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China's Trajectory from Production to Innovation. Insights from the Photovoltaics Sector

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Abstract

China's photovoltaics sector provides an interesting case to examine, if and how the country is aiming at innovation leadership after having established itself as the global manufacturing leader. Due to the dominance of Chinese companies in the global PV market, their innovation and production decisions have become crucially important for the global transition towards renewable energy. Another aspect of PV technology is that technological progress has driven the development of various types of PV cells, which can be categorised in three different technology generations. The functional analysis of the technological innovation system for PV in China conducted in this paper shows, that the government has indeed strengthened indigenous innovation efforts, which has resulted in a rapid rise of academic publications and to a lesser extent of patents for PV technology. A disaggregated analysis of transnational PV patents demonstrates that technological catching-up of China picked up speed in the period between 2008 and 2010 and takes place in all three technology generations. However. technological catch-up has been most successful in the third generation of PV cells, which is still at an experimental stage and predominantly conducted at public research entities. Overall, China's PV sector seems to be still quite far from attaining global innovation leadership, which is mainly due to the relatively low engagement of the corporate sector. However, as the first generation of PV currently dominates the world market and is technologically mature, this will probably not threaten industrial leadership in the short to medium term.

Keyword: Economic Catch-Up, Photovoltaics, Technological Innovation System, China

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1 Introduction

After a period of rapid economic growth in the years between 1980 and 2015, which was characterized by an average annual growth rate of 8.7 percent, China's growth rates have come down to 6-7 percent and are expected to continue to decrease. Important structural explanations for China's economic slowdown are rising labor costs and a reduction of the working age population (Wei et al. 2017). Against this backdrop, the question whether China is approaching or even is already caught in the so called middle-income trap is widely discussed in the macroeconomic literature (Glawe, Wagner 2017). The middle-income trap is characterised by a situation where a developing country is no longer competitive in markets for standardised, labour-intensive goods due to rising wages, but still cannot compete in markets for high value added goods due to lower productivity (Paus 2017). Besides stressing the continued need for structural reforms of the Chinese economy (Wagner 2015), one of the most popular policy recommendations in this situation has been to strengthen innovation and quality upgrading. The question whether China can embark on such a growth path, which is less reliant on investments in physical capital and more oriented towards increasing total factor productivity has been identified as being crucial for the country's future development (Wei et al. 2017; Altenburg et al. 2008).

Naturally, the capability to innovate varies widely among firms, but with regard to China as a country, innovativeness hinges on the quality of its national innovation system (NIS). According to Lundvall et al. (2009, p. 6), "a national innovation system is an open, evolving and complex system that encompasses relationships within and between organizations, institutions and socio-economic structures which determine the rate and direction of innovation..." Pertaining to developing countries and countries in transition, absorption and adaptation of foreign technology are important mechanisms for technological learning (Chaminade et al. 2009, 2009). Thus, linkages to external actors are of particular relevance and the integration of Chinese companies into global value chains has been identified as an important mechanism for the transfer of production capabilities to China (Altenburg et al. 2008).

An interesting question in this context is, if China still follows the paths established by the technological leading countries, for which it would basically be sufficient to invest in technological learning and adaptation, or if the country has started to create its own pathways for technology development. China's photovoltaics (PV) sector provides an interesting case to analyse, if and how the country is aiming

at innovation leadership after having established itself as the global manufacturing leader. Another aspect of PV technology is that technological progress has driven the development of various types of PV cells, which can be categorised in three different technology generations. This allows us to address the question whether China as a latecomer in PV technology is leapfrogging towards the most recent technology generation. This would follow from the hypothesis proposed by Lee (2013), who states that successful catch-up requires adopting the most recent technology design and not simply following the beaten paths of the technologically leading countries. An additional motivation for this study is, that due to the dominance of Chinese companies in the global PV market, their innovation and production decisions have become crucially important for the transition towards renewable energies and the global fight against climatic change.

In the following, the methodological approach and data sources of the study are described. The methodology is based on the functional approach of technological innovation systems (TIS) analysis (Section 2). Section 3 provides background information on the different generations of PV technology. Section 4 identifies and describes the most relevant actors and institutions of the TIS. Section 5 assesses to what extent the TIS performs in terms of key innovation processes. These key processes have also been termed 'functions of innovation'. Finally, section 6 draws conclusions from this analysis.

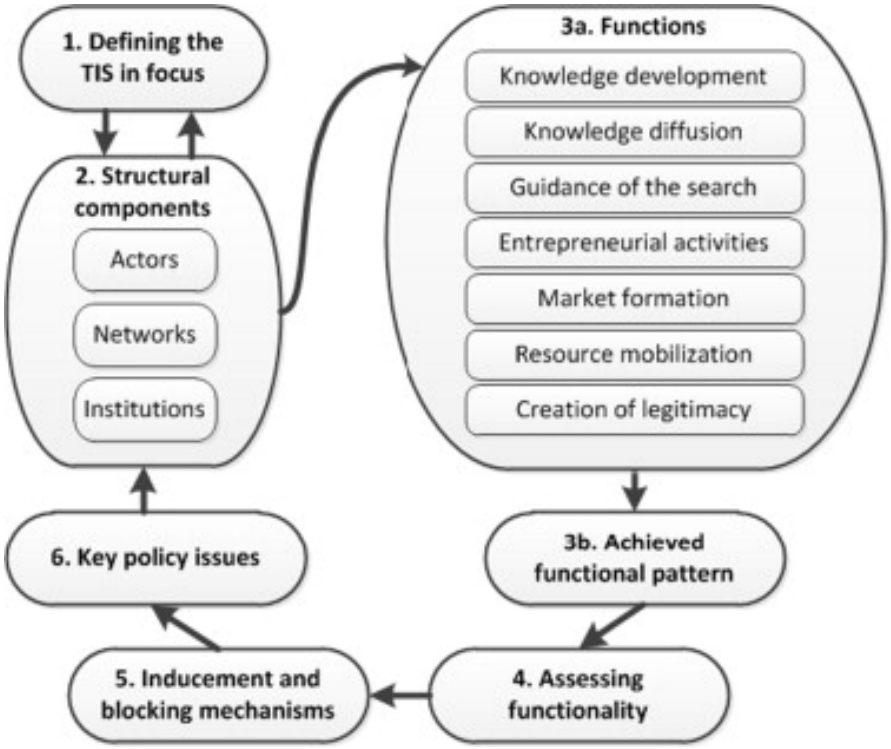
2 Methodological Approach

A framework widely applied for the analysis of innovation in the field of environmental technology is the Technological Innovation Systems (TIS) approach (Gosens, Lu 2013). The TIS approach was originally developed to complement the analysis of national and regional innovation systems, which is confined to innovation taking place within clearly defined geographic boundaries (Bergek et al. 2008). In contrast, the TIS framework acknowledges that many innovation processes are international in nature and thus focuses on the development, diffusion and use of a particular technology (Bergek et al. 2008). The functional approach towards technological innovation systems stresses the importance of innovation processes which determine the overall performance of the innovation system (Hekkert et al. 2007).

Bergek et al. (2008) distinguish the following innovation functions: knowledge development and diffusion, guidance of search, entrepreneurial activities, market formation, resource mobilisation, and creation of legitimacy. The main objective

of this analysis is to identify relevant policy issues and to set goals for the future development of the TIS. The overall scheme of analysis is displayed in Figure 1.

Figure 1: The TIS functional analysis scheme



Source: Bergek et al. 2008

The TIS framework has been applied to the PV in China before by other authors, e.g. (Huang et al. 2016; Quitzow 2015; Iizuka 2015, 2015). According to Huang et al. (2016), the rapid rise of the Chinese PV industry can be explained by the interaction of external factors, i.e. institutional changes, technology transfer and the large European market, as well as the strong internal dynamics of the TIS. The authors point out, that the development of the domestic market could further strengthen the performance of the Chinese TIS. Quitzow (2015) found that trans-national linkages had a strong influence on the development of the Chinese TIS and stresses the importance of interdependencies between the TIS in China and Germany. Likewise, Iizuka (2015), who applies a multilevel perspective to explain sustainability transitions in emerging economies, demonstrates on the example of China's PV industry how sustainability oriented regimes in developed countries influenced transitions in emerging economies.

Several earlier studies have arrived at the conclusion, that the success of China's PV industry can rather not be explained by high investments in R&D and superior innovation performance, e.g. De la Tour *et al.* (2011), Wu and Mathews (2012), and Grau et al. 2012). Instead, extant research points to the importance of technology acquisition and international technology transfer along the global PV value chain (Zhang, Gallagher 2016).

As most of these studies focus on crystalline silicon PV cells (e.g. Zhang and Gallagher, 2016; Quitzow, 2015), which is at present the dominant technology, the scope of analysis needs to be expanded to the newest technology generation. Moreover, the Chinese government has made innovation in renewable energy technology are priority in recent years and started several initiatives to strengthen innovation activities in this sector. As a more recent study suggests, China is currently on its way to establish itself as an R&D leader in the field of PV (Ball et al. 2017, p. 79). Hence, an updated analysis of the Chinese TIS for PV might reveal important differences compared to prior analysis.

The data for this analysis was gathered from various patent and publication analyses, company reports and other publicly available sources about policy, market, industry and technology development in China.

3 Technological Background and Intermediate R&D Output for Different Cell Types

Technological progress in photovoltaics has driven the development of different types of photovoltaic cells, each with distinct technological and economic properties. The related literature has proposed various approaches to categorize cell types, e.g. Placzek-Popko (2017), Mir-Artigues/del Rio (2016), and Wu/Mathews (2012), which differ primarily with respect to their level of granularity. For the purpose of this study, the approach of Wu and Mathews (2012) seems to be most appropriate for simplicity reasons and has the additional advantage to lend itself to the analysis of patent applications. Based on these authors, three different generations of solar cells can be discerned:

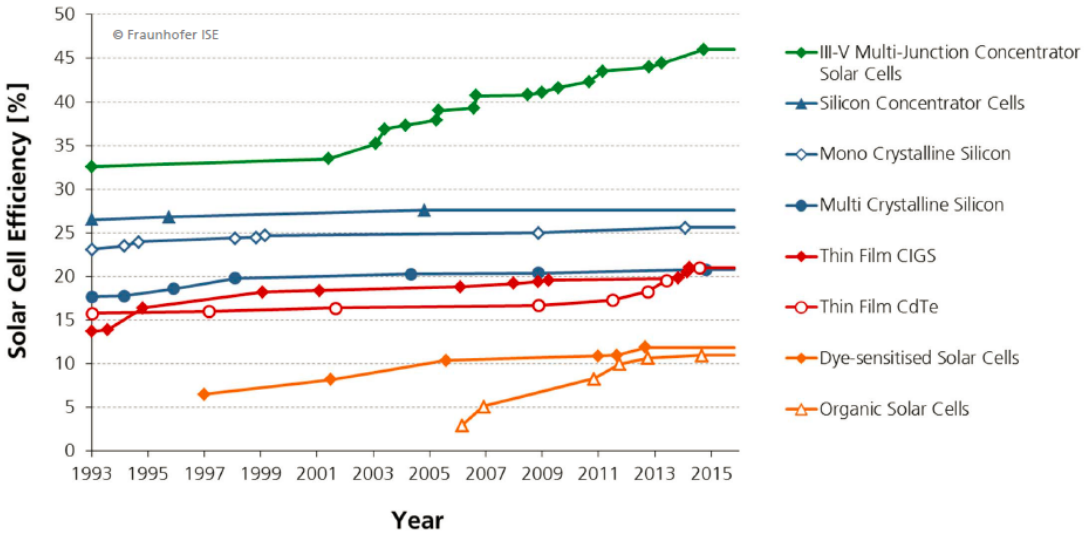
The first generation (G1) encompasses monocrystalline and multi- or polycrystalline cell types (c-Si). These cell types currently dominate the world market with 43.9 GWp annual production of multicrystalline cells (equivalent to 69.5% market share in 2015) and 15.1 GWp annual production of monocrystalline cells (23.9%) (Fraunhofer ISE 2016). As evident from Figure 2, the monocrystalline cell types have a higher efficiency than the multicrystalline cells. Their production process

can be roughly divided into six stages: silicon production, silicon purification, silicon crystal growth, wafer slicing, cell fabrication and module assembly (Mir-Artigues, del Río 2016).

The second generation (G2) of solar cells is thin-film solar cell based on amorphous silicon (a-Si), a combination of amorphous and microcrystalline silicon or other semiconducting materials, in particular cadmium-telluride (Ca-Te), copper-indium-gallium-selenide (CIGS), and gallium-arsenide (Ga-As) (Placzek-Popko 2017). In 2015, production of Ca-Te cells reached 2.5 GWp (equivalent to 4.0% market share), and of CIGS 1.1 GWp (1.7%) and of a-Si 0.6 GWp (0.9%). Since 2009, market shares of thin film solar cells have come down from well above 16% to 6.6% (Fraunhofer ISE 2016). The second generation solar cells have a cost advantage over the first generation due to lower materials requirements, but in general show a lower efficiency (Placzek-Popko 2017). However, as evident from Figure 2, in recent years Ca-Te and CIGS cells have matched the performance of multicrystalline cells in the laboratory.

The third generation (G3) encompasses cell types which are still in an experimental stage. Among them are cells whose active layer consists of organic molecules or dye-sensitized cells. The efficiency of these cell types is currently still low (see Figure 2), but could rise to 15% within the next ten years (Mir-Artigues, del Río 2016). In addition, these cell types still face stability problems and have a much lower expected lifetime than the cell types of G 1 and G 2. Another promising emerging technology are perovskite solar cells, which started with an efficiency of 3-4% in 2009 and have quickly reached 22.1% in 2015, but likewise still face major technological challenges (Placzek-Popko 2017).

Figure 2: Development of Laboratory Solar Cell Efficiencies



Source: Fraunhofer ISE (2016)

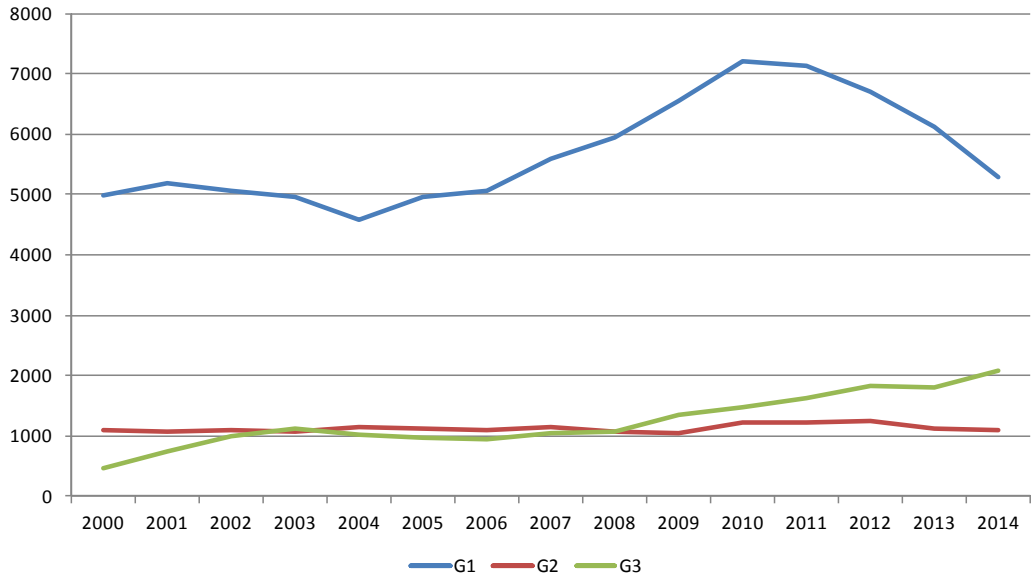
The number of transnational patent applications can be used as a proxy to measure and compare the innovation efforts in the three generations of PV cells. Wu and Mathews (2012) applied a three-step procedure to assign patents to the different generations of PV cells, based on their IPC (International Patent Classification) code. In total, they identified 12 IPC codes, thereof seven for G 1, two for G 2, and three for G 3.[1]

Data on transnational patent applications in the field of PV was extracted from the European Patent Office's (EPO) Worldwide Patent Statistical Database (PATSTAT). Patent applications were identified according to the priority year, i.e. the year of their worldwide first filing, and based on the concept of 'transnational patents' suggested by Frietsch and Schmoch (2010). In detail, all filings at the World Intellectual Property Organisation (WIPO) under the Patent Cooperation Treaty (PCT) and all direct filings at the EPO without precursor PCT filing are counted. This excludes double counting of transferred PCT filings to the EPO. Thus, all patent families with at least either a PCT filing or an EPO filing are taken into account. Patent applications were assigned to different countries based on the inventor's country of residence.[2]

1 However, it has to be noted that five of these IPC codes (E04D13/18, H01L21, H01L27, H01L31, H02N6) describe general technology platforms which apply to all three generations. For simplicity reasons, these IPC codes were assigned to the first generation, which of course leads to an overestimation of activities in this field of research.

2 This methodology applies to all further analysis of patenting activity in this paper unless explicitly mentioned.

Figure 3: Transnational Patent Applications for Different Generations of PV Technology



Source: PATSTAT, author's calculations

The results from this analysis are displayed in Figure 3. The number of patent applications in G 1 was relative stable during the period running from 2000 to 2006. Between 2007 and 2010 the number of patents increased to more than 7,000 patents per year. However, in 2011 these figures began to decrease towards approximately 5,000 patents per year. For the G 2, the development was relatively stable with about 1,000 patents per year and a moderate peak in 2012 (1,240 patents). The G 3 saw a fairly steady increase from less than 500 patents in the year 2000 to more than 2,000 patents in 2014.

4 Identifying the structural components of the Chinese TIS for PV

The objective of this chapter is to identify the most relevant actors and institutions of the Chinese TIS for PV. At first, the relevant institutional framework addresses the crucial importance of demand creating policies for the development of PV. Here, the focus is on the regulative dimension of institutions, which encompasses aspects such as formal rulemaking, monitoring, and sanctioning (Scott 2009). Besides regulation that creates incentives for the deployment of PV, the body of relevant institutions also encompasses policies directed at the promotion of R&D and industrial development. After describing these institutions, the most important actors of the TIS are discussed.

4.1 Institutions

China's Five Year Plans (FYP) form the basis for the institutional environment of PV in China as they formulate targets for domestic PV deployment, development of the PV industry, and innovation. PV first became a topic of a FYP in 2001, when the 10th FYP (2001-2005) was published. The vision of this plan was to scale up the production capacity for PV cells and modules and to reach 15 MW annual production capacity by 2005. In fact, by 2005 the Chinese PV industry had already reached a capacity of 500 MW. The 11th FYP (2006-2010) put a greater emphasis on productivity enhancing R&D and on the full development of the domestic PV supply chain (Ball et al. 2017).

The 12th FYP targeted capacity of 21 GW by promoting large on-grid PV stations in resource abundant regions in the North-Western provinces (Qinghai, Gansu, Xinjiang, Inner Mongolia) and encouraging distributed generation in the Eastern and Central provinces (Zhang, He 2013). By the end of 2016, China had reached a cumulative PV capacity of 77.4 GW and had, thus clearly surpassed the objectives of the 12th FYP.

The alternating influences of foreign and domestic policies on the development of China's PV industry have attracted much attention from previous research (Quitzow 2015; Iizuka 2015; Liu, Goldstein 2013). The introduction of feed-in tariffs for renewable energy in Germany and other countries has facilitated the rapid development of the Chinese PV industry in the early 2000s. But since the global financial crisis in 2008 and the anti-dumping policies initiated by the USA and the EU in 2011, the importance of foreign markets has decreased (Zhang, He 2013). In contrast, domestic policies have gained in importance for the Chinese PV industry since then. This is in line with the findings of Huang et al. (2016) who stress the significance of domestic institutions for the future development of the Chinese TIS.

With respect to the most relevant national policies for the development of PV in China, Zhang and He (2013) refer to the Renewable Energy Law and other renewable energy policies (2006-2008), the Brightness program (1996), the Township Electrification Program (2002), the Rooftop Subsidy Program (2009), the Golden Sun Demonstration Program (2009), the PV Concession Program (2009), the national Feed-in tariff (FIT) scheme (2011), the free connection service policy (2012) and the 12th Five Year Plan for Renewable Energy Development (2012).

The Renewable Energy Law, which came into effect in 2006, created the framework for the development of renewable energy in China. It stipulates important

mechanisms and principles, which have been subsequently specified by more specific renewable energy policies. The Brightness and the Township Electrification Program both aim at the use of PV and wind energy to provide electricity for villages in remote areas of China (Zhang, He 2013). The latter had a total PV capacity of 20 MW and, according to Zhang and He (2013), contributed significantly to the emergence of the Chinese PV industry. The adoption of the Rooftop Subsidy and the Golden Sun Demonstration Program in 2009 can be regarded as the Chinese government's response to trade frictions and reduced demand in export markets in the wake of the global financial crisis. The Rooftop Subsidy Program provides upfront subsidies of 15 RMB/W for rooftop systems and 20 RMB/W for building integrated PV (BIPV) systems. Eligible projects have a scope of at least 50 kW and minimum efficiency levels of 16% (monocrystalline cells), 14% (polycrystalline cells), and 6% (amorphous silicon cells). The Golden Sun Demonstration Program targets projects of at least 300 kW size and provides a subsidy of 50% of the investment in solar power projects, i.e. grid connected rooftop systems, BIPV, and ground mounted systems (Zhang, He 2013). Off-grid PV systems in remote regions receive a subsidy of 70%. Under the Solar PV Concession Program the Chinese government has organized public biddings for solar power projects. Successful bidders have the right to operate solar power plants for 25 years with a fixed on-grid price (Zhang, He 2013). The national FIT became effective in 2013 and initially guaranteed on-grid power tariffs of RMB 0.9 (area 1), RMB 0.95 (area 2) or RMB 1 (area 3) per kWh, dependent on the solar resources area where the project is located. The three solar resource areas of China take into account national differences in solar power resources and construction costs. Distributed PV projects receive a standard subsidy of RMB 0.42 per kWh. The FIT is granted for 20 years. Subsequently, the FIT for new PV projects was reduced two times, at the beginning of 2016 and 2017, in order to adjust the tariff to decreasing technology costs and investment needs. The amendment which came into force in 2017 stipulates a FIT of RMB 0.65 (area 1), 0.75 (area 2) and 0.85 (area 3) per kWh. The subsidy for distributed solar PV remained unchanged (IEA/IRENA 2017b).

Free grid-connection services for distributed PV systems by the State Grid Corporation of China (SGCC) are another element of the institutional framework that supports the diffusion of PV. Prior to this regulation, the SGCC had only connected large-scale solar power plants and refused to connect distributed PV systems due to the higher costs for connecting many small entities (Zhang, He 2013).

Besides these demand creating policies, there are a series of R&D programs for PV. According to Ball et al. (2017), China's National Natural Science Foundation

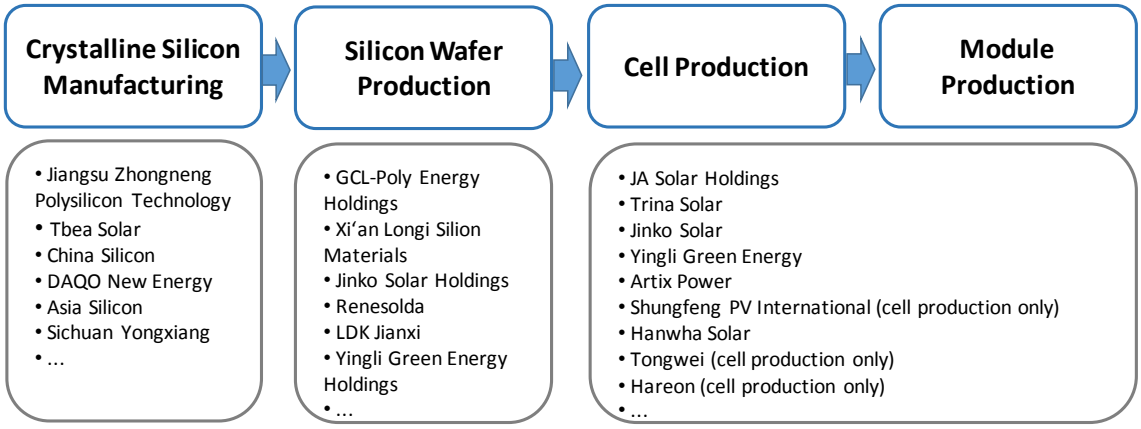
has strongly promoted R&D in the 3rd generation of PV cells since 2007. Further important R&D programs for PV are the 973 program for basic research, the 863 program for more applied research and the State Key Lab (SKL) and State Engineering and Technology Research Center (SETRC) programs (Ball et al. 2017).

4.2 Actors

With regard to energy policy making, the highest authority in China is the National Energy Commission (NEC). The National Development and Reform Commission (NDRC) is responsible for the government's FYP and has a broad set of responsibilities, including policy, planning and pricing decisions in the energy sector (Downs 2008). The National Energy Administration (NEA) is an agency within the NDRC, which is responsible for the operative affairs of the NEC. The NEA consists of nine different departments, including the office for New and Renewable Energy. The Ministry of Science and Technology (MOST) is responsible for China's Science and Technology Policy and publishes subordinate FYP for specific technologies, inter alia for PV (Ball et al. 2017). As the PV industry has been identified as a strategic emerging industry by China's State Council (Wang et al. 2014), it has received a lot of encouragement from national and provincal government levels. Important policy-making actors in this context are the Ministry of Industry and Information Technology (MOIIT), which is responsible for industrial policy, and the Ministry of Finance (MOF).

During the initial stages of industrial development, Chinese PV companies have been active primarily in the production of PV cells and modules. However, since the Chinese government has been determined to develop the entire value chain for PV, Chinese companies have successively entered upstream (crystalline silicon production, silicon wafer production) and downstream segments (development of solar power projects) as well as the market for relevant machinery and equipment. Figure 4 displays the most important actors in the supply chain for crystalline silicon cells as of 2015.

Figure 4: Crystalline Silicon Cell Supply Chain and Main Chinese Producers in 2015



Source: Based on Fang et al. 2017

The most relevant producers of crystalline silicon cells and modules and thin-film cells with their respective annual production, total production capacity, and capacity utilization in 2015 are listed in Annex 1. The most active companies, research institutes and universities in the area of R&D are presented in the following section.

5 Mapping the functional pattern of the TIS

5.1 Knowledge development and diffusion

This function captures the development and diffusion of the PV related knowledge base in China over the past two decades. Various innovation indicators (Kleinknecht et al. 2002) are applied to measure efforts and performance of the Chinese TIS at different stages of the innovation process and with regard to different types of technological knowledge. Based on data on R&D expenditures, transnational patent applications, and scientific publications, knowledge development in China is compared with other technologically leading countries. Moreover, patent applications at the Chinese patent office are used to identify those companies, universities, and research institutes in China with the highest activity in PV innovation and to draw conclusions about the diffusion of PV related knowledge in China.

Table 1 provides an overview of R&D expenditures of PV companies with manufacturing base in China. Except for the Canadian Solar and Hanwha, which are

multinational enterprises headquartered in Canada and South-Korea respectively, all other companies have their headquarters in China. In general, the data shows that R&D expenditures as measured in percent of sales have risen from 0.27% in 2006 to 1.86% in 2015. Considering the fact that the PV industry is widely assessed as a high-tech sector and compared with US-based competitors First Solar and SunPower, which had spent on average 8.93% and 3.67% respectively of their sales on R&D between 2013 and 2015 (Ball et al. 2017), investment of Chinese PV companies in formal R&D appears to be rather low.

There are only a few exceptions: Since 2010, the company ReneSola constantly invested more than 3% of sales on R&D and, more recently, Yingli and Hanwha have also increased their R&D spendings. ReneSola operates an independent R&D Laboratory in Jiangsu Province and Hanwha conducts some R&D at their manufacturing base in Qidong, likewise in Jiangsu Province, and Malaysia, but their headquarter for Technology and Innovation is based at Bitterfeld, Germany (Hanwha Q Cells 2016). Thus, Hanwha's R&D expenditures in China are probably only a fraction of the company's total R&D budget. The increasing R&D spendings of Yingli might be related to the launch of the State Key Laboratory for PV Materials and Technology, which is collectively funded by MOST and Yingli.

Table 1: R&D Expenditures of PV Companies with Manufacturing Base in China, in % of Net Sales

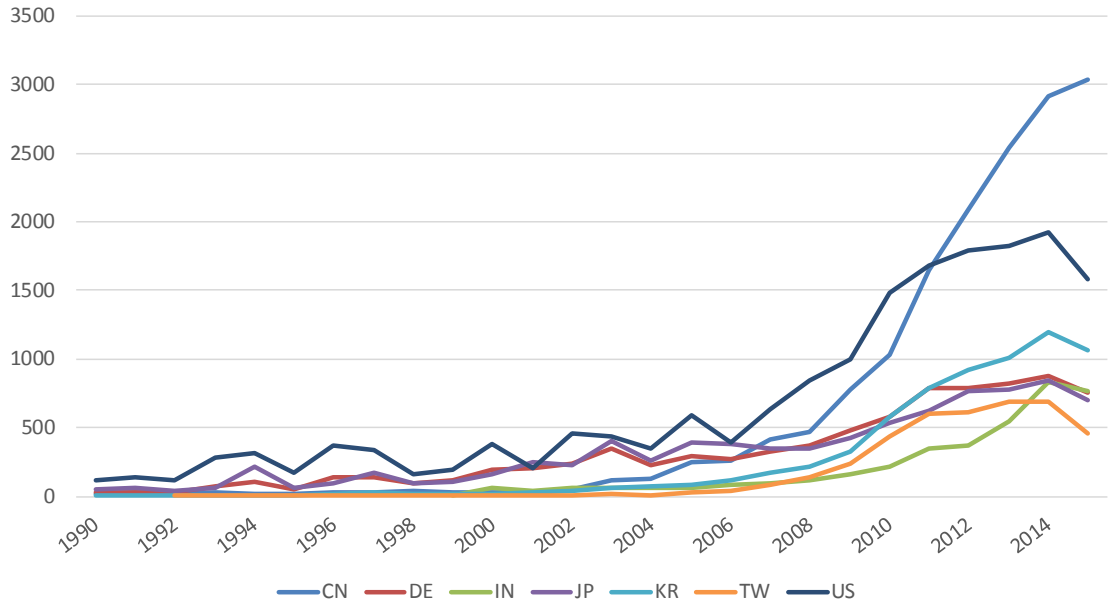
Company	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Canadian Solar	0.58	0.33	0.26	0.50	0.46	1.04	1.00	0.71	0.41	0.49
GCL	0.00	0.00	0.43	0.29	0.07	0.44	0.87	0.88	1.33	1.18
Hanwha	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.54	2.68
JA Solar	0.19	0.16	0.52	1.19	0.54	0.64	1.29	1.23	1.24	1.10
Jinko	0.00	0.01	0.02	0.38	0.68	0.41	1.44	0.93	1.07	0.89
ReneSola	0.04	0.46	1.45	2.84	3.01	4.78	4.55	3.06	3.37	3.42
Shunfeng	0.00	0.00	0.19	0.40	0.43	0.21	1.47	0.91	1.26	1.86
Trina	1.66	0.93	0.37	0.64	1.00	2.15	2.04	1.12	0.97	1.12
Yingli	0.00	0.43	0.76	2.54	1.10	1.94	1.65	2.15	4.44	3.98
Average	**0.27**	**0.26**	**0.44**	**0.98**	**0.81**	**1.29**	**1.59**	**1.22**	**1.96**	**1.86**

Source: Based on data from Bloomberg as cited by Ball et al. 2017.

Scientific publications are used as an output indicator for innovation activity in the area of basic research in the field of PV, which in China is conducted predominantly in state-owned research institutes and universities. Data on scientific publications in the field of PV was extracted from Scopus, a scientific citation indexing service. Figure 5 shows how the number of scientific publications on PV from seven technologically leading countries has developed between 1990 and 2015. It becomes evident that the number publications has considerably increased

throughout the observed 25-years period. In 2014, 11,998 new publications on PV were published worldwide, whereas in the year 1990 there were only 691 publications. In 2015, the total number of publications had decreased to 11,024. Publications of authors affiliated with Chinese universities or research institutes started to increase in 2003. Subsequently, the annual number of Chinese publications had surpassed the USA in 2012 and, since then, China is by far the leading country with regard to scientific publications on PV and, thus, contributes significantly to global knowledge generation in this field.

Figure 5: Development of Scientific Publications on PV from Selected Countries

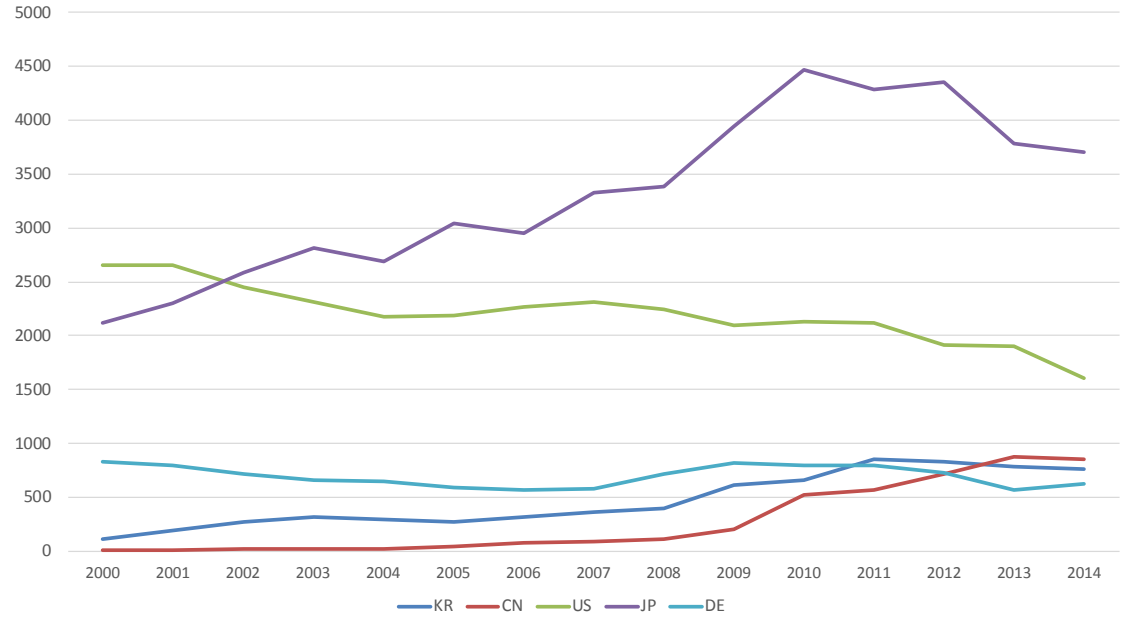


Source: Based on Scopus Request with TITLE-ABS-KEY ("solar cell*" OR "photo voltaic*")

To measure output from applied research, transnational patent applications are used. Figure 6 indicates that in contrast to the picture emerging from the analysis of scientific publications, China still faces a rather large gap to Japan and the USA, but has recently managed to catch-up with Korea and Germany. Interestingly, patent applications of inventors from the USA had reached a peak of 2,314 patents already in 2007 and, since then, have been decreasing. Similarly, patent applications of Japanese inventors have dropped from a peak of 4,473 (2010) to 3,704 (2014). German patent applications likewise peaked in 2009 and have been decreasing from that time on. Thus, the gap between China and the leading countries is closing due to increasing R&D activity in China, but also due to decreasing efforts in Japan, USA, and Germany. The total number of worldwide

patent applications began to decrease in 2011, which roughly coincided with increasing R&D activity in China since 2009. However, China could not compensate for the decreasing output of Japan and the USA.

Figure 6: Transnational PV Patent Applications of Technologically Leading Countries



Source: Based on data from PATSTAT

In order to gain additional insight into knowledge creating activities of different actors of the Chinese TIS, domestic patent applications for PV at the State Intellectual Property Office (SIPO) of China were examined. As evident from Table 2, applications from organisations headquartered in China have surged since 2007, but only in 2009 Chinese applicants became responsible for more than half of annual patent applications at SIPO (55%) and by 2012 had reached a share of 79%. Roughly in line with the results from the analysis of transnational patents, SIPO applications from the USA, Japan, and Germany reached a peak in 2010 and started to decline afterwards.

Table 2: Annual Patent Applications for PV at SIPO

Year	CN	DE	JP	KR	US	Total	CN in % of Total
2000	28	14	114	6	23	209	13%
2001	32	12	127	12	45	270	12%
2002	75	12	212	25	76	435	17%
2003	106	32	319	46	90	647	16%
2004	123	17	242	49	112	588	21%
2005	155	21	139	17	79	457	34%
2006	200	29	166	17	117	575	35%
2007	386	36	165	40	131	832	46%
2008	563	51	174	50	177	1166	48%
2009	912	70	241	100	172	1673	55%
2010	1358	74	293	116	237	2272	60%
2011	1821	55	212	133	122	2538	72%
2012	2189	44	192	77	116	2777	79%

Source: Author's elaboration, based on data from SIPO

The most active corporate applicants from China in 2010-2013 are listed in Table 3. Respectively, the most active universities and research institutes are displayed in Table 4.

Table 3: Most active corporate applicants for PV at SIPO (2010-2013)

Manufacturer	Patent Applications	in % of Total
TRINA SOLAR ENERGY	207	2.6%
YINGLI SOLAR	204	2.6%
CANADIAN SOLAR POWER	155	2.0%
JIFU NEW ENERGY TECH SHANGHAI	128	1.6%
OCEANS KING LIGHTING SCIENCE	103	1.3%
BYD CO LTD	95	1.2%
SUNTECH POWER CO LTD	80	1.0%
IRICO GROUP CORP	72	0.9%
EGING PHOTOVOLTAIC TECH	56	0.7%
CHINA ELECTRONICS TECHNOLOGY	51	0.6%

Source: Author's elaboration, based on SIPO

Table 4: PV Patent Applications of Chinese Universities and Research Institutes at SIPO (2010-2013)

University / Research Institute	Patent Applications	in % of Total
SUZHOU INST NANO TECH-CAS	115	1,4%
INST SEMICONDUCTORS-CAS	78	1,0%
UNIV ZHEJIANG	72	0,9%
UNIV TSINGHUA	58	0,7%
UNIV SUN YAT-SEN	56	0,7%
UNIV SHANGHAI	55	0,7%
SHANGHAI TECH PHYSICS INST-CAS	54	0,7%
UNIV HUAZHONG	50	0,6%
UNIV NANKAI	50	0,6%
UNIV FUDAN	49	0,6%

Source: Author's elaboration, based on SIPO

The results displayed in Table 3 and Table 4 suggest that applied scientific knowledge of PV technology in China has widely diffused and is now quite evenly spread over a relatively large group of companies and research facilities. However, even the two most active corporate applicants, Trina Solar and Yingli Solar, were responsible for only 2.6% of total applications. This suggests that the leading manufacturers of PV cells and modules are reluctant to take leadership in R&D. Table 3 also lists some companies, which are not among the group of 1st tier PV manufactures, but suppliers of critical components. For example, the list's No. 4, Jifu New Energy Technology designs and produces turn-key production lines for thin-film solar panels (Jifu n.a.) , the list's No. 8, Irico Group, is a state-owned multidivisional company that produces glass for solar panels, and No. 10 (Irico n.a.), China Electronics Technology Group, is likewise a state-owned company that is host to the State PV Tooling Engineering and Technology Research Center (China Electronics Technology Group n.a.).

Another insight from this analysis is, that the Chinese Academy of Sciences (CAS) plays a very important role in the generation of new technological knowledge. Table 4 lists three CAS institutes that have collectively applied for 247 patents, which makes the CAS the most important applicant for PV in China.

What can be concluded from this analysis is, that since the early 2000s the Chinese TIS for PV started to constantly increase output from basic research and is now the world's leading country in terms of scientific publications. The output from applied research started to increase at a later stage and, although China managed to catch-up with Germany and South-Korea, there stills exists a rather large

gap between China and the USA and Japan. Compared with their global competitors, the Chinese PV companies invest a smaller portion of their sales in R&D and even at the domestic patent office, these companies' shares in total PV patent applications are low. Furthermore, publication and patenting data suggests, that PV related innovation activities in the Western frontrunner countries have been decreasing, which has facilitated the catching-up of China.

5.2 Guidance of search

This function addresses, how the search for new technological solutions is influenced by certain mechanisms and to what degree new companies and other organizations are enticed to engage in the TIS. Among others, important mechanisms that influence the direction of search are visions and expectations of actors, their perceptions regarding the relevance of different sources of knowledge, future technological opportunities, as well as political priorities and regulations (Bergek et al. 2008). The development of the TIS for PV in China is heavily influenced by the targets formulated in the government's FYP. At least with regard to research conducted at state-owned companies and research facilities it can be assumed that the direction of search will be responsive to the priorities formulated in the FYP. Still, one has to keep in mind that the 1st tier Chinese PV industry is to a large extent dominated by private companies, which are very active exporters and faced with international competition. Thus, their research priorities might differ from those explicated in the FYP and based more on entrepreneurial visions and assessments as well as the expectations and needs of their global customer base. Nevertheless, the R&D targets formulated by the FYP will be briefly described here, due to their importance for innovation conducted in the overall TIS.

Ball et al. (2017) have analyzed the 11th, 12th, and 13th Chinese FYP and find that R&D in the field of PV has successively become a subject of growing importance. In the 11th FYP (2006-2010), the government emphasized the need to fully develop the domestic supply chain for PV and to increase the efficiency of solar cells manufactured in China. At that time, China was still very much dependent on imports of high-purity polysilicon as well as on imports of other materials and equipment for PV production. The 12th FYP (2011-2015) specified very detailed R&D goals for each part of the PV value chain, e.g. for the efficient mass production of polysilicon, for the efficiency of solar cells, and PV grid integration. Moreover, the FYP includes targets for production costs (Ball et al. 2017). The 13th FYP for Renewable Energy Development (2016-2020) states the following overarching objectives (IEA/IRENA 2017a; NDRC 2016):

- Increase the share of non-fossil energy in total primary energy consumption to 15% by 2020 and to 20% by 2030;
- Increase installed renewable power capacity to 675 GW by 2020;
- Lead renewable energy technology innovation;
- Further support development of the renewable energy industry in China and decrease reliance on foreign companies in this domain;
- Resolve renewable power curtailment issue problem;
- Reach a capacity for PV and wind of 105 GW and 210 GW respectively by 2020.

As explicated by Ball et al. (2017), the 13th FYP implements a fundamental restructuring of China's approach towards R&D and its funding. The basic idea behind this restructuring is to 'vertically integrate' different R&D programs, which were designed to foster innovation at specific technology stages. In particular, the 843 program, which is targeted at applied research, and the 973 program for basic research were merged under the so-called *National Key Research and Development Projects*, in order to make sure that more technological innovation can successfully progress from basic research to commercialization. In a similar fashion, the *National Key Science and Technology Special Program* integrates activities from different stages of the R&D process by funding research projects directed at the import substitution of key materials. Furthermore, the *Technology-Innovation Guiding Program* will strengthen R&D in small and medium sized companies. Finally, the *Innovation Base and Talent Program* envisages to strengthen R&D by attracting the world's best researchers and to create world-class research facilities (Ball et al. 2017).

With regard to technological progress in the PV sector, the 13th FYP continues to include very detailed and ambitious R&D targets for different steps of the PV value chain, as listed in Table 5 (Ball et al. 2017).

Table 5: The 13th FYP R&D Targets for PV

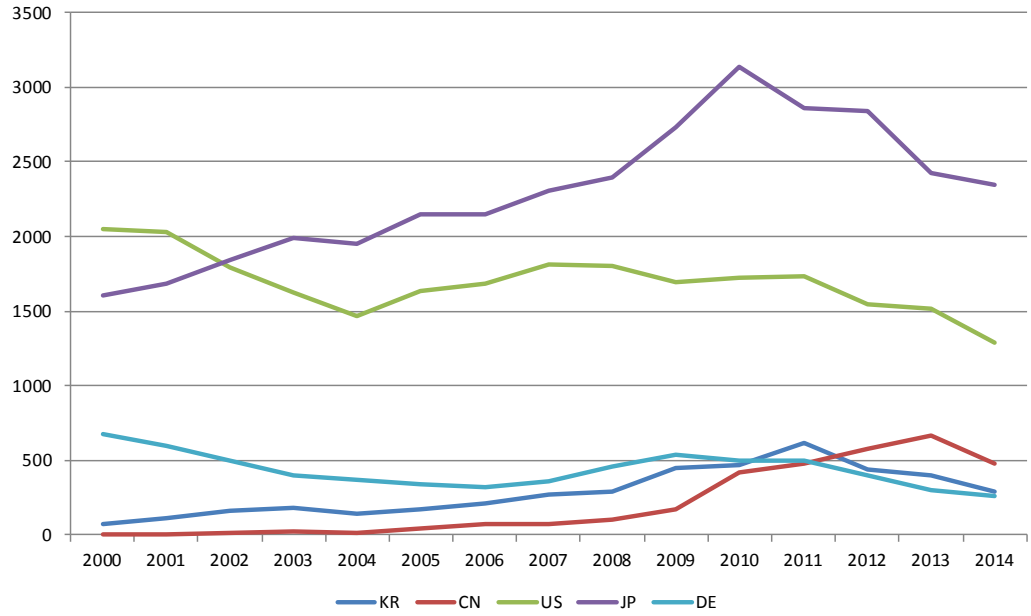
Technology	Innovation Goals
Monocrystalline silicon	Commercialized cells with efficiency of at least 23%
Multicrystalline silicon	Commercialized cells with efficiency of at least 20%
Thin-film	Commercialize various emerging thin-film technologies
Solar production equipment and materials	Ability to domestically produce equipment needed to manufacture high-efficiency solar cells; improvements in production equipment through automation and other techniques; 90 % of equipment used by commercial solar-product manufacturers in China is made in China
Solar grid-integration and energy-storage technologies	Overcome technical barriers for: grid integration of large-scale solar and distributed-solar systems; solar-connected smart grids and microgrids; and balance-of-system
Solar-cell and -system testing and efficiency verification	For example, tests to improve solar-system performance at high elevations

Source: Ball et al. 2017

Table A.2 in the Annex provides a snapshot on the results of China's strategy to substitute imports of PV production equipment. In its annual report for 2015, Trina Solar reports major equipment of their manufacturing activity and their technology source. Except for wafer sawing machines, all types of equipment have at least partly been sourced from China, which provides at least some incidence for the success of China's strategy to fully develop the domestic PV supply chain.

Based on the discussion in chapter 3, the question arises how the Chinese TIS performs with respect to the three different generations of PV technology. In Figure 7-10, the results of a differentiated analysis of transnational patent applications in 1st, 2nd, and 3rd generation of PV technology are presented. In contrast to the decreasing trend in other technologically leading countries, China's output of transnational patents in the 1st generation of PV, which is at present by far the commercially most relevant PV technology generation, has been increasing between 2009 and 2013. During that period, the gap between China and Germany as well as between China and South-Korea was closed and China is now ranked No. 3 in the world. Even though the R&D output of Japan and the USA in the 1st generation of PV has been decreasing, the gap between China and these two countries is still considerable. The decreasing trend in the total number of G 1 patent applications can be interpreted as a sign of technological maturity and decreasing returns to R&D. Another explanation might be the lack of commercial interest of PV companies outside China, due to the dominant market position and competitiveness of the Chinese industry.

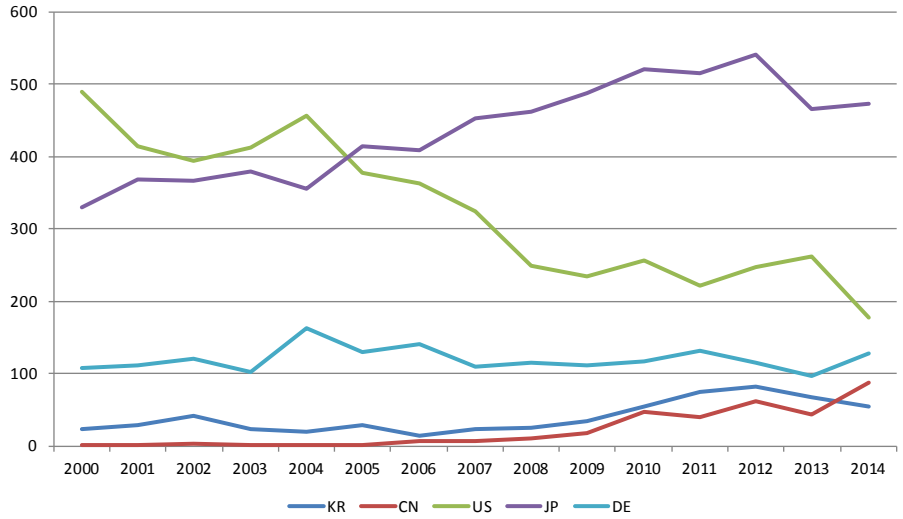
Figure 7: Transnational Patent Applications of Selected Countries in 1st Generation Solar Cells



Source: Own elaboration, based on PATSTAT

The total number of patent applications for the 2nd generation of PV technology, thin-film PV cells based on different materials, is much smaller than for the 1st generation PV cells and China's technological catch-up has proceeded at a slightly slower pace, because Japan, South-Korea, and Germany have maintained a fairly steady or even increasing level of R&D activity. The USA, however, have reduced their R&D activity even more rapidly than for G 1 technology.

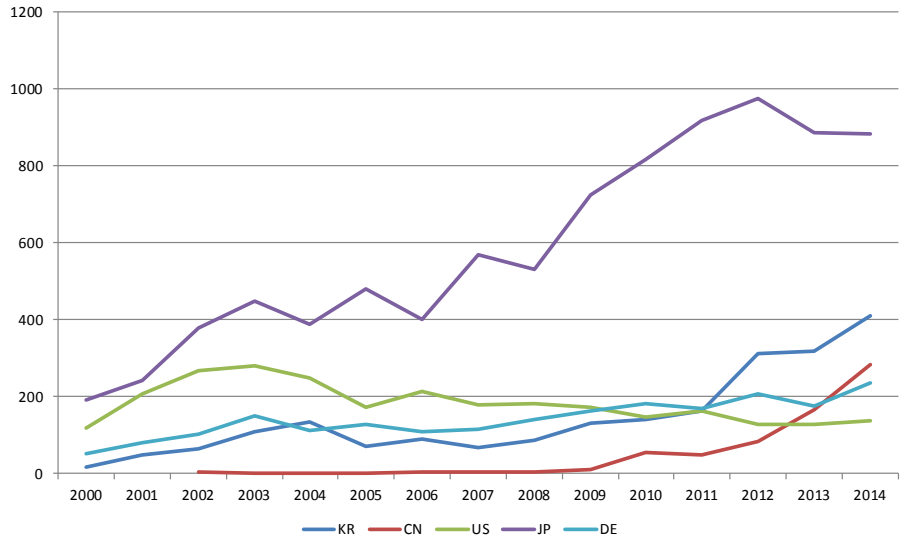
Figure 8: Transnational Patent Applications of Selected Countries in 2nd Generation Solar Cells



Source: Own elaboration, based on PATSTAT

Patent applications for the 3rd generation of PV technology show a very different pattern than that of the 1st and 2nd generation, because Japan, South-Korea, China, and Germany have significantly increased their level of R&D activity.

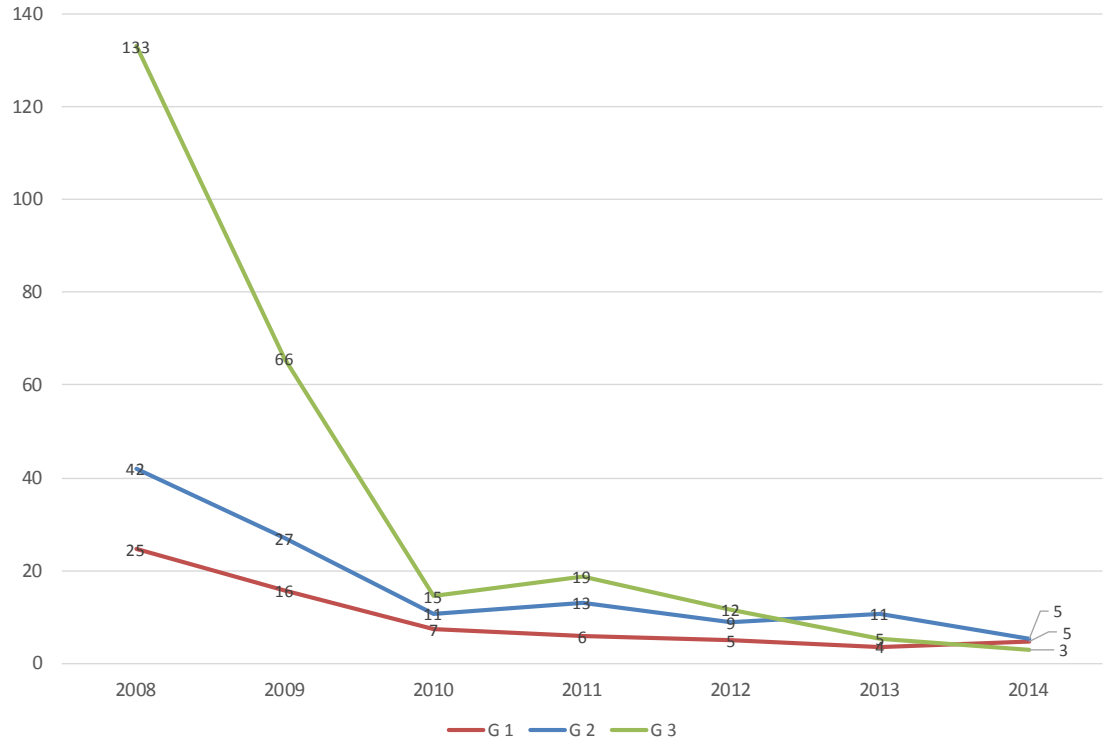
Figure 9: Transnational Patent Applications of Selected Countries in 3rd Generation Solar Cells



Source: Own elaboration, based on PATSTAT

China's catch-up process for the different generations of PV technology can also be illustrated with the help of Figure 10, which displays the ratio of annual patent applications of Japan and China for the three technology generations.

Figure 10: Annual Ratio of Japanese to Chinese Patent Applications for Different Generations of PV Technology



Source: Own elaboration, based on PATSTAT

One has to keep in mind that a ratio of five, e.g. for G 1 in 2014, can still represent a considerable gap if the absolute number of patent applications is sufficiently high. Nevertheless, Figure 10 clearly demonstrates that China's technological catch-up was very fast during the period from 2008 to 2010 and afterwards steadily continued. The gap between Japan and China seems to be smallest for the newest technology generation.

5.3 Entrepreneurial activities

Entrepreneurial experimentation in the Chinese TIS for PV began in the 1970s (Wang et al. 2014) and started to gain momentum in the late 1990 with the foundation of Yingli Solar (1997) and Trina Solar (1998), which was rapidly followed by market entries of other Chinese PV companies. During the initial stages of industry formation, Chinese PV companies focused on the production of solar

cells and modules. Market entry was facilitated through the purchase of turn-key production lines and equipment from Western companies and motivated by the market potential created through demand stimulating policies adopted in Europe and the USA (Quitzow 2015).

As the TIS for PV in China matured, new companies emerged at up- and downstream segments of the PV value chain and the breath of technological capabilities expanded. In particular, Chinese manufacturers acquired the capability to produce polysilicon, a material on which the Chinese PV industry had been dependent on imports for a long period. Furthermore, there is a trend to integrate different value chain activities in single companies (Ball et al. 2017). As of 2016, Chinese PV companies retained considerable global market shares in all important segments of the PV value chain, i.e. 52% of global polysilicon production, 81% of wafer production, 59% of silicon cell production, and 70% of module production (Ball et al. 2017).

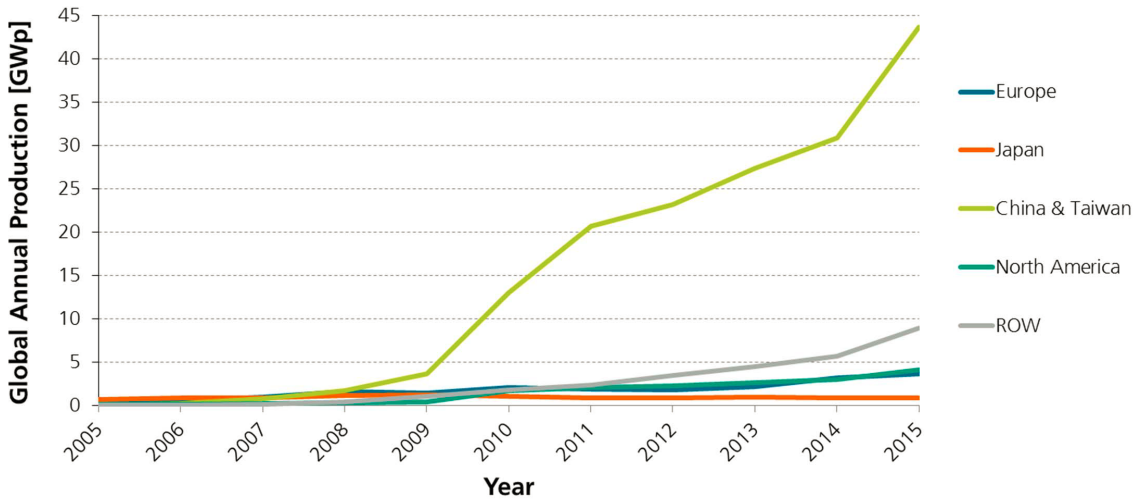
However, Goodrich et al. (2013) have arrived at the conclusion that the competitive advantage of the Chinese PV industry is not stemming from country-specific factors, as for example labour costs or subsidies, but rather from scale effects and supply-chain integration - a competitive advantage which could in principle be replicated by other countries. Moreover, after a period of rapid expansion, China's PV industry is now facing a less favorable market environment characterised by trade barriers, overcapacities, intense competition, shrinking product prices, and low profitability, which will probably result in further industry consolidation.

5.4 Market formation

As the number of reports on market development for renewable energies is abundant, this section will recap only some crucial aspects. As global PV capacity had reached 303 GW in 2016 (REN21 2017) and the Compound Annual Growth Rate (CAGR) of PV installation was 41% between 2000 and 2015 (Fraunhofer ISE 2016), it becomes obvious that the global PV market has left the stage of market formation and entered a rapid growth phase since a couple year already. This stage is characterised by technological maturity and economic benefits over other energy technologies (OECD/IEA 2016). However, one has to keep in mind that this refers mainly to the first generation of PV technology.

In recent years, global market development has been driven by rising demand from China, which for instance was responsible for 46% of newly added PV capacity in 2016 (REN21 2017). One of the main driving force behind this development is the decline of costs for electricity generation from PV. Between 2008 and 2015, the levelised costs of utility scale PV have decreased by roughly 80% (OECD/IEA 2016). The current dominance of China as a technology supplier is underlined by Figure 11.

Figure 11: PV Industry Production by Region (2005-2015)



Source: Fraunhofer ISE 2016

5.5 Resource mobilization

The TIS for PV in China has been increasingly able to mobilise financial resources. In 2015, Chinese investment in renewable energy technologies has grown by 17 % from 2014. In total, China invested 102.9 billion US$, which was equivalent to 36 % of the world's total investment. On a global level, solar energy was able to attract 161 billion US$ in the same year. Of the investment in China, 47.6 billion US$ were spent on wind energy, 44.3 billion US$ on solar energy, and 2.7 billion US$ on small hydropower (FS-UNEP Collaborating Centre 2016).

These figures include spending on R&D, which in 2015 has risen by 4% and reached 2.8 billion $ for all renewable energy technologies in China. For the first time, this amount was almost equivalent to the EU's spending on renewable energy R&D. At the global level and for all renewable energy technologies, R&D spending amounted to 9.1 billion, thereof 50 % on government R&D and 50 % on corporate R&D. The ratio of R&D investment (government and corporate) to total

investment in the world was 0.032; whereas in China it was 0.027. For all renewable energy technologies, the split between corporate and government R&D in China was 1.0 to 1.8 billion US$; whereas in the EU it was 1.7 to 1.2 billion US$. Government R&D in China increased by 7%, whereas corporate R&D remained stable (FS-UNEP Collaborating Centre 2016). Thus, compared to the global situation, investment in China is strongly bend towards public R&D.

These figures suggest, that the PV TIS in China is profiting from China's overall investment in renewable energy technologies. The bulk of the investment (97.3%) is spend on projects for electricity generation. However, driven by the rise of government R&D, spending on R&D is growing rapidly as well and China has almost reached the same level of R&D investment as the EU. Compared to the situation in the EU, the private sector in China is more reluctant to invest in R&D, which corresponds to the findings in section 5.1.

5.6 Creation of legitimacy

Given the evidence presented so far, it can be assumed that at least during the initial stages of industry formation the legitimacy of the TIS rested largely upon the success of the PV industry's export-oriented business model (Liu, Goldstein 2013). As China's PV industry continued to grow and started to face a more difficult environment in its overseas markets, the Chinese government supported the industry by developing the domestic market for PV. At the same time, the legitimacy of renewable energy technologies and of PV specifically increased due to rising environmental concerns in China and the need to take part in the global action against climate change (Liu, Goldstein 2013). The government's investment in PV deployment has been steadily growing and now already matches investments in wind energy, which can at least partly be attributed to the decreasing technology costs of PV. As these cost decreases have been achieved by a combination of technological improvements, scale effects, and value chain integration (Goodrich et al. 2013; Fraunhofer ISE 2016), it becomes obvious that supply and demand driven factors have been mutually reinforcing which results in a situation with a robust legitimacy of the technology.

6 Conclusions

The functional analysis of the TIS for PV in China presented in the previous sections allows us to draw some conclusions with regard to the research questions raised in the introduction. The question whether China is moving from production

to innovation leadership and how this transition takes place, was addressed by the analysis of various innovation indicators. Although the Chinese PV sector had initially focused on technological learning from more advanced countries, the government has successively strengthened indigenous innovation, which has resulted in a rapid rise of academic publications and to a lesser extent of patents for PV technology. Whereas China is the worldwide leading country in terms of publications, the analysis of patenting activities revealed that China is still lagging behind Japan and the USA. A closer analysis of R&D investments arrived at the conclusion that most of the leading Chinese PV companies invest only a very small fraction of their sales in R&D. In accordance with that, China's leading PV companies are responsible for only a small proportion of domestic patents.

Nevertheless, as the first generation of PV is technologically relatively mature, the reluctance of Chinese PV companies to invest in R&D will probably not threaten their industrial leadership. In contrast, government sponsored research institutes seem to be more responsive with regard to the political ambition to increase innovation efforts. Although the establishment of State Key Laboratories and the restructuring of China's R&D funding programs might result in strengthened links between basic and applied research as well as between public and private R&D, hitherto China's PV sector is still far from the goal of attaining innovation leadership, which supports findings from previous research.

A disaggregated analysis of transnational PV patents has revealed that technological catching-up of China picked up speed in the period between 2008 and 2010 and takes place in all three technology generations, not only the most recent one. However, technological catch-up has been most successful in the third generation of PV cells, which is still at an experimental stage and predominantly conducted at public research entities.

The overall analysis of the TIS for PV revealed that entrepreneurial activity, market formation, resource mobilisation and creation of legitimacy have reached virtuous cycle where different functions of the TIS are mutually reinforcing. The most significant contributions of China to the global fight against climate change seem to be the reduction of technology costs due to economies of scale in manufacturing and the rapid development of the domestic market for PV.

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8 ANNEX

Table A.1: Crystalline Silicon Cell/Module and Thin-film Producing Companies in China 2015

Company	Total Production (MW)		Production Capacity (MW/yr)	
	Cell	Module	Cell	Module
Wafer-based PV manufacturers				
JA Solar Holdings	3600	3300	4400	
Trina Solar	3300	4300	3500	
JinkoSolar Holdings	2500	3300	2500	
Yingli Green Energy Holding	2400	2500	4000	
Artix Power	2000	3800	2700	
Shunfeng PV International	1900		3000	
Hanwha Solar	1700	1900	1750	2070
Tongwei Solar	1630		2300	
Hareon	1500		1600	
Risen Energy	1260	1360	1300	1800
BYD	1036	1000	1040	1500
Zhongli Talesun Solar	1000	1100	1000	1500
Eging PV	983	1300	1000	1600
Fortune Energy	937		1080	
DMEGC	720		1500	
GCL System Integration		2100		3700
SunTeck		1200		2400
Zhengtai		1000		1200
ReneSola		820		1200
Lerri Solar		800		1500
HT SAAE		800		800
Miscellaneous	14537	15220	20330	30030
Total	**41003**	**45800**	**53000**	**49300**
Thin-film manufacturers				
Hanergy Holding (Si-based)			2820	
Hanergy Holding (CIGS)			100	
Advanced Solar Power (CdTe)	25			
Total	**25**		**2920**	

Source: Based on Fang et al. 2017

Table A.2: Sources of Key Operating Equipment of Trina Solar

Manufacturing Facility	Major Equipment	No. of Units in Operation as of Dec. 31, 2015	Source (Country)
Silcon ingots	DSS furnaces	187	China, United States
Silicon wafers	Wafer sawing machines	179	Japan, Switzerland
Solar cells	Diffusion furnaces (sets)	76	China, Germany, the Netherlands
	Screen printing machine sets	79	Italy, China
PV Modules	Automatic laminators	159	China

Source: Trina Solar 2015

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