Development Bank to Support Expansion Plan", December 23, 2008. Accessed on September 11, 2013 at: http://ir.yinglisolar.com/phoenix.zhtml?c=213018&p=irol-newsArticle&ID=1302113&highlight=

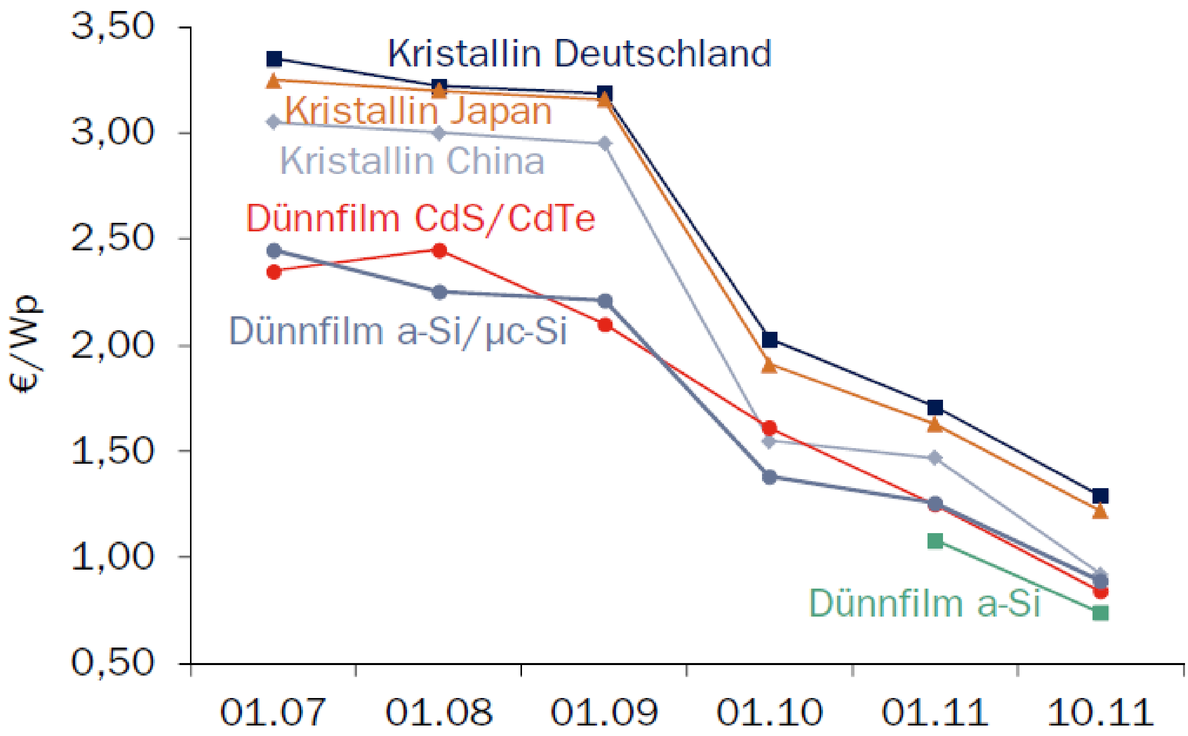
[43] Based on entry in News&Analysis on the website of Mercom Capital Group. Accessed on September 11, 2013 at: http://mercomcapital.com/loans-and-credit-agreements-involving-chinese-banks-to-chinese-solar-companies-since-jan-2010

Finally, parallel to these large-scale investment activities, an important wave of smaller scale, private investments in the industry was taking place. Investments targeted smaller scale module production and the supply of components for the PV industry. While such SMEs are likely to have access to investment incentives offered by local high-technology industrial parks, they do not enjoy easy access to government-backed VC funding or bank financing. Rather Chinese small and medium-sized enterprises operate in a severely finance-constrained environment where investments by individuals and other informal financing mechanisms represent the bulk of early stage financing (Allen, Qian, & Qian, 2005; Huang, 2006; Xiao, 2011).

4.2.5 Development of scale economies and cost reduction

As mentioned above, in China system prices did not come down to the levels of Germany by 2010, presumably due to the relatively small market, the availability of capital subsidies and the lack of competition at the local level. Modules, however, have been priced significantly below those produced in Europe (see Table 6). From 2007, spot market prices for Chinese modules have been €0,30 to €0,45 lower than for European modules (see Figure 10).

Figure 10: Spot market prices for modules from Germany, Japan and China



Source: Fawer & Magyar (2011, p. 10)

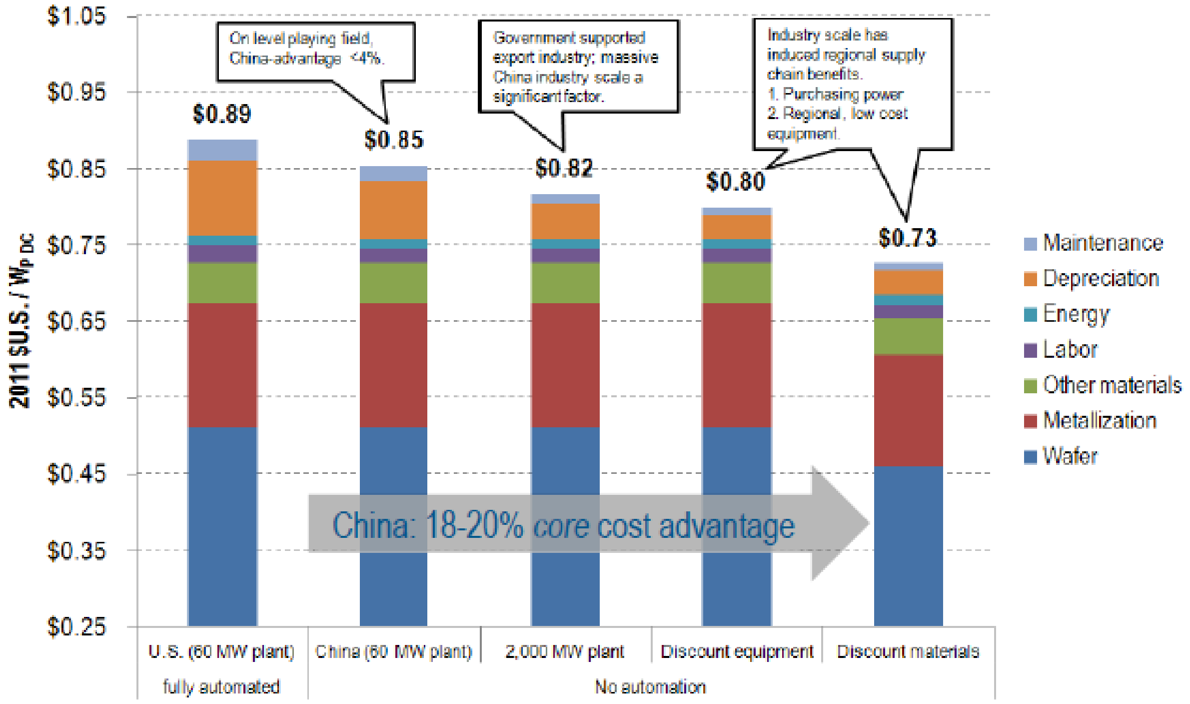
There is a considerable degree of dispute regarding the question of how Chinese firms have been able to sustain this price difference. While no final conclusion can be drawn here, a number of contributing factors may be cited. Firstly, Chinese firms have focused almost exclusively on the low-cost production of silicon-based solar modules and have exploited China's enabling environment for low-cost manufacturing. According to annual reports of major Chinese manufacturers, semi-automated production processes and the increasing availability of domestically-produced low-cost equipment and components have helped reduce costs in China compared to other countries. According to media reports, Suntech was producing modules at a cost of $2,80 per W as early as 2003 (Powell, 2009). Secondly, not all Chinese manufacturers, in particular those entering the sector at a later date, had secured long-term supply agreements for large volumes of polysilicon. As a result, they could take better advantage of falling spot market prices. Given the large additional investments in production capacity in 2009 and 2010, it is likely that an important share of total production has been able to benefit from these lower raw material prices.

Additionally, Haley & Haley (2013a, 2013b) and others have argued that investment support measures and subsidies and with access to abundant financial resources have provided Chinese manufacturing firms with an (unfair) cost advantage in relation to their European counterparts. Whether or not subsidy levels are truly above those in Europe or the US is difficult to establish, given the fundamentally different role of State actors in economic and financial sector governance in China and the West[44]. What is clear, however, is that governance of China's PV sector enabled further expansion of productive capacity after 2008, despite clear signals that further investments would most likely exacerbate already existing over-supply in the sector. This "irrational exuberance", fuelled in no large part by equity from international investors, was further stimulated by the central government's announcement in 2009 that it would support the PV industry within its strategy to support "strategic emerging industries".

The result was a further doubling of production capacity in 2009 and 2010 (see Figure 3) and the emergence of 7 or 8 companies with a production capacity of more than 1 GW. The largest producers, Suntech and JA Solar, even reached close to 2 GW of production capacity (Jäger-Waldau, 2011 p. 26-32). This provided these firms and the Chinese industry as a whole with important scale economies. Goodrich, James, & Woodhouse (2011) have estimated that the combination of internal and external economies of scale translate into a cost advantage for Chinese producers of approximately $0,12 per Wp (see Figure 11). More importantly, it created an unprecedented over-supply and a market environment driven by aggressive pricing strategies aimed at increasing market share. The result has been a dramatic reduction in module prices since 2009 (Jäger-Waldau, 2012; Mints, 2012; Willeke & Räuber, 2012).

[44] A number of commentators refer to China as a system of "State capitalism" in contrast to the liberal capitalist system of the West (Bremmer, 2008).

Figure 11: Estimates of core manufacturing costs of silicon-based PV cells



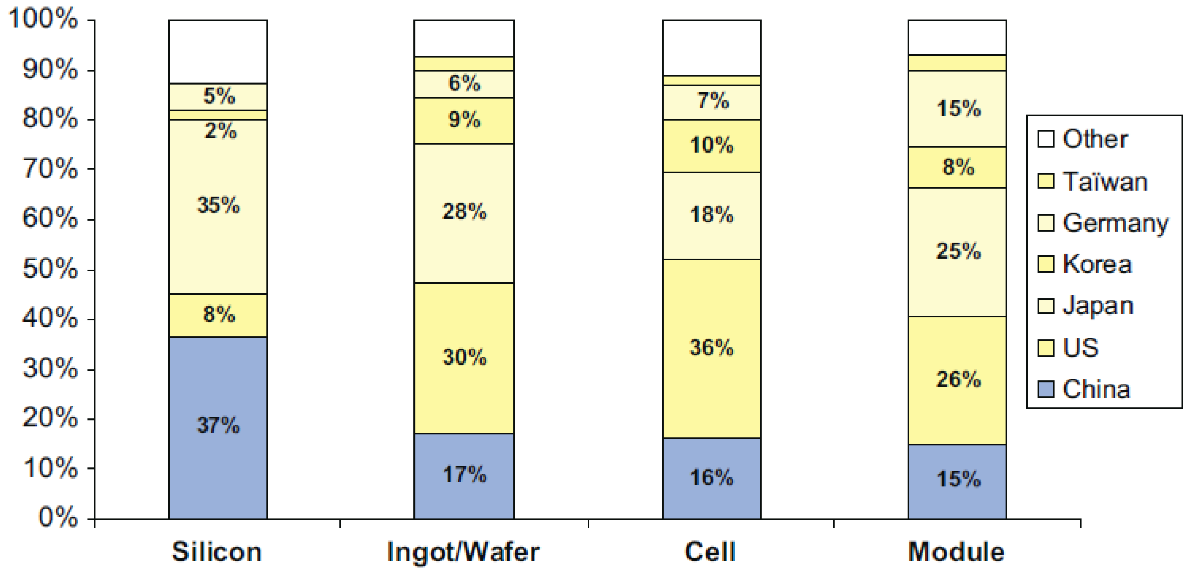
Source: Goodrich, James, & Woodhouse (2011)

4.2.6 Knowledge development and diffusion

Until 2010, knowledge development in the Chinese solar energy sector still lagged significantly behind the activities in the leading countries of Germany, Japan or the US. The 11th Five Year Plan for Science and Technology did not place an important emphasis on supporting research in the PV sector, labeling it as low priority compared to wind or biomass-related energy technologies. Nevertheless, R&D funding increased to approximately $30 million[45] for the period 2006 to 2010 (Huo & Zhang, 2012). R&D in the field of silicon production was considered the highest priority. Among other things, a strategic cooperation with a Russian research institute had the purpose of narrowing the significant technology gap between Chinese and Western silicon producers (Fischer, 2012, p. 138). A result of these efforts, China's share of international patents in this particular area shot up to 37 percent in 2006/2007, more than any other country (see Figure 12). In other segments of the supply chain patenting activities also increased, but have remained significantly behind world leaders Germany and the US. Similarly, in 2008, R&D intensity among the top Chinese firms remained well below 1 percent of annual turnover and thus below global leaders, like Schott, Q-Cells or Solar World (de la Tour et al., 2011, p. 766). More recently, however, a number of Chinese firms have begun to close the gap in R&D spending as figures for 2009 and 2010 reveal (see Table 7 in the annex).

[45] Based on an estimated of ¥210 million. Converted based on exchange rate on 1.1.2010 (¥6,82 per 1 US$).

Figure 12: Percentage of world patented innovation by segment and country in 2006-2007



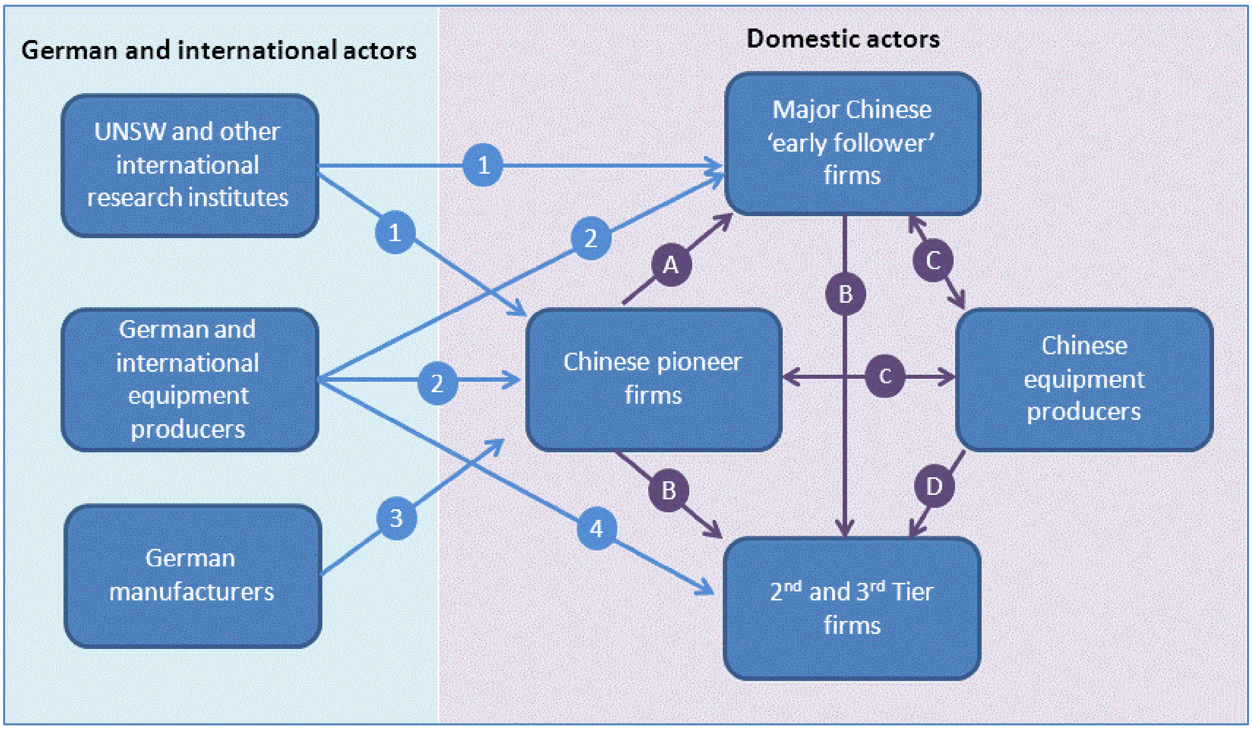
Source: de la Tour et al. (2011, p. 766)

At the firm-level, knowledge development up to approximately 2007 remained mainly focused on acquiring existing know-how to launch state-of-the-art production lines. This had both a domestic and an important international dimension. Figure 13 below provides a stylized depiction of the key actors and processes of knowledge diffusion. It highlights four central international linkages through which knowledge was transferred to Chinese firms. The most important of these linkages remained the commercial relationships between German and other international equipment producers, on the one hand, and Chinese manufacturing firms, on the other. With a world market share of over 50 percent, German equipment producers supplied the majority of foreign machinery to Chinese firms (Wessendorf, 2012). Moreover, the sale of equipment was typically accompanied by consulting services for commissioning. This enabled Chinese firms to equip their production lines with cutting-edge technology as they rapidly built up their capacity. From 2006, so-called turnkey production lines from firms like Centrotherm and Schmid Group[46] appeared on the market, further lowering the barrier to enter the PV sector. Such turnkey lines were mainly supplied to 2nd or 3rd tier producers without the in-house expertise available at the larger firms[47].

[46] Based on company annual reports and websites.

[47] Based on interviews with industry experts.

Figure 13: International and domestic processes of knowledge diffusion



International knowledge transfer mechanisms

1. Human resources transfer, R&D cooperation, licensing agreements; 2. Equipment purchase, consulting services and human resources transfer; 3. Coaching; 4. Purchase of (turnkey) equipment and consulting services; 5. Human resources transfer

Domestic knowledge transfer mechanisms

A. Human resources transfer; B. Cooperation via OEM agreements and cross-licensing; C. Mutual learning via equipment purchase and installation; D. Equipment purchase and installation

Further linkages emerged between leading manufacturing firms from Germany and a number of earlier entrants among the Chinese firms, including Suntech, Trina and SolarFun. These relationships might be characterized as pre-commercial. To meet the burgeoning demand in Germany, a number of manufacturers had explored the possibility of establishing OEM agreements and joint ventures with Chinese manufactures. In this context, they provided support to enable these firms to meet international quality standards[48]. Such direct exchanges were complemented by indirect linkages between Chinese and US firms via the transfer of human resources. A large number of Chinese-born professionals with experience, in particular in the American solar energy industry, returned to China to take key positions in the emerging Chinese industry (de la Tour et al., 2011, p. 765). This was not

[48] Based on interviews with industry experts.

limited to manufacturing firms but also included equipment providers. For example, LDK Solar recruited an entire research team from the US-based equipment supplier GT Solar[49].

Last but not least, a key linkage was established between leading Chinese firms and international research institutes, most importantly the School of Photovoltaic and Renewable Engineering at the University of New South Wales in Sydney. Not only Suntech's Dr. Shi, who obtained his PhD from the school, had close ties to the institute (Davila et al., 2009). Also a number of other PV firms were founded by or recruited Chinese graduates from UNSW, including CTOs and key R&D personnel at Yingli, Sunergy, SolarFun and JA Solar (Zhang & White, 2012). As the industry matured, these close ties became a central element of the emergent firm-based R&D strategies. A number of companies developed partnerships with the UNSW aimed at adapting and integrating the university's cutting-edge research into their production lines. These ranged from licensing agreements to broader knowledge partnerships, such as the collaborative agreement between UNSW, Sunergy and the JaiNing Development Zone in Nanjing[50]. In some cases, patents, which had been developed decades earlier were finally commercialized via these partnerships (Bullis, 2011). From approximately 2008, similar forms of cooperation began to emerge with other important international research centers. Notably the energy research center ECN in the Netherlands entered in cooperation agreements with a number of Chinese manufacturers, including Yingli, Canadian Solar and JA Solar[51]. In partnership with Dutch equipment producer Eurotron, ECN has been able to introduce its newest production techniques and cell concepts into the Chinese industry[52].

While these international linkages enabled Chinese firms to appropriate and develop cutting-edge knowledge from around the world, the transfer of human resources from China's pioneers to the early followers facilitated the transfer of key domestic knowledge. Additionally, domestic knowledge resources from the semiconductor industry and electronics manufacturing have contributed to the absorptive capacity of the young Chinese solar industry. Both researchers and industry professionals from these sectors have assumed key positions in many of the newly founded PV companies (Zhang & White, 2012). Moreover, a number of research centers have developed out of departments focused on semiconductors

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[49] Based on interview with staff at LDK Solar.

[50] School of Photovoltaic and Renewable Energy Engineering, University of New South Wales, "China Sunergy signs with SPREE," August 3, 2011. Accessed on September 11, 2013 at http://www.pv.unsw.edu.au/node/651

[51] Germany's major research institutes did not participate in these developments for the large part, remaining committed to their German counterparts.

[52] ECN, "ECN as gateway to the Asian energy technology market", March 2013. Accessed on September 11, 2013 at https://www.ecn.nl/newsletter/english/2013/march/ecn-as-gateway-to-the-asian-energy-technology-market/ and ECN, "New solar energy technology ready for mass production," December 2012. Accessed on September 11, 2013 at: https://www.ecn.nl/newsletter/english/2012/december/new-solar-energy-technology-ready-for-mass-production/

and material science research. For instance, researchers from the School of Material Sciences at Nanchang University founded the School of Photovoltaic Engineering in 2008, drawing on support from UNSW[53]. Finally, with the proliferation of 2nd and 3rd tier firms and a growing number of domestic component suppliers regional industrial clusters have developed in Jiangsu, Zheijang, Hebei, Jiangxi, Henan and Inner Mongolia (MIIT, 2012, p.4). Exchange of skilled personnel, supply relationships and cooperation in the form of OEM agreements are likely to have facilitated additional knowledge diffusion within the Chinese solar industry.

4.2.7 Influence on the direction of search

In the initial phase of industry development, activities in China were predominantly guided by developments in Germany and other markets, which developed in Spain, Italy and other European countries. To a lesser degree, prospects of capturing market share in the US also drove developments. The key goal was to reach European and US quality standards and attain corresponding certifications[54]. The importance of reaching a consistently high product quality was further reinforced by conditions imposed by certain investors engaged in the financing of medium-to large-scale solar parks. To ensure the expected return on investment, panels for use in large-scale European installations were individually checked by independent auditors[55]. Efforts to secure the needed quality for market entry was complemented by activities aimed at attaining cost leadership and at increasing market share via increased volumes of production and aggressive pricing strategies (Mints, 2012).

Like in Germany and elsewhere, a key driver of R&D efforts was the high-price of polysilicon, stimulating research aimed at reducing material inputs and developing the ability to utilize lower grade silicon[56]. This was complemented by a strategic focus of public R&D efforts in developing the technological capabilities for producing low-cost silicon in China (de la Tour et al., 2011; Fischer, 2012). Overall, however, the low levels of public R&D spending in China suggest that domestic R&D policy played only a minor role in influencing activities among Chinese firms. Instead ties with international research institutes provided firms with the needed orientation for developing R&D programs.

4.2.8 Development of positive externalities

The investment boom from 2004 to 2010 enabled a wide-range of positive externalities to take shape, offering significant benefits to later entrants. As a first step, the increasing investment in production facilities motivated European equipment suppliers to target the

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[53] Information collected at visit to Nanchang University.

[54] Based on company annual reports.

[55] Based on interviews with industry experts.

[56] Based on company annual reports.

Chinese market and develop offices and services targeting the needs of Chinese customers. Conversely, pioneers like Yingli, Suntech and CSI established Chinese solar modules with international credibility, facilitating easier access to the German and other European markets for later entrants. Next, as the number and size of production facilities increased, markets for suppliers and equipment producers emerged locally, enabling manufacturers to procure low-cost equipment (Honghua et al., 2012, p. 3)[57]. Manufacturers and suppliers have concentrated in clusters around a number of lead firms. The largest cluster is located in the neighboring provinces of Jiangsu and Zheijang (Suntech, CSI, GCL, JA Solar, Solarfun, ReneSola, Sunergy, Trina, Hareon), while secondary clusters have emerged in Hebei (Yingli, JA Solar) and neighboring Inner Mongolia and Henan provinces as well as Jiangxi province (LDK Solar, Jinko).

Next to the Marshallian externalities typically associated with industrial clusters, i.e. local knowledge spillovers, labor market pooling and the availability of specialist suppliers (Krugman, 1991; Marshall, 1920), the emergence of these clusters stimulated action first by local governments and eventually the central government. In other words, the successful performance of the pioneer firms helped garner increasing support aimed specifically at strengthening the emergent cluster dynamics.

5 Co-evolutionary dynamics: the role of transnational linkages and feedbacks

As already alluded to throughout the analysis above, a number of system functions both in Germany and China were not supported locally but were supplied by actors and dynamics abroad. To enable this, an increasing number of transnational linkages, in particular between the Chinese and the German TIS, developed. These linkages in turn unleashed a series of mutually reinforcing inter-dependencies and feedbacks, which helped to accelerate developments in China, Germany and a number of third countries. The following section provides a characterization of the most important transnational linkages as well as the dynamic feedbacks they helped trigger.

Given their unparalleled scale, the German-Chinese linkages may be considered the core drivers of growth and geographic reconfiguration of the TIS for solar PV during the period under consideration. In the following, they are, therefore, treated as exemplary for the broader dynamics of the TIS. Linkages with third countries are mentioned only if the particular type of relationship is not represented in the set of linkages between Germany and China and if they had important repercussions for developments in China or Germany.

The linkages discussed in this section are divided into three categories, which serve as a basic analytical framework for the following section:

[57] Solarbuzz, “Chinese PV Equipment Suppliers Grab Further Market-Share Gains,” January 16, 2012.

1. Commercial linkages: Commercial linkages are loosely equated to what Bell & Albu (1999) have called “transaction linkages” within a production system. According to Bell & Albu, “The production system can be understood to encompass the product designs, materials, machines, labor inputs, and transaction linkages involved in production of goods to a given specification.” (p. 1723).
2. Knowledge linkages: The linkages across production systems are distinct from a second set of linkages, which help bridge the knowledge systems of China and Germany and which are hence referred to as knowledge linkages. Again following Bell, “The knowledge system concept […] encompasses those flows of knowledge, stocks of knowledge and organizational systems involved in generating and managing changes in the products, processes or organization of production.” (p. 1793). While partly overlapping with the production system (Bell & Albu, 1999, p. 1793), it serves as a useful analytical device for distinguishing linkages directly related to the transfer of hardware, i.e. the exchange of productive inputs and finished products, from linkages supporting the transfer or development of knowledge.
3. Financial linkages: A third set of transnational linkages, particularly important in the development of China’s PV industry, relates to interconnections within the realm of the international system of finance. While also inter-related with the production system, these financial linkages involve a distinct set of actors and processes and are, therefore, treated separately. Notably, this is one key area where linkages between Germany and China did not play a central role in TIS development.

5.1 Emerging transnational linkages from 1999 to 2003

In the early phase of Chinese industry development to 2003, linkages between Germany and China remained relatively limited. The only foreign-invested ventures in China’s solar industry were Japanese and Canadian. Nevertheless, first commercial linkages had emerged. While equipment was primarily sourced from the US in the 80s and 90s, Chinese companies began to source equipment from Germany and other European countries towards the turn of the century (Marigo, 2007, p. 146). Japanese equipment imports were less important, since Japanese manufacturers have been less reliant on the external procurement of equipment and have limited exports of their in-house equipment to protect their technologies from competitors (Marukawa, 2012, p. 13).

Simultaneously, the first Chinese modules were being shipped to Germany. In 2002, Chinese exports of solar cells and modules to Germany stood at US$11,8 million (Kirkegaard et al., 2010, p. 54). The relationship between Germany at this stage should not be characterized as unique or especially intense when compared to other leading countries, i.e. the US or Japan, however. Exports to Japan and the US had a similar volume. Overall shipments of solar products from China to the rest of the world represented less than 1 percent of global shipments in 2003 (Mints, 2012, p. 62). In addition, China’s rural electrification programs were co-financed by international donors and, like Germany’s 100,000 rooftop program, were partly supplied by established foreign module producers.

As mentioned above, an important knowledge relationship for the development of the Chinese TIS was the link between Suntech's Dr. Shi and the UNSW in Australia. The location of a world-class solar energy research institute in a country, which is not only relatively close to China geographically but which had not developed a significant solar PV sector of its own, made this collaboration particularly promising for both sides. As will be argued in the following section, this international knowledge partnership evolved into one of the crucial factors in enabling the rapid development of the Chinese industry after 2003. In Germany, international knowledge partnerships played a less significant role, given the substantial domestic stock of knowledge that firms could draw on. Nevertheless, a number of new ventures also engaged in exchanges with producers in the US to acquire important know-how. For instance, Solar World cooperated with US-based GT Equipment Technologies to establish its first in-house facility for the production of solar-grade silicon[58].

5.2 Transnational linkages from 2004

5.2.1 Core commercial linkages between Germany and China

As the TIS entered its growth phase in 2004, the core commercial linkages between China and Germany started developing rapidly. Firstly, Chinese manufacturing firms imported increasing volumes of German-made equipment for establishing and expanding their production lines in China. As indicated in the graph below, German equipment exports to Asia had already surpassed domestic sales by 2007, representing between one third and one half of total sales. With annual world market shares of 30 to 50 percent (see Figure 14), German equipment suppliers have thus played a central role in enabling the development of the Chinese TIS. Not only did equipment suppliers deliver the needed machinery, but they also supplied important consulting services to make use of this equipment.

The depth of German engagement in enabling China's industrial development is further underlined by the dominance of German suppliers of turnkey equipment. In 2009, five of the six largest producers of turnkey equipment for silicon-based PV wafers, cells and modules were German (Heup & Rentzing, 2009, p.60). With an even larger share of Asian sales than overall, German-made turnkey production lines have represented a key vehicle for second or third tier producers to enter the sector. Since contracts for the delivery of turnkey equipment typically included warranties for the performance of machinery, suppliers were obliged to help manufacturers with commissioning[59].

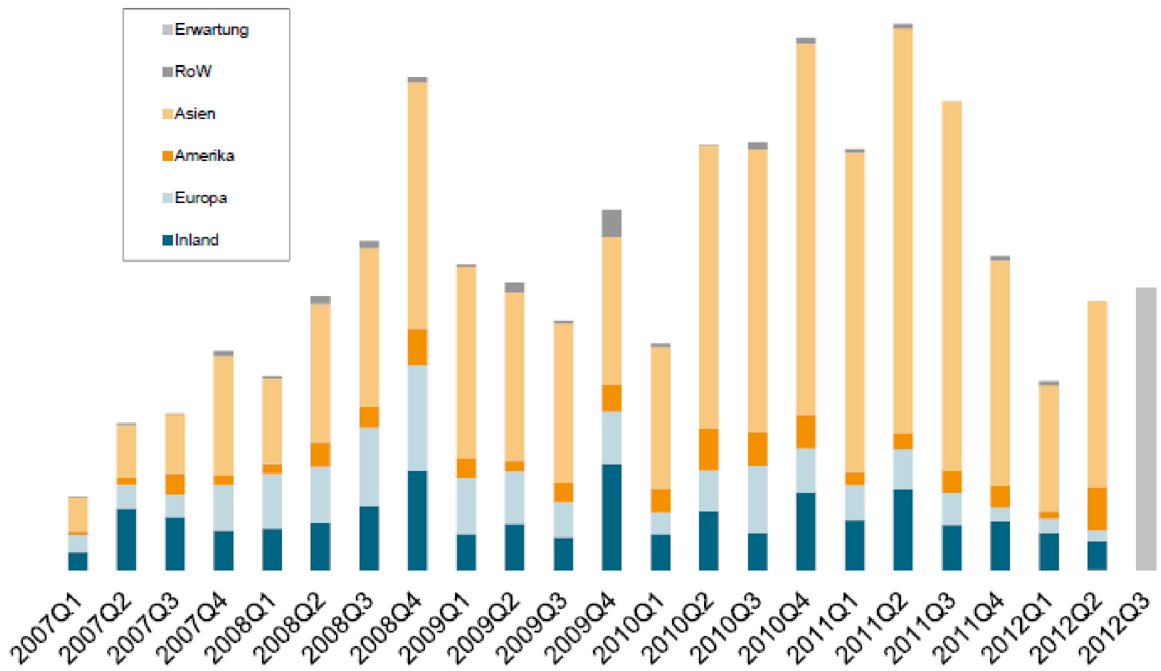
Simultaneously, equipment sales to China and other Asian countries have enabled German equipment producers to generate the needed revenue to reduce equipment costs and invest in industrial-scale production of specialized components. In other words, Asian in-

[58] Based on SolarWorld company website: http://www.solarworld.de/nc/konzern/der-konzern/unternehmensgeschichte/2001/?sword_list[0]=gt&sword_list[1]=equipment

[59] Based on interviews with industry experts.

vestments have represented a key to the development of economies of scale within the German equipment sector. Moreover, they helped German equipment suppliers in making some of the highest R&D expenditures in the industry, both in absolute terms and by share of revenue (see Table 7 in the annex), thus helping to drive further improvements in equipment and processes.

Figure 14: Sales of German equipment manufacturers by region



Source: VDMA 2012

The second key linkage directly followed from the rapid entry of Chinese firms in the PV sector. With the support of German equipment producers, Chinese manufacturing firms rapidly increased their exports of modules, cells and wafers to Germany and other European countries. The share of Germany's PV-related imports from China grew from 19 percent in 2005 to almost 50 percent in 2010 (Kirkegaard et al., 2010, p.54). Underlying this export success were a number of commercial relationships with German firms as well as certification bodies. In the beginning stages, Chinese module producers established relationships with project developers as well as German manufacturing firms, for which they provided OEM services. Only after having established the credibility of Chinese modules in the German market and having acquired certifications from TÜV and VDE did Chinese manufacturers pursue strategies targeting the residential market via distributors. In addition, as specialized cell and wafer producers from China started entering the market from approximately 2006, supply contracts with German module or cell producers became a third important supply chain linkage[60].

It may also be noted here that mergers and acquisitions did not play a significant role in developing international linkages between Chinese and foreign firms. Notable exceptions are Suntech's acquisition of the German firms Kuttler Automation Systems and CSG Solar and Japanese module manufacturer MSK Corporation as well as LDK Solar's acquisition of SPI, a US-based project development firm.

5.2.2 Knowledge linkages

While the Chinese-German commercial linkages represented the core drivers of TIS dynamics, the knowledge linkages discussed in the following section might be considered important enabling factors. Three partly inter-related, transnational knowledge linkages supported the development and increasing competitiveness of the Chinese TIS. As described in section 4.2.6, one important linkage between China's PV industry and leading sources of global knowledge was embodied in the increasing number of Chinese returnees (de la Tour et al., 2011). They brought international experience, mainly from US-based firms, as well as skills developed in foreign educational institutions to the Chinese PV sector. A key source of foreign graduates was the School of Photovoltaic and Renewable Engineering at the UNSW in Sydney, while returnees from Germany played no major role.

Out of the strong personal ties between the Chinese PV industry and UNSW a number of formalized knowledge partnerships between UNSW and the Chinese PV industry developed. These included licensing agreements, R&D partnerships and broader cooperative agreements. As the TIS developed, licensing agreements and R&D partnerships were also established with other foreign research institutes, notably ECN in The Netherlands (see section 4.2.6 above) . This did not, however, include partnerships with institutes in Germany. Given the large dependence on German government funding, a tacit agreement existed to refrain from activities aimed explicitly at transferring knowledge to industry in foreign countries[61].

Ironically, however, in the early stages of Chinese industry development, a number of large German manufacturers entertained ties with selected Chinese firms with the prospect of entering into a joint venture at a later data. Although these joint ventures did not materialize, these firms provided their emergent competitors with important support in developing the capacity to produce solar modules with sufficient quality to meet international standards.

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[60] Based on company annual reports.

[61] Based on interviews with German researchers.

5.2.3 Financial linkages

Transnational financial linkages were another key enabler of TIS development and growth. As indicated in section 4.2.4, international investors supplied Chinese manufacturers in the form of VC, private equity and public equity. Important foreign VC and private equity funds were based in the US, Hong Kong, Singapore, the UK, Switzerland, Australia, Israel and Japan. Interestingly no major investment was made by a German fund. In addition, major capital injections came from international investment banks and their subsidiaries. Important investments were made by Goldman Sachs, Citigroup, Merrill Lynch, JP Morgan Chase, HSBC as well as Deutsche Bank (Zhang & White, 2012, p. 52-53). Finally, with one exception, all IPOs were made via the New York-based stock market, i.e. NYSE and NASDAQ. ReneSola represents the exception with two successive IPOs, a first in London (LSE) and a second in New York (NYSE). The importance of public equity in driving Chinese industry growth was immense. According to BNEF data public equity accounted for more than half of total investment in 2005, 2007, 2008 and slightly under 50 percent in 2006 and 2009, while government debt remained negligible at that stage. Only with the entry of the China Development Bank in 2010 did this change[62].

5.3 Key impacts and feedbacks

As a result of these increasing cross-country linkages as well as the market and industry dynamics they triggered, developments in the solar energy sectors of China and Germany have also become increasingly inter-dependent. At the beginning of the period under consideration, developments in the respective policy, market and industrial systems were still relatively unaffected by each other. With the growth of a large, export-oriented solar industry in China, largely dependent on sales to Germany, this changed drastically. As a consequence, developments have become increasingly co-evolutionary, characterized by distinct country-level dynamics yet influenced by developments in the other country. In the following, the most important cross-country impacts and feedbacks are outlined.

Firstly, Chinese exports to Germany may be considered both the cause and the effect of the rapid growth of Chinese PV industry. On the one hand, they supplied the revenue and the credibility – both domestically and in the international financial markets - to pursue large-scale investments in productive capacity. On the other hand, they represent the outcome of increasing investment activities. Simultaneously, Chinese module production enabled the exponential growth of the German PV market. As early as 2007, Chinese productive capacity had outstripped Germany's. By 2008, Chinese capacity was almost 50 percent greater, and by 2010 it had reached more than five times the level of Germany (Figure 3). These large investments in productive capacity became a key to the decline in module prices and the subsequent market acceleration in Germany. In the absence of these price

[62] Based on the Bloomberg New Energy Finance Investment Database.

declines, profit margins for project developers and residential customers would not have permitted the large scale market growth witnessed in 2009 and 2010.

In a second step, these market and industry dynamics had feedbacks at the policy level with important implications for the further development of the sector. The immediate result of industry growth and the resulting price reductions was the ability and necessity to reduce German feed-in tariffs without jeopardizing continued market development. In a revision of the Renewable Energy Act on passed on October 31, 2008, German policy makers increased the annual reductions of the solar feed-in tariff from 6.5 percent to between 8 and 10 percent, depending on the type of installation. As these measures failed to curtail market growth, another revision of the law was initiated in early 2010, leading to a host of one-time FIT reductions as well as a scheme for a dynamic system of tariff reductions for subsequent years. Based on the growth recorded in the market, FIT reductions were to be adjusted to contain market growth within a fixed corridor. While the measures were largely unsuccessful, they increased uncertainty in the market. This was further compounded by even more dramatic events in Spain. There the same underlying dynamics resulted in a spectacular overheating of the market in 2008 followed by the total collapse of the Spanish subsidy scheme in 2009.

In a third step, these events in Germany and Spain were in turn mirrored by important policy changes in China initiated in 2009. Next to the launch of the Rooftop and Golden Sun programs, the government raised the solar PV target for 2011 to 2 GW. This was followed up in 2010 with the implementation of a bidding process for the allocation of feed-in tariff-style subsidies for a total of 280 MW. Moreover, in an explicit effort to boost the sales of its renewable energy industry, the Chinese announced plans to launch a new energy stimulus plan, including a target of 20 GW for solar PV by 2020 (Martinot, 2010; SEMI & CPIA, 2011). While no single factor can explain this major shift towards developing a domestic market for solar PV, the following impacts and subsequent feedbacks from the largely export-led development of China’s PV industry were clearly crucial:

- The development of over-capacity, mainly in China, leads to a rapid decline of module prices, making solar energy both more affordable as an energy source and less lucrative for domestic manufacturers.
- Resulting rapid market growth leads to policy responses in Germany as well as Spain, creating a rise in policy- and hence market uncertainty.
- The Chinese government, faced with a large-scale manufacturing industry for photovoltaic cells and modules, responds by launching policies to develop its own market for solar energy, while elevating the sector to the status of a “strategic emerging industry”.

6 Summary of findings and conclusions

The above analysis has helped unpack the co-evolutionary process of TIS development in silicon-based solar PV technologies in the growth phase from 2004 to 2010 with a focus on the key countries, China and Germany. In doing so, it has not only shed light on the important role of transnational linkages and feedbacks in overall TIS development. It has also provided an analysis of China's rapid insertion in a global TIS, and its rise from its status as industry outsider to the position of the world's leading production center. Conversely, it contains a number of lessons regarding the interplay between policy, market and industry in Germany, the policy-driven lead market during the period under consideration. The following section offers a synthesis of key empirical insights in these three areas and discusses their theoretical and policy-related implications.

6.1 Co-evolutionary dynamics

As already highlighted in the previous section, this study has demonstrated the growing importance of transnational linkages between China and Germany for understanding the dynamics of TIS development in both countries. In a process of co-evolution, each country depended on developments in the other country to enable the rapid growth of the global solar energy sector that occurred between 2004 and 2010. Nevertheless, in many respects, each national-level TIS remained highly autonomous. Given the policy-driven nature of demand, domestic markets also remained dependent on national policy makers. Moreover, firms retained a clear national identity with no multinational players emerging who entertained production facilities in both countries. As a result, industry dynamics and firm strategies were strongly shaped by the respective national innovation system and its underlying model of economic governance.

In the resulting co-evolutionary dynamics of global TIS development, the mutual support of weak or missing system functions enabled an international process of cumulative causation, accelerating TIS development in both countries via a number of cross-country impacts and feedback loops. Of particular importance for this mutually reinforcing process are the exploitation of the asymmetries across country-level TIS by actors based in one country yet entertaining linkages to developments abroad. While the German feed-in tariff and the highly developed project-based financing mechanisms in Germany were key to large-scale market formation, China's strongly production-oriented investment climate with a focus on established business models and technologies was an important enabler of the development of scale economies and cost reduction.

This depiction of TIS development revises the simplistic notion of a lead market, where an innovation reaches significant market penetration before diffusing to other lag markets (Beise, 2001, 2004). It gives rise to a more nuanced understanding of how country-level differences shape the development and geographic reconfiguration of emerging industries. In this case, China, a lag market in terms of demand, has played a key role in fuelling the expansion of supply to the emerging lead market and, via the feedbacks described above, has enabled the acceleration of market growth. Moreover, while China acquired important production equipment and expertise from Germany, it has also tapped into other international knowledge resources to advance the technology frontier. Rather than merely absorbing and adapting knowledge, China has become a producer of knowledge in its own right

(Bullis, 2011). In other words, as China has matured as a country-level TIS, it has not only fuelled the spectacular growth of the global industry but it has also begun to support innovation within the emergent global TIS.

6.2 The rise of China

A second important contribution of the study has been to identify the key factors, which have contributed to the success of Chinese TIS development. It has shown the importance of the cooperation between entrepreneurs and local governments in combination with key transnational linkages, which helped support relatively weak or virtually non-existent system functions, like resource mobilization, market formation or knowledge development. While the local governments provided entrepreneurs with support in accessing domestic capital and other key inputs, like land or low-cost energy, entrepreneurs remained in control of developing the strategic direction of their companies. Tapping into international market opportunities and resources, they took their main orientation from booming markets in Germany and other European countries, which helped them fuel their strongly growth-oriented strategies. This included the core import-export relationship with German equipment suppliers, on the one hand, and German manufacturers, system integrators and eventually distributors, on the other. This was complemented by the recruitment of foreign-trained Chinese and other international talent and knowledge partnerships with UNSW and other international research centers. Finally, the core source of funding to finance industry expansion came from international investors.

The central government on the other hand played no active role in promoting industry expansion until 2009. By 2008, however, China had already reached close to 30 percent of global production capacity and dominated imports in the major markets of Spain and Germany, accounting for a share of 51 and 37 percent, respectively[63]. In other words, it has been the broader Chinese innovation system and its model of economic governance, which provided suitable conditions for attracting the international investments, which fuelled the industry’s growth and ultimately over-supply. Many have pointed out the role of subsidies and access to abundant capital resources as the key explanatory factor for Chinese competitive advantage. However, until the entry of China Development Bank in 2009, the abundance of capital resources was a decidedly international phenomenon.

In an alternative perspective, the growth of China’s solar energy sector might be viewed as the outcome of an industrial development-oriented governance system, which places a high priority on channeling scarce financial resources into productive investments. Moreover, it represents a system where the mobilization of financial resources and the access to land remains inherently linked to State actors who remain key mediators in enabling entrepreneurs to access needed inputs. In this context, local governments act as entrepre-

[63] Author’s own calculations based on Kirkegaard et al. (2010, p. 54).

neurs and managers of local industrial growth, placing bets on the most promising ventures and supporting local champions. They engage in a process of firm selection followed by a period of collaboration and support to enable firm success.

In the past, hi-tech enterprises, which have been selected and promoted in this way, have largely been State-owned enterprises, foreign-invested enterprises or joint ventures between the two (Bai, Lu, & Tao, 2010; Tuan & Fung-Yee Ng, 2007; Whalley & Xin, 2010).The solar energy sector reflects a trend towards the increasing importance of privately owned Chinese firms with the ability to attract funding from the financial markets (i.e. foreign portfolio investment) (Deng, 2013). In this case control over productive investments remained in the hands of Chinese entrepreneurs and their management teams. Moreover, unlike FDI-driven ventures, transnational linkages and access to foreign knowledge resources were not inherent to the firms themselves. Instead Chinese entrepreneurs have been particularly successful in leveraging the synergies of China's system of industry promotion, on the one hand, and international knowledge resources and production equipment, on the other.

While this study provides key insights on how this success took shape in one prominent industrial sector, a key avenue for future research is the exploration of the *industry*-specific aspects, which explain this Chinese success story. Why has this been possible in the PV sector, while other sectors have been less successful? What industry-level characteristics or policies might explain these differing trajectories?

6.3 Lead market dynamics in a policy-driven environment

In the German media, China's rise as global production center for solar cells and modules is frequently equated with the loss of Germany's industrial leadership (Gratzla, 2011; Volkmann, 2013). This is only partially true. Portraying Germany's cell and module manufacturing industry as the leaders of the PV industry is and was inaccurate. While Germany has represented the undisputed lead market from 2004 to the present, it has not held the same position in the supply of solar modules. While individual firms have recorded impressive growth stories, Germany has never represented the largest production center for solar modules and cells. Until 2007, Japan remained the leading manufacturer, albeit closely followed by Germany. By 2008 China had taken over that role. Moreover, German firms were never able to meet domestic demand, so that more than half of the German market was always supplied by foreign suppliers. Given the high export ratios of German manufacturers, import quotas were consistently above 60 percent.

As discussed above, this lag in supply represents an important factor in explaining the successful market entry of Chinese firms in Germany. No attempt will be made here to speculate on what might have occurred in the absence of the supply shortages witnessed between 2005 and 2008. Rather it is taken as a symptom of the fact that Germany's bold demand-side policies lacked a complementary supply-side strategy. While Germany maintained a high level of R&D and even provided investment support, especially in the Eastern part of the country, there was no strategy to address strategic bottlenecks, such as the silicon shortage. Given the fairly broad anticipation of the shortage and the leading position of German silicon producer Wacker, addressing this was merely a question of financing. Hence it could theoretically have been addressed by a concerted industry effort, possibly with the support of government or a public financial institution.

In addition, German firms were relatively late in exploiting the opportunities of low-cost manufacturing locations, including China. Given the rising importance of China, in particular in the area of clean energy technologies, this represents a second industry-wide miscalculation. While discussions to collaborate with leading Chinese manufacturers existed, these apparently did not yield the expected agreements. Given the ease with which technological capacities were developed by Chinese manufacturers, an earlier, more pro-active strategy to engage with the emerging Chinese firms would have been strategically important. It might have yielded a large, international firm under German leadership rather than vice versa.

Mobilizing large volumes of long-term finance to support such a venture represents a third systemic bottleneck. While China Development Bank entered the sector in 2010 and helped China's leading solar energy firms bridge the twin crises facing the sector (i.e. the global financial crisis and the mismatch between supply and demand), Germany's firms could not depend on similar, long-term financing commitments. Given the significant volumes of finance already committed via feed-in tariffs, investment support and R&D subsidies as well as the long-term strategic importance of the sector, the lack of a corresponding source of strategic financing to support emerging industries represents a key weakness in the German and European model of economic governance - in particular when considering the large volumes of public resources mobilized to support the European financial sector. It raises questions whether State support to the European financial sector has sufficiently taken into account the financing challenges currently constraining the development of leading European firms in emerging industries like solar photovoltaics.

Finally, it should be noted that, in spite of these weaknesses, Germany has developed and still maintains a leadership position in the global production of inverters and equipment for the solar industry. In other words, China's leadership position only applies to certain segments of the supply chain. Correspondingly, Germany has been able to leverage its lead market to promote leading industrial firms in selected segments of the supply chain. Unsurprisingly, these firms have developed out of existing businesses in areas where Germany exhibits a traditional strength and are mostly located in Southern Germany. Manufacturers of modules and cells on the other hand developed primarily as greenfield investments in East Germany. Hence their initial position was not drastically different from that of Chinese firms.

7 Annex

Table 7: Correlation of PV industry sales growth rates and R&D investment growth rate for public listed PV companies for the years 2004 – 2009

	Company		Value Chain Position	2009 R&D/sales	2009 [m€]	2008 [m€]	2007 [m€]	2006 [m€]	2005 [m€]	2004 [m€]	2003 [m€]
1	Solyndra[1,2]	US	CIGS module	84.2%	58.7	90.2	58.4	15.1	0.7	0.0	0.0
2	SMA Solar Technology[1,2]	DE	inverter	6.0%	56.3	34.7	19.7	15.6	12.3	n/a	n/a
3	First Solar[2]	US	CdTe module, system	3.8%	54.3	24.1	10.3	4.9	2.0	0.9	3.0
4	oerlikon Solar[2]	CH	Si-TF: equipment	13.9%	42.5	33.7	12.7	n/a	n/a	n/a	n/a
5	REC[2]	NO	c-Si: wafer, cell, module	3.3%	36.6	21.7	20.9	13.0	6.3	7.5	4.8
6	centrotherm PV[1,2]	DE	c-Si, CIGS: equipment	5.6%	28.4	16.8	7.4	1.9	1.9	1.1	n/a
7	MEMC Electronic Mat.	US	c-Si: Si, wafer, system	3.5%	28.0	29.3	26.7	27.2	28.0	28.3	26.1
8	Q-Cells[1,2]	DE	c-Si: cell, module, system; CIGS/CdTe module	3.3%	26.5	33.1	21.9	8.1	3.5	1.1	0.5
9	SunPower[1,2]	US	c-Si: cell, module, system	2.1%	21.9	15.4	9.2	7.4	5.5	10.1	7.8
10	Suntech Power[1,2]	CN	c-Si: cell, module, system; Si-TF module	1.7%	20.1	11.0	10.2	6.4	2.8	0.3	0.1
11	Yingli Green Energy[1,2]	CN	c-Si: Si, wafer, cell, module	2.5%	18.7	6.0	1.6	2.4	0.2	0.4	n/a
12	von Ardenne*[,2]	DE	TF equipment	10.0%	16.7	16.7	19.6	n/a	n/a	n/a	n/a
13	Roth&Rau[1]	DE	c-Si, CdTe: equipemnt	8.3%	16.5	4.9	2.5	2.7	n/a	n/a	n/a
14	Meyer Burger[1]	CH	c-Si: equipment	5.3%	15.2	14.6	7.7	6.2	n/a	n/a	n/a
15	GT Solar[1]	US	c-Si: equipment	4.4%	15.0	11.9	6.8	2.9	1.5	n/a	n/a
16	Schott Solar*[,2]	DE	c-Si: cell, module, system, Si-TF module	4.0%	13.5	13.5	13.3	12.7	9.8	n/a	n/a
17	Evergreen Solar[1,2]	US	ribbon-Si: wafer, cell, module	6.7%	12.6	15.8	14.0	14.0	9.7	3.7	3.0
18	Manz automation[2]	DE	c-Si-, TF: equipment	14.1%	12.1	10.3	3.6	2.3	1.4	n/a	n/a
19	SolarWorld[1,2]	DE	c-Si: wafer, cell, module, system	1.2%	12.0	13.0	10.8	8.6	8.3	8.5	4.5
20	Wacker BU Polysilicon	DE	c-Si: Si	1.0%	11.3	5.4	6.3	5.1	5.3	6.0	n/a
21	DayStar Technologies[2]	US	CIGS	-	10.2	12.7	7.1	7.6	3.0	1.2	0.2
22	ReneSola[1]	CN	c-Si: wafer	2.8%	10.1	7.0	0.7	0.0	0.0	0.0	0.0
23	PV Crystalox Solar	DE	c-Si: Si, wafer	3.5%	8.4	6.2	4.4	4.1	4.2	3.8	n/a
24	Satcon Technology[1,2]	CA	inverter	16.0%	5.8	3.7	1.6	1.5	5.0	4.5	5.2
25	LDK Solar[1]	CN	c-Si: Si, wafer, cell, module, system	0.8%	5.8	5.5	2.2	0.2	0.1	0.0	0.0
26	E-Ton Solar	TW	c-Si: cell	1.7%	4.8	9.5	2.6	0.8	n/a	n/a	n/a
27	Arise Technologies[2]	CA	Si-TF module	22.4%	4.7	3.8	2.7	0.4	0.4	0.3	0.3
28	Motech	TW	c-Si: cell, module	1.2%	4.7	5.7	4.1	1.1	n/a	n/a	n/a
29	JA Solar[1,2]	CN	c-Si: wafer, cell, module	1.2%	4.6	3.0	0.4	0.2	0.0	0.0	0.0
30	Solon[1,2]	DE	c-Si: module, system	1.1%	3.8	2.5	2.5	2.5	1.2	0.9	0.9
31	ECD Ovonic Solar[2]	US	Si-TF module	1.8%	3.8	2.6	2.5	2.3	2.2	6.4	3.0
32	Trina Solar[1,2]	CN	c-Si: wafer, cell, module	0.6%	3.7	2.2	1.9	1.44	0.10	0.19	0.0
33	Solarfun[1,2]	CN	c-Si: wafer, cell, module	0.8%	3.3	2.1	2.6	0.7	0.1	0.0	0.0
34	China Sunergy[2]	CN	c-Si: wafer, cell, module	1.5%	3.1	1.4	1.8	0.4	0.0	0.0	0.0
35	Dyesol[2]	AU	DSSC material	192.5%	3.0	1.1	1.0	0.6	0.2	n/a	n/a
36	PVA TePla	DE	c-Si: equipment	1.8%	2.5	1.8	1.7	1.6	1.3	1.5	1.7
37	Canadian Solar[1,2]	CN	c-Si: cell, module	0.5%	2.2	1.3	0.7	0.3	0.0	0.0	0.0
38	Timminco	CA	c-Si material	3.2%	2.2	0.2	0.8	0.7	0.5	0.4	0.0
39	Day4 Energy[2]	CA	c-Si: cell, module	5.2%	2.1	1.3	1.3	0.9	0.8	0.3	n/a
40	Sunways[1,2]	DE	c-Si: cell, module	1.2%	2.1	3.0	2.7	2.9	2.3	1.5	1.0
42	Conergy[1,2]	DE	c-Si: wafer, cell, module, system, inverter	0.3%	1.7	1.2	14.2	10.6	12.8	5.1	1.2
43	Neo Solar Power	TW	c-Si: cell, module	0.7%	1.5	1.8	0.5	0.5	n/a	n/a	n/a
44	Gintech	TW	c-Si: cell, module	0.4%	1.4	1.1	0.7	0.5	n/a	n/a	n/a
45	5Nplus	CA	CdTe material	1.7%	0.8	0.5	0.5	0.5	0.3	n/a	n/a

Source: Breyer et al. (2010)

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