Renewable and Sustainable Energy Reviews 64 (2016) 777–789

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

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

How China became a leader in solar PV: An innovation system analysis

Ping Huang [a,b,c,*,1], Simona O. Negro [b], Marko P. Hekkert [b], Kexin Bi [a,d,**,2]

[a] School of Economics and Management, Harbin Engineering University, 150001 Harbin, China
[b] Innovation Studies, Copernicus Institute of Sustainable Development, Faculty of Geosciences, Utrecht University, Heidelberglaan 2, 3584 CS Utrecht, The Netherlands
[c] Bartllett Development Planning Unit, University College London, WC1H 9EZ London, UK
[d] School of Management, Harbin University of Science and Technology, 150040 Harbin, China

ARTICLE INFO

Article history:
Received 24 October 2014
Received in revised form
17 April 2016
Accepted 26 June 2016
Available online 14 July 2016

Keywords:
Solar PV
Technological innovation system (TIS)
Context factors
China

ABSTRACT

In this paper we focus on understanding the rapid rise of the Chinese PV industry and its profound impact on the global PV industry. We investigate how it is possible that a nation that is still focusing on catching up in terms of industry, innovation and technology has been able to bring manufacturers from leading industrialized nations to their knees. This paper applies the framework of the Technological Innovation System (TIS), and also takes the context into account, in terms of the Chinese national innovation system (NIS) and the global PV TIS. It concludes that the rise of the Chinese PV TIS can be explained by the interaction of three context factors (the change in Chinese institutions, technology transfer, and the large European market) and specific PV TIS dynamics. The study empirically shows the importance of extending the national TIS studies by including the influences of context factors.

Contents

---

[*] Corresponding author at: Bartllett Development Planning Unit, University College London, WC1H 9EZ London, UK.
[**] Corresponding author at: School of Economics and Management, Harbin Engineering University, 150001 Harbin, China.
E-mail addresses: huang_ping1987@hotmail.com (P. Huang), s.o.negro@uu.nl (S.O. Negro), m.p.hekkert@uu.nl (M.P. Hekkert), bikexin@hrbeu.edu.cn (K. Bi).
[1] Present address: 34 Tavistock Square, WC1H 9EZ London, UK.
[2] Permanent address: No.145–1, Nantong Street, Nangang District 150001 Harbin, Heilongjiang Province, China.

http://dx.doi.org/10.1016/j.rser.2016.06.061
1364-0321/

1. Introduction

The market for solar photovoltaics (PV) is growing rapidly. In the past decade, solar PV generation has expanded by 50% per year worldwide. In 2012, solar PV generation reached almost 100 TWh, which is sufficient to cover the annual power supply needs of over 30 million European households. In the same year, the world's cumulative total installed capacity exceeded 100 GW, up from only 1 GW in the year 2000 [1,2].

This rapid market growth is mainly due to a massive reduction in production costs [3]. For example, the inflation-adjusted prices of crystalline-silicon (*c*-Si) PV modules have fallen from 5.0 USD/watt in 2000 to around 0.6 USD/watt in June 2014 [4,5]. This sharp drop in production costs has mainly been caused by process innovations in manufacturing technology [1], such as improvements in wire cutting technology. In addition, mass production has led to more efficient and cheaper solar cell production machinery. PV production lines have been optimized, for example by developments in intelligent and self-correcting control of process flow, and this has increased throughput volume. Furthermore, the efficiency of solar cells and modules has increased, resulting in higher returns on investments [6].

Lower prices are good for consumers and for governments that use financial instruments to support the adoption of PV technology. However, the PV industry is severely struggling, as many companies cannot make sufficient profits due to the low market prices. Specifically since 2011, some major global PV manufactures have suffered a sharp decrease in self-financing, including First Solar (USA), Kyocera (Japan) and Trina Solar (China) [7]. Moreover, some large global PV companies have gone bankrupt, including PV manufacturer Suntech (China) and PV panel producers Ever-green Solar and Solyndra (USA), as well as Q-Cells and Solon (Germany) [8–11].

This industry shake-out had a typical geographical pattern. In 2002, Japan became the world leader in PV manufacturing, with four companies in the top 10 largest PV manufacturers in terms of solar cell sales. In 2007, the German PV company Q-Cells took over first place, while the number of Japanese PV companies in the top 10 fell to three. From 2010, Chinese firms took over the top position at the cost of Japanese and German players [6]. In 2012, of the top 10 solar PV manufacturers in terms of actual production/shipments, seven were Chinese companies, and there were no longer any Japanese or German companies in the top 10 [12–15]. This shake-out is a typical pattern in emerging industries. The literature on industrial dynamics has empirically shown that in many emerging industries the number of firms increases at first, but that a shake-out occurs when process innovations instead of product innovations start to dominate the innovation direction of the industry [16–19]. However, in the case of the PV industry, which is heavily supported by government policies, this industry shake-out posed serious legitimacy questions regarding government support of the PV industry. More specifically, Germany's renewable energy policy was criticized for not delivering the vibrant industry that was hoped for. Subsequently, the blame for these losses was put on China and this eventually led to EU trade restrictions on PV from China [20].

The influence of Chinese PV manufacturing on the structure of the global industry is noteworthy. In general, Chinese industrial activities have replaced western production capacity in the past 20 years, due to low resource costs, including labor, land use and electricity, abundant human and material resources, and potentially massive markets. However, it is for the first time that Chinese industrial activities have had such a profound impact on a high-tech and emerging sector.

In recent years, there has been a sharp increase in the number of studies into Chinese PV technology, industry and policy, and these studies have uncovered some major factors contributing to the rapid rise of the Chinese PV industry. The great demand of global markets is believed to be one of the most important factors. Zhang et al. [21] showed that the Chinese solar PV industry has been influenced greatly by overseas markets, for example in European countries such as Germany. Another important factor is the active role of the Chinese government, with its various policy tools. Zhang et al. [21] found that China's top policy objective is to develop the emerging renewable energy industry, aiming to shift from a low-cost manufacturing-based economy to a more high-tech, high-value-added, innovative economy. Similarly, Zhao et al. [22,23] showed that the Chinese government aims to play a vital role in fostering an environment that promotes the development of the PV power industry.

In addition, a necessary factor seems to be the innovation and development of PV power technology. Zhao et al. [22] showed that China's PV power technology has improved dramatically, with technological advances in the efficiency, reliability, and reduced pollution of PV cells and PV power generation systems, leading to a rapid increase in both PV production capacity and the value of exports [22]. China seems to be at the industrial forefront of innovative PV production technology. However, it is as yet unknown how this process occurred. Zheng & Kammen [5] and Grau et al. [24] both reported that Chinese PV manufacturers tend to have lower R&D intensity than the PV manufacturers in other major countries. Current investment in Chinese PV is mainly focused on manufacturing and application rather than on R&D. This conclusion is in line with the findings of Lei et al. [25] and Wu & Mathews [26], both based on the USPTO (United States Patent and Trademark Office) data. In addition, De la Tour et al. [27] stated that the success of some Chinese PV manufacturers cannot be attributed to innovation.

Thus, even though several experts have studied the rise of the Chinese PV industry and a few factors have been singled out that explain the current dominance, we lack insight into the mechanisms that explain the emergence of the Chinese PV industry. Also there is still a debate on the role of domestic innovation in explaining the rapid rise of Chinese PV industry. In this article we therefore present a detailed historical review of the rise of the Chinese PV industry in relation to the context in which this industry emerged. For this purpose, we adopt the innovation system since this perspective allows us to analyze the complex nature of industry emergence and highlights the collective nature of innovation and the interdependencies between actors and institutions in the development and deployment of innovation [28]. Since we focus specifically on the innovation system around the Chinese PV technology and the Chinese PV industry we adopt the Technological Innovation Systems (TIS) framework [29]. To create insight into the mechanisms that explain the successful emergence of the Chinese PV industry we use a process method approach [30–32].

We also contribute to the conceptual development of the TIS perspective by explicitly differentiating the Chinese PV TIS and the context in which the innovation is embedded. We discern the international PV innovation system and the Chinese National Innovation System as context systems. By explicitly conceptualizing the context of an innovation system we answer to the call of Truffer & Coenen [34] for a better spatially conceptualized TIS analysis and the suggestions of Bergek et al. [33] to conceptualize different context systems of a TIS.

2. Methodology

2.1. TIS and its contexts

TIS approach views innovation as a collective activity and analyzes how innovations are developed and deployed through the complex interactions among a multitude of different actors and organizations that are enabled and constrained by physical artifacts as well as by institutions that are regarded as 'the rules of the game'. The TIS perspective has often been applied to describe and analyze the emergence of radical innovations [34–37]. Many of the studies have focused on sustainable energy technologies in various countries around the world [35,38–40], and many apply the scheme of analysis suggested by Bergek et al. [29]. This scheme suggests that analysts should create insight into the structure of the innovation system (the network of actors, institutions and physical infrastructure) and complement these insights by focusing on the key processes that take place in the innovation system [29]. Hekkert et al. [28] propose the following key processes: entrepreneurial experimentation, knowledge development, knowledge exchange, guidance of the search, market formation, resources mobilization, and creation of legitimacy (the seven system functions). The focus on key processes or functions complements the analysis of the structure of innovation systems since many different structural configurations may lead to a similar performance of the innovation system. The analysis of key processes sheds light on how an innovation system is performing. Weak system functions require attention by actors who have an interest in improving the functioning of the innovation system.

A cause of weak system functions can be found in other system functions. Suurs and Hekkert [41] have shown that innovation systems have properties similar to complex systems and that positive feedback loops between system functions are not only responsible for speeding up system performance but also for slowing down it. It is important to note that system functions do not interact directly: they interact via the actors in the innovation systems. An example of a positive feedback loop can be found in the following situation: when actors express high expectations about an innovation, other actors are more likely to make resources available for this innovation, and this makes it easier for entrepreneurs to obtain access to resources and to increase their innovation activities. At the system functions level, there is a positive feedback loop between guidance of the search, resources mobilization and entrepreneurial experimentation. Similarly, negative interaction or lack of interaction explains why certain system functions are not fulfilled well.

Even though interaction patterns can explain system performance, for system interventions it is necessary to find the deeper causes for a lack of positive feedback loops or the presence of negative feedback loops. Different authors label these deep causes as systemic problems [42], system failures [43], or blocking mechanisms [44]. These causes are mostly found in the structure of the innovation system, but they may also be outside the innovation system (see Weber and Rohracher [43] for an elaborate overview of these systemic problems). An abundance of cases has shown that the framework is well suited to analyze the emergence of both radical innovations and industries as well as to investigate the reason why more mature innovation systems function as they do [35,45,46].

However, the framework is also criticized. An important criticism is the often national focus in TIS studies. A TIS is a global system, but still many studies delineate the TIS to the border of a specific country, e.g. Biofuels and Solar PV in the USA [47], Micro-CHP in the UK [48], Biomass Digestion in Germany [35], Fuel Cells in Sweden [49], and CCS in China [50]. This national delineation is justified by the argument that many institutions that influence an innovation system are of a national character and that national governments often have a specific interest in accelerating specific technological trajectories. Truffer & Coenen [34] have discussed the problems with national delineation. They believe that the research on TIS overemphasizes the national level at the expense of other geographical levels. A specific socio-technical regime structure is always embedded in wider institutional context conditions and political economies, and regimes may therefore be subject to spatially differentiated transformation trajectories. This is why they suggest taking more account of the geographical information surrounding the TIS. Moreover, the current TIS literature has yet been able to explicitly address the globalization of technology development and diffusion [51], while the geography of emerging technologies may exhibit highly distributed spatial patterns of development, such as the technological leapfrogging potentials in emerging economies [52]. To adjust for this spatial blindness, Truffer & Coenen [34] believe that the role of the global network needs to be considered.

In line with the suggestions of Truffer & Coenen [34], we have explicitly taken the context of the Chinese PV TIS into account. We did this by studying the general institutional and politico-economic context of China, illustrated by the concept of the Chinese National Innovation System (Chinese NIS), as well as the role of the global PV production and consumption, illustrated by the concept of Global PV TIS. Theoretically, the Chinese PV TIS forms part of the Chinese NIS and Global PV TIS, while the Chinese NIS plays only a marginal role in the Global PV TIS since PV is only a small sector in the Chinese economy (see Fig. 1). At the bottom of Fig. 1, we have included a category of exogenous factors that are not part of either the Chinese NIS or the Global PV TIS; still, these factors clearly influence PV developments in China.

2.2. Material and methods

Qualitative analysis has mostly been used in recent empirical work concerning system functions. This method is strongly based on the results from interviews. The set of system functions mainly serves as a way to structure empirical material (see [45,53]). However, interviews generally only lead to information on a limited number of key events that are subject to recall problems of the interviewees and are therefore less suited to construct the history of an emerging innovation system. An alternative method is historical event analysis, which has been applied in TIS studies, e.g. Negro et al. [54]. This method strongly builds on the work on process analysis as deployed in the Minnesota Studies by Van de Ven et al. [55]. Fundamentally, this approach consists of retrieving as many historical events related to a technological development

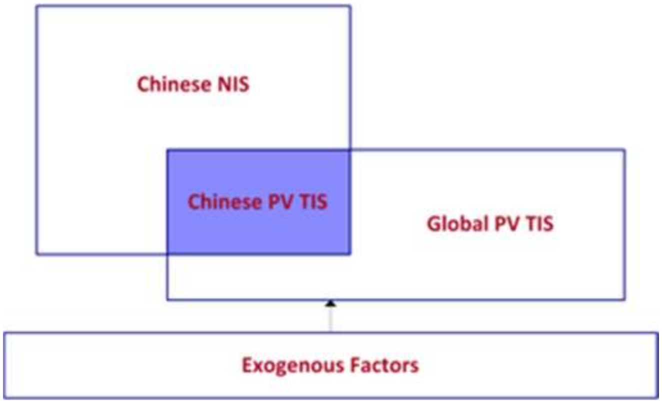

Fig. 1. Chinese PV TIS and its context.

as possible, based on professional journals, newspapers and websites. The events are stored in a database, classified and systematically allocated to the seven system functions. Functional patterns can then be extracted from the database. The methodology results in a coherent sequence of events and trends that describe how things have changed over time [54]. The events in this study are retrieved from Chinese professional journals on PV and renewable energy, including *Solar Energy*, *Energy of China*, *Energy Engineering*, *Renewable Energy Resources*, *Applied Energy Technology* and *Energy Research and Information*. 'PV' and 'photovoltaic' have been used as keywords in the title or abstract of each article of these journals from 1985 to 2012, since 1985 is the year in which all six journals became available online. As a result, 1348 articles are selected, from which the events are extracted. These are supplemented by Chinese newspapers and Chinese websites.

When depicted in graphs, all events are weighted the same, but in the historical narrative the importance of events are indicated. In addition, a distinction should be made regarding the nature of the contribution of an event to the fulfillment of a function. Some events contribute negatively to the development of the technology, and these are counted separately and are represented as negative scores. The negative and positive scores are not added, since the difference between the negative and positive components describes the debate that is going on (see Table 1 for the indicators). In the event analysis, we focused on the rise and fall of the number of activities over time and on the occurrence of interactions between system functions. However, the event data did not always provide enough information to make statements whether a system function is fulfilled sufficiently or not. We added interviews to obtain expert statements on this issue so that the evaluation of system functions is not based solely on the event analysis. Also the interviews were used to shed light on causal links between system functions, which were not apparent from the event analysis. In other words, sometimes the event analysis showed a rise in events or appearance of events that we could not explain. We questioned experts in those specific areas where the problematic interpretation of the event analysis occurred. Appendix A presents further information on the interviewees, in which the names of interviewees are not provided due to confidentiality reasons. We interviewed eight experts in prominent academic and industry positions. We highlighted the system functions by referring to the system functions number F1, F2, etc., adding a C when the event can be considered as part of the Chinese PV TIS and a G when the event takes place outside China and is part of the Global PV TIS.

3. Empirical results: the rise of the Chinese PV innovation system

3.1. The beginning

PV in China can be dated back to 1958, when the first piece of silicon single crystal was invented by the Chinese Academy of Sciences (CAS). Subsequently, the new Institute of Semiconductors, a subdivision of the CAS, started researching solar cells [59]. In 1968, the first solar cells aimed at uses in space satellites were successfully developed and manufactured by an institute in Tianjin; they were installed on China's second satellite, Practice I, in 1971. In the 1970s, a few factories in the cities of Shanghai, Ningbo and Kaifeng produced solar cells for satellites; these factories were operated by the government [22]. It is believed that at the time there was hardly any difference between the efficiency of the solar cells developed in China and of those developed in western countries [60]. In 1973, PV started to be used on land as the energy source for the beacon light in Tianjin port. In subsequent years, some PV demonstration projects were set up for military communication systems, systems for the protection of petroleum pipelines, microwave relay stations, water pumps, and rural broadcasting stations [61,62].

3.2. 1985–1996: the pioneering era

In the early 1980s, the economy of China, a socialist country, was dominated by public ownership of businesses; officially, privately-owned entrepreneurial activity was not permitted. It was

Table 1
Description and indicators for 'Functions of Innovation Systems'.
Sources: [54,56–58]

Function	Indicator	Sign/ value
Function 1: entrepreneurial activities	Project started	+1
	Project stopped	−1
Function 2: knowledge development	Domestic R&D projects, investment in R&D, desktop/ assessment/feasibility studies on PV production	+1
	Training or R&D projects started through turn-key production line/machinery/patent import	
Function 3: knowledge diffusion	Domestic workshops, conferences	+1
	Joint research projects, subsidiary of transnational companies, international conferences or seminars	
Function 4: guidance of the search	Positive expectations on PV	+1
	Explicit regulations by government	
	Negative expectations on PV	−1
	Expressed deficit of regulations	
Function 5: market formation	Specific favorable tax regimes and environmental standards	+1
	Expressed lack of favorable tax regimes or favorable environmental standards	−1
Function 6: resources mobilization	Subsidies, investments for PV	+1
	PV streams allocated to project	
	Expressed lack of subsidies, investments	−1
	Shortage of PV streams allocated to project	
Function 7: advocacy coalition/creation of legitimacy	Support by government, industry	+1
	Expressed lack of support by government, industry	−1

not until 1987 that the National People's Congress (NPC) affirmed for the first time that the private economy was part of the socialist economy [63]. In the following year, the Interim Regulations on Private Companies was established by the Central People's Government (CPG), aiming to safeguard the legitimate rights and interests of privately-owned companies. Since then, privately-owned entrepreneurial activity in China has officially been allowed and even encouraged in certain sectors, including the manufacture and generation of PV [64]. This institutional reform is external to the Chinese PV TIS but has had a major influence on the rise of the Chinese PV industry.

From 1979 to 1992, eight PV companies and research institutes owned by the Chinese government [C-F3] purchased from US and Canadian firms (including Spire and TPK) [G-F3] several turn-key production lines as well as manufacturing equipment for c-Si solar cells (first generation solar PV), a-Si solar cells (second generation solar PV), polycrystalline silicon, and amorphous silicon [65]. Several of our interviewees believed that at that time China lacked the ability to design and manufacture turn-key production lines and manufacturing equipments for the mass production of both c-Si and a-Si solar cells. One interviewee claimed that the technology import hardly had any influence on China's ability to produce PV technology, but merely served as a means to train a group of people destined to become key technical staff members [C-F6] of newly-established PV companies in the following years [66,67]. In the 1990s, besides the import of technology, the only activity was the emergence of a few PV companies [C-F1] based on technology developed at Chinese universities [C-F2]. For example, Jinglong Amorphous Silicon Factory was established in Hebei province in 1995, and this factory was the starting point of the Jinglong Group[3] [68].

In 1992, the United Nations Framework Convention on Climate Change (UNFCCC) was established to "stabilize greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system" [69]. After this event, the Chinese CPG proposed to optimize the relationship between environment and development, by explicitly mentioning solar power and other renewable energy technologies [C-F4]. In 1995, the 'New Energy and Renewable Energy Development Outline for China (1996–2010)' [70] was drafted by the National Scientific and Technological Commission (NSTC). This Outline was aimed at coordinating economic growth and environment protection, especially for rural areas. It was the first time that the concept of renewable energy had been singled out in a national document. The document put forward a development plan for PV in the following five years and highlighted the development of PV cell modules and PV machinery. Moreover, the diffusion of small-scale PV systems and PV demonstration power stations had been highlighted. In 1996, the Electric Power Act was issued, and this law explicitly mentioned "encouraging and supporting the application of renewable energy and the generation of clean energy" [C-F4] [71].

Thus the pioneering era was characterized both by permitting private enterprise and later by specific guidance by the Chinese government. This led to the import of foreign technology [G-F3], followed by entrepreneurial activities by mostly state-owned PV manufacturers [C-F1], made possible by the information gained from using the production technologies [C-F2]. In addition, the increased global guidance in low carbon solutions influenced the guidance by the central government with respect to solar power and other renewable energy technologies [C-F4] (see Fig. 2).

3.3. 1997–2003: opening up of the economy and start of privately-owned entrepreneurial activities

The beginning of this period is characterized by the Kyoto Protocol that imposed binding obligations on industrialized countries to reduce greenhouse gas emissions, and explicitly proposed the development and use of renewable energy [G-F4], leading to several governmental programs of PV application in the USA, EU and Japan from 1997 onwards [G-F4]. Triggered by the potentially huge foreign market, Chinese entrepreneur Jifan Gao believed that renewable energy would in the long run substitute fossil energy, in order to meet the energy needs and emission reduction goals [72]. With this in mind, he set up Trina Solar[4] in 1999 [C-F1]. This was one of the first privately-owned PV companies in China, and it developed the first building powered by solar PV in China [C-F2]. One of the interviewees from a Chinese PV company stated that the first privately-owned PV companies mainly relied on previous capital accumulation by entrepreneurs [C-F6] rather than investments by the government or capital market [73].

In 1999, renewable energy was included as one of the 107 key fields prioritized by the Chinese government in the 'Guide to High-tech Industrialization: Key Fields of Current Priority' [C-F7], which also prioritized the industrialization of PV cells [74]. The results of this plan were less than impressive: there appeared to have been only one investment [C-F6], namely by the company Yingli Green Energy[5] for purchasing a complete set of advanced PV machines and technologies from abroad [G-F3], so as to build three production lines [C-F1] for the production of polycrystalline silicon wafers, polycrystalline silicon solar cells, and solar cell modules [75].

At the end of 2001, China officially became a member of the World Trade Organization (WTO). This proved to be a great accelerator for the Chinese PV industry. As a WTO member, China could gain easier access to foreign open markets and products made in China were no longer subject to foreign trade barriers. Baofang Le, chairman of the board of the Jinglong Group, stated that "before joining the WTO, as a Chinese PV company, we always ran into trade barriers everywhere, leading to very high transaction costs" [76]. Xiaofeng Peng, the initiator of LDK Solar,[6] founded in 2005 [C-F1], even stated that "if China had not become a member of the WTO, there would have been no market for our PV products and I might not have founded LDK Solar" [C-F4] [77]. It is fair to say that the Chinese PV manufacturing experienced significant stimulating effects from the opening up of the Chinese economy [78].

From 2001 onwards, the Chinese government also specifically highlighted the importance of PV technology. In the 'Plan for New Energy and Renewable Energy Industry Development in the Tenth

---

[3] The Jinglong Group, founded in 1995, is a Chinese manufacturer of photovoltaic products. In 2005, JA Solar Holdings was set up as a subsidiary of Jinglong Group, which in 2007 was publicly listed on the National Association of Securities Dealers Automated Quotations (NASDAQ) (http://www.jinglong.net/).

[4] Trina Solar is a Chinese manufacturer of photovoltaic modules; it was founded in 1997 as a system installation company. Trina Solar is currently one of the few photovoltaics manufacturers that have developed a vertically integrated supply chain from the production of monocrystalline ingots, wafers, and cells to the assembly of high quality modules. Trina Solar successfully completed its initial public offering on the New York Stock Exchange (NYSE) in December 2006 (http://en.wikipedia.org/wiki/Trina_Solar).

[5] Yingli Green Energy, established in 1998 by Liansheng Miao, is a solar energy company and photovoltaic (PV) manufacturer. Yingli Green Energy completed its IPO on NYSE in June 2007. Nowadays, Yingli Green Energy has a balanced vertically integrated production capacity of 2450 MW per year (http://en.wikipedia.org/wiki/Yingli).

[6] LDK Solar, located in the city of Xin Yu, was founded by Xiaofeng Peng in July 2005. It manufactures polysilicon, mono and multicrystalline ingots, wafers, cells, modules, systems, power projects, and solutions. On June 1st, 2007, LDK was successfully listed on the NYSE, financiering 0.486 billion USD, thus becoming the largest IPO of the new energy industry and the largest single IPO in China (http://en.wikipedia.org/wiki/LDK_Solar).

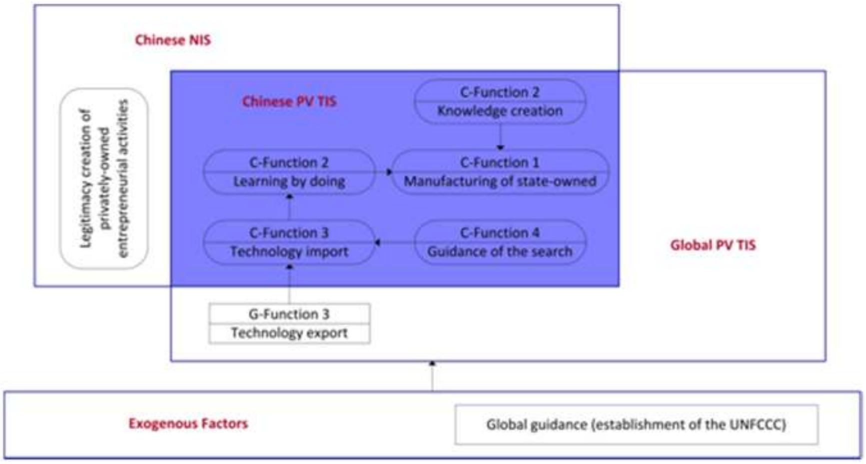

Fig. 2. The main functional pattern of the Chinese PV innovation system in the period 1985–1996.

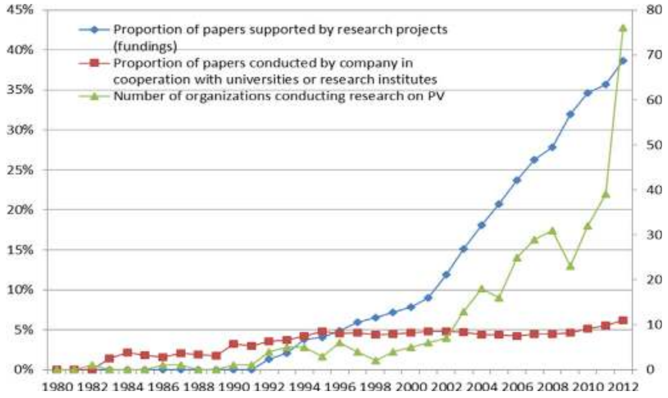

Fig. 3. Knowledge development regarding PV from the journal *Acta Energiae Solaris Sinica*.

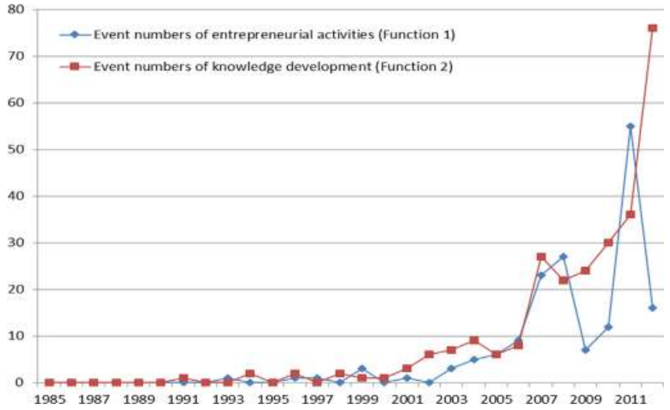

Fig. 4. Entrepreneurial activities and knowledge development regarding PV from six professional journals about energy in China.

Five-Year (2001–2005)' [79], renewable energy was regarded as an important solution to optimize the energy structure and to reduce the impact on the environment [C-F7]. Furthermore, PV technology was included in the three most significant national research programs in China during 2000–2001 [80], namely the 'National Basic Research Program of China (973 Program)', the 'National High Technology Research and Development Program of China (863 Program)', and the 'Plan of National Key Science and Technology (2001–2005)'. The first two national research programs were regarded as guidelines for the development of national strategic key technologies in China [81,82]. Triggered by this strong guidance, investment in the R&D of PV [C-F6] increased faster than before in 2002, followed by more R&D projects [C-F2] focusing on PV (see Fig. 3). In 2002, there was a rapid increase in the number of papers that resulted from externally funded research projects at universities, illustrating the increased investment in PV research. In 2003, there was again an increase in the number of organizations conducting research on PV, and this most likely was the result of the greater availability of funding for PV R&D. Moreover, US patents granted to China [C-F2] began to increase in 2003 [26], indicating a bolstering of the local knowledge development in China. However, entrepreneurial activities were not greatly influenced by this strengthening of the knowledge infrastructure (see Fig. 4), since the cooperation between companies and universities or research institutes was still weak. This was illustrated by the low proportion of co-authored papers conducted by companies in cooperation with universities or research institutes. Several of our interviewees stated that there was a wide gap between academic R&D related to new PV technologies and the application of this knowledge by PV manufacturers in China. This was mainly due to the architecture of the Chinese scientific research system that is strongly knowledge-oriented rather than product-oriented [60,66,67,73].

In 2002, the interaction between foreign PV producers and China started to increase. There were several international aid projects focusing on the application of PV in China. For example, the China-Germany Western PV Village Program was the largest project on PV in China aided by a foreign country thus far. In this project, Germany planned to provide non-reimbursable assistance of about 34 million USD [G-F6], and this assistance involved PV systems and capital [83,84]. The reason for this interest in China was the high expectations about the size of the Chinese domestic PV market. Western countries began to explore the Chinese PV market by offering capital and technological support, aiming to sell more PV products, PV production lines, and knowledge (mainly in the form of patent licensing), as well as obtain contracts for PV installation [85]. Germany even supplemented an 8 million USD investment in the 2.8 MW Qinghai PV Power Station Project in 2002 [86]. That same year saw a peak in the investment in PV by the Chinese government. The 'Delivering Electricity to the Countryside Program' was established; this program covered 783 rural villages which until then had no access to electricity (off-grid) in the provinces of Tibet, Xinjiang, Qinghai, Gansu, Shaanxi, Inner Mongolia, and Sichuan. The program included small-scale hydropower, PV generation and wind-solar hybrid power systems. The

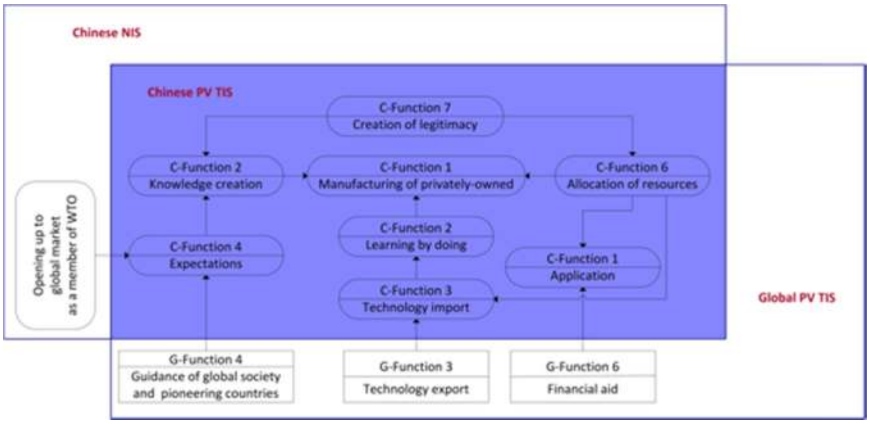

Fig. 5. The main functional pattern of the Chinese PV innovation system in the period 1997–2003.

expected total investment was 1.8 billion CNY (about 0.2 billion USD),[7] and the expected total installed capacity was 12 MW [87–89]. However, considering the huge energy demand in China and in comparison with other renewable energy technologies, the home market for PV was still very small [73]. Foreign firms and governments were overly optimistic about the potential of the Chinese PV market.

To summarize, in this period the privately-owned entrepreneurial activity in the manufacturing sector [C-F1] began to increase, triggered by the guidance from international organizations and several pioneering countries on PV [G-F4], the opening up of the Chinese economy in relation to the WTO, as well as the high expectations of PV [C-F4]. The increased legitimacy of PV [C-F7] resulted in more resources [C-F6]. These resources triggered the import of technology [C-F3], which in turn led to learning from the use of the production technologies [C-F2] in newly-established privately-owned PV production set-ups [C-F1]. The strengthening of guidance [C-F4] in this period also led to knowledge creation [C-F2]; however, this was not closely related to privately-owned entrepreneurial activities [C-F1]. Moreover, the application of PV [C-F1] in China started to take place, triggered by both foreign projects [G-F6] and domestic capital [C-F6] (see Fig. 5).

3.4. 2004–2008: boost of the PV manufacturing sector triggered by the European market

In 2004, a new amended version of Germany's Renewable Energy Sources Act (EEG) came into force, replacing the previous version from the year 2000. This act gave priority to electricity generated from renewable energy sources, guaranteeing each plant operator a fixed tariff for electricity that was generated from renewable sources and fed into the public electricity grid [G-F5] [90]. In addition, some other European countries initiated policies that stimulated the demand for PV. These developments strongly increased the demand for PV products. There was a very strong correlation between the growth rate of European PV installed capacity and the Chinese PV cell production output (see Fig. 6), which clearly indicates that the expanding European PV market was the main driver for the growth of the Chinese PV manufacturing sector. The European subsidy regimes, especially in Germany and Italy, attracted many Chinese companies to enter into the PV manufacturing sector [C-F1] by purchasing turn-key production lines from western countries to produce PV cells, even though they had no previous experience in the PV manufacturing sector [66,85]. Thus, it was the plug-and-play character of solar cell manufacturing that enabled Chinese manufacturers to move in quickly.

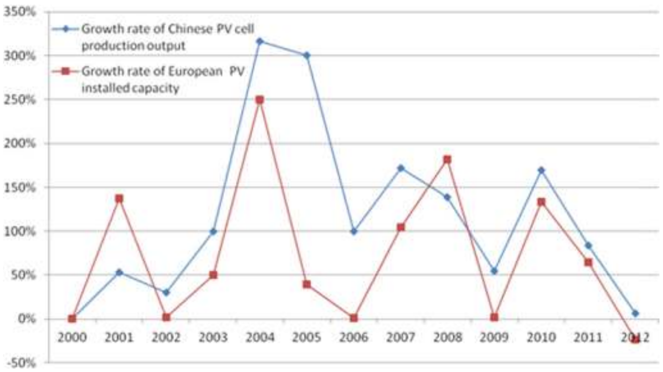

Fig. 6. Comparison of the growth rate of Chinese PV cell production output and European PV installation capacity from 2000 to 2012 (MW_p).
Source: [2,91,92]

Due to the strong increase in demand for PV, a global shortage of high purity polycrystalline silicon occurred in 2004 [85]. Especially in the Chinese PV cell manufacturing sector, there was consensus that the factories in possession of silicon were the key players in the field [66,67]. As a result of the shortage, the price of high purity polycrystalline silicon rose to about 300 USD/kg in 2007, while the production cost was just about 25–35 USD/kg [93]. Not surprisingly, this led to a huge increase in entrepreneurial activity in the polycrystalline silicon manufacturing sector [C-F1]. However, since the purity requirement of solar grade polycrystalline silicon is much higher than for computer chips, hardly any company in China was able to manufacture solar grade polycrystalline silicon before 2007, and this led to a greatly increased import of technology [G-F3]. For example, silicon company ORISI Silicon purchased an in-house pilot line from Russia and started producing, even though the line was not mature enough. Moreover, a large number of technical staff in this field were recruited with high salaries from the seven major global silicon companies[8] [C-F6] [66].

However, it seems that the development of the competence in PV machinery design and manufacturing did not come from technology import, but from the R&D development of the Chinese machinery manufacturers. Several interviewees noted that

---

[7] We use the USD to CNY exchange rate of the year to make these conversions in this paper. In 2002, the exchange rate for USD to CNY is 8.277-1.

[8] These seven major global silicon enterprises are Hemlock, Wacker, Tokuyama, REC, MEMC, Mitsubishi, and Sumitomo.

Chinese machinery manufacturers from the semiconductor industry had a good technological background, which allowed for quick adjustment to manufacturing PV machinery for c-Si solar cells [67,73]. Therefore, it was the close connection between the knowledge necessary for PV manufacturing technology and the knowledge necessary for the semiconductor industry that facilitated this rapid Chinese involvement.

In 2005, the 'Renewable Energy Act' was issued in China, which demanded compulsory grid connection and full purchase of renewable power [C-F7] [94]. This law triggered local governments to support PV firms in their region [67]. For example, the newly-established PV company LDK Solar was founded as a result of strong support from local government. In 1997, the initiator of LDK Solar, Xiaofeng Peng, started Suzhou Liouxin to manufacture personal protective equipment products such as gloves. He considered moving into PV production [C-F1] when he realized that the European PV market was highly promising. In the meantime, the mayor of the city of Xin Yu, Dehe Wang, was looking for investments in renewable energy. As a result, LDK Solar was established in Xin Yu in 2005, with strong support in the form of financial resources, human resources and cheap power supply, provided by the local government of Xin Yu [C-F6], [67].

Late in 2005, Suntech Power became the first PV manufacturer to be listed in the New York Stock Exchange (NYSE) [G-F6], which indicates that by then Chinese PV manufacturing was also able to obtain investment from the global capital market. This proved to be a strong driver for other PV manufacturers and entrepreneurs in China [95,96]. In addition, the promising European PV market also led to more local capital resources allocated to the PV manufacturing sector [C-F6] [73]. As a result, with easy access to global and local capital resources, most PV cell manufacturers purchased production lines from western countries [G-F3], ironically mainly from Germany, to produce PV cells and to export them back to Europe. One of our interviewees stated that in this period German machinery was favored for its greater stability and reliability. This machinery outperformed the much cheaper Chinese machinery, whose frequent repairs led to production stops and thus to higher production costs [66]. Due to the generally high profitability of solar cells, it took less than one year for manufacturers to earn back their investment in production lines, which was much shorter than the payback times in any other sector [66,67]. It is fair to say that Chinese PV manufacturers began to enter the global market with the advantage of lower production costs compared to other nations [97]. According to the 2007 report on PV in China, published by the China Renewable Energy Industry Association, the costs of a 1 kW solar system for 2006 were between 3.7 CNY/kWh (0.46 USD/kWh) and 5.5 CNY/kWh (0.69 USD/kWh). A leading Chinese PV manufacturer even estimated that the cost of smaller scale PV could be lower at 2.1 CNY/kWh (0.26 USD/kWh). In the meantime, the estimated cost in Europe was up to roughly 0.75 EUR/kWh (0.94 USD/kWh) [92]. Following abundant global and local investment and strong support from local governments, entrepreneurial activities in the PV manufacturing sector remained very active in 2005 [C-F1], even though the growth of the European PV installed capacity dropped dramatically (see Fig. 5). Under these circumstances, there was a huge shortage of trained staff for PV, since the speed of domestic personnel training was lagging far behind the expansion of the Chinese PV manufacturing sector. At the time, Chinese PV manufacturers were vying for Chinese PhD graduates in solar cell technology from foreign universities. Local PhD graduates in solar cell technology could also easily earn formidable salaries of about 500,000 CNY per year (about 61,000 USD) [66].

In the meantime, a lobby emerged for new policy programs stimulating local demand for PV. There was a call for an explicit national target for PV, and for financial incentives to stimulate a National PV market [C-F7] [98]. In 2006, the following three detailed regulations were drafted: the 'Special Renewable Energy Fund', the 'Regulation of Renewable Energy Generation, and the 'Renewable Energy Price and Cost-Sharing Management' [44]. However, compared to the explicit regulations on the price of wind power generation and biomass generation, a clear regulation on the price of PV generation was still missing. As a result, installed capacity increased to 20 MW in 2007, an increase which was dwarfed by the PV cell production capacity of 1088 MW [92].

In summary, in this period the European PV market formation was strengthened [G-F5], especially in Germany, and entrepreneurial activity in the Chinese PV solar cell and polycrystalline silicon sectors [C-F1] increased dramatically. This was mainly as a result of knowledge import [C-F3] and learning by using the production technologies [C-F2], as well as increased global capital and human resources [G-F6] entering the PV manufacturing sector. In addition, entrepreneurial activities regarding PV machinery started to emerge [C-F1]. For this, local knowledge regarding PV technology was used instead of the imports of turnkey machines. Also, the legitimacy of PV [C-F7] increased, which induced strong support from local governments [C-F7], leading to the availability of more local resources [C-F6]. Along with the continuing strong demand from the European PV market [G-F5], the strong local supports in turn induced entrepreneurial activities in the PV manufacturing sector [C-F1]. Besides this virtuous cycle [C-F1], lobbying activities started for favorable policies to support

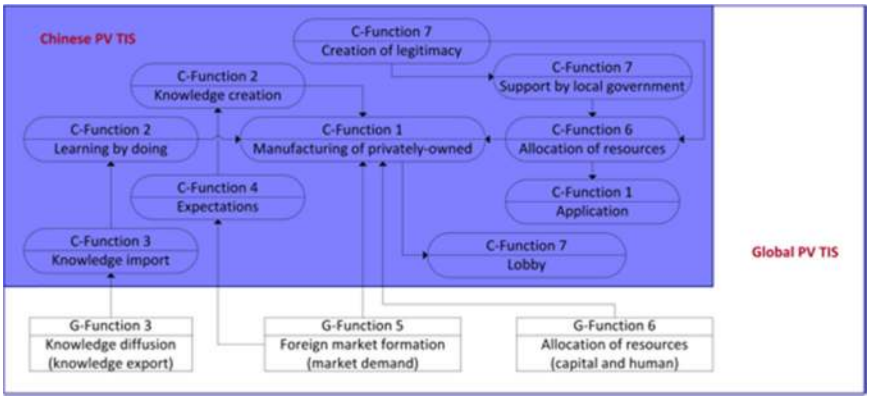

Fig. 7. The main functional pattern of the Chinese PV innovation system in the period 2004–2008.

a domestic market [C-F7] and this seems to have had some effect (see Fig. 7).

3.5. 2009–2012: the beginning of the formation of a domestic market for PV

At the beginning of 2009, the effects of the global financial crisis became visible and the PV industry suffered severely [99]. At the same time, competition on the PV market became fierce and the price of PV started to drop. It became harder for Chinese entrepreneurs to remain profitable, and as a result Chinese entrepreneurs [C-F1] made an even greater effort to convince the Chinese government to invest in a domestic market [C-F7]. Traditionally, the lobby process is not very effective in China; however, due to the importance of this sector in economic turnover and employment, local governments joined forces with the entrepreneurs in the lobby. Moreover, this lobby can be associated with the Chinese central government's macroeconomic policy, which responded to the global financial crisis with a stimulus package of 4000 billion CNY (about 585.6 billion USD) for 2009 and 2010, in order to increase public expenditure and thus stimulate domestic demand. As a result, this initially led to some market formation programs (the ‘Golden Sun Demonstration Program’ and the ‘Solar Building Program’) financed through the Special Renewable Energy Fund [C-F6] [100,101,102]. However, these subsidies were allocated based on installation capacity rather than generated output, which resulted in the strange phenomenon of Chinese PV manufacturers preferring to sell PV products of poorer quality to domestic projects in order to reduce inventories. This, in turn, caused a relatively low generating capacity of PV [67].

Following the tremendous expansion of the Chinese PV manufacturing sector and the long-term support from both central and local government in the previous period, a negative regulation on PV manufacturers emerged in 2009 [C-F7]. After several years of rapid expansion of the polycrystalline silicon industry since 2006, the Chinese CPG believed the production capacity of polycrystalline silicon to be excessive, with about 80 thousand ton under construction. In addition, polycrystalline silicon started to be regarded as a product of high energy consumption and high pollution. Accordingly, the development of the polycrystalline silicon industry was restrained by the CPG, leading to less available capital and to restraining policies by local governments, and consequently the termination of some projects [C-F1] [67]. As a result, the growth rate of the production capacity and output of polycrystalline silicon has shown a clear reduction since 2010.

While the polycrystalline silicon industry was facing restrictive measures, the manufacture of solar cells and modules was still able to acquire support from both central and local government. In 2009 and 2010, the China Development Bank (CDB), a policy bank, provided a line of credit of approximately 30 billion USD for Chinese solar cell and module manufacturers [C-F6]. Moreover, some local governments issued various refund policies to promote investment [C-F6] in new PV manufacturing plants [C-F1]. For example, the city of Huai'an provided refunds on loan interest, corporate income tax, and land transfer fees in addition to low electricity tariffs for local newly-established PV manufacturers [24].

In 2009, the 48th Research Institute of China Electronics Technology Group Corporation built twenty c-Si solar cell production lines for Chinese PV solar cell manufacturers [C-F1], which largely consisted of self-developed PV machinery [C-F2] [103]. Chinese PV machinery manufacturers obtained the technology competence for most special equipment in the turn-key production line of c-Si solar cell, with the exception of fully automatic printers and cutting apparatuses, and by 2009 occupied a reasonable share of the domestic market [104]. It also became clear that Chinese manufacturers of PV machinery were on the way to becoming serious competitors for foreign machinery manufacturers in the field of the c-Si solar cell machinery in which China specialized [85]. One of the interviewees, who worked as CTO in a major Chinese PV company, claimed that many PV manufacturers preferred to use domestic machinery, since most of the domestic machinery for c-Si solar cell performed as well as imported machinery but at a much lower price [73]. This increased competence resulted in a situation in which about 70% of new manufacturing machines used in Chinese PV c-Si solar cell manufacturing were now being made by Chinese manufacturers. However, the stability and reliability of some core Chinese PV machinery for c-Si solar cell were still lagging behind the advanced level of international machinery. In addition, the PV machineries and production line for thin film solar cells still depended mainly on import [60,66,67].

In 2010, the Chinese PV Industry Alliance was established, in which 22 PV manufacturers were involved [C-F1]. This reinforced the lobby for policies favorable to PV [C-F7] [73,105]. The target of the lobby was to introduce a specific domestic feed-in tariff for PV. In the same year, the renewable energy industry, including the PV manufacturing sector, became one of the seven Strategic Emerging Sectors (SES) [C-F7]. In fact, the seven SES were regarded as important forces of Chinese economic development in subsequent years [106]. Since 2010, PV has officially been regarded as a strategic necessity for China.

In 2011, a feed-in tariff (FIT) for PV generation was finally established [C-F5], which was considered as a milestone for PV in China [107]. The grid-connected price of PV electricity was set at 1.15 CNY/KWh (about 0.18 USD/KWh) for installations from before 2012 and 1 CNY/KWh (about 0.15 USD/KWh) for installations from 2012 [108]. Although the FIT for PV-generated electricity was lower than expected and the detailed rules and regulations remained vague, the announcement of the FIT still triggered a fast rise in PV installations in 2011 (see Fig. 8), which was the fastest growth rate ever. However, this rapid growth in 2011 may also have been induced by the price difference between projects completed before and after 2012. In 2012, the growth rate of PV installations fell dramatically (see Fig. 8). The FIT seems to have had little impact on the Chinese PV manufacturing industry, since the production of solar cells continued to drop in these two years (see Fig. 6).

In the same year, in order to absorb the excessive production capacity, Chinese PV manufacturers started to explore emerging markets such as South America, South-East Asia and Africa, where 40 projects were commissioned [C-F1] [109]. Moreover, Chinese PV machinery manufacturers began exporting PV machinery to foreign PV manufacturers in 2010 [110], and made 100 million CNY

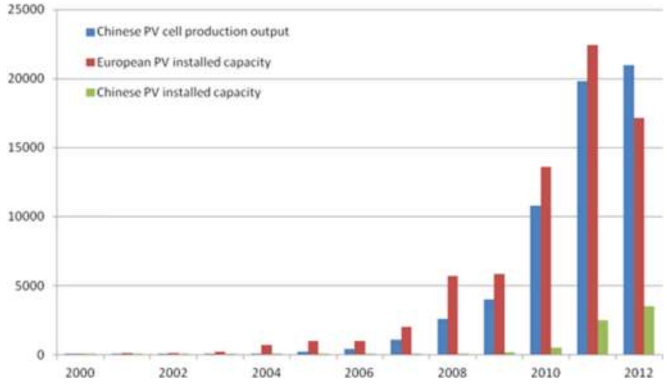

Fig. 8. Chinese PV cell production output, Chinese PV-installed capacity and European PV-installed capacity from 2000 to 2012 (MW_p).
Source: [2,91,92]

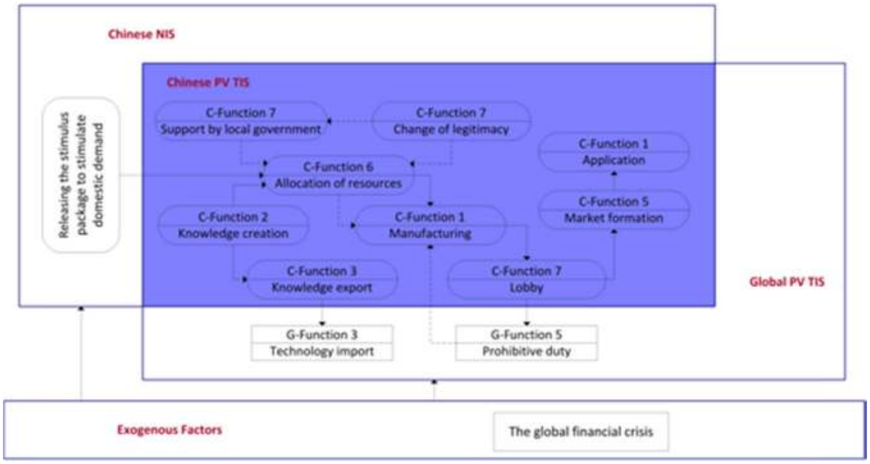

Fig. 9. The functional pattern of the Chinese PV innovation system in the period 2009–2012 (In this figure, dotted lines linked between functions refer to negative effect).

(about 15.5 million USD) in exports from the total sales revenue of 4 billion CNY (about 0.6 billion USD) [104]. For example, the Jinglong Group exported a single crystal silicon furnace to an Uzbekistani PV manufacturer in 2011 [C-F1, C-F3] [111].

Following the decline of the European PV market, the European Commission initiated anti-dumping proceedings against Chinese PV manufacturers in 2012, in order to protect their own PV manufacturing sector. These proceedings included PV panels and their key components. Up to then, this had been the largest trade litigation initiated by the EU against China, involving more than 20 billion USD [G-F5] [20]. Moreover, at the end of 2012, the US Department of Commerce imposed the anti-dumping and anti-subsidy duties on Chinese crystalline silicon PV cells and modules [112]. Aiming to take action in response to the investigation initialized by the USA, the 'PV Generation Promotion Alliance' was set up by several major Chinese PV manufacturers, including Suntech Power, Yingli Green Energy and Trina Solar. [C-F7] [113]. In the same year, the annual European PV installation fell for the first time in a decade, resulting in no growth in China in 2012 for the PV cell production output (see Fig. 6) and the polycrystalline silicon production output [C-F1] [20,112].

While the Chinese PV sector lost its legitimacy due to the foreign anti-dumping initiatives, the Chinese central government strengthened its support for Chinese PV by drafting three dedicated, nationwide documents. These documents covered almost all aspects of PV, including PV manufacturing, PV generation and PV technology [C-F7]. In fact, this was the first time that the PV industry and technology had been singled out for national documents, rather than just being included in documents on renewable energy. Moreover, the objectives became quite specific and ambitious. For example, until 2015 leading polycrystalline silicon manufacturers were to reach a production volume of five tons, leading solar cell manufacturers were to reach a production volume of five GW, and three to four PV machinery manufacturers were to earn an annual sales revenue of more than 1 billion CNY (about 0.2 billion USD) [104,114].

In summary, following the huge impact of the global financial crisis and the fierce competition on the international PV market, the Chinese PV manufacturing sector [C-F1], together with some local governments, tried hard to lobby for the formation of a domestic market [C-F7], and this led to the beginning of the formation of the Chinese PV market [C-F5]. However, the domestic PV market had little impact on the Chinese PV manufacturing sector [C-F1], since the domestic market was still very small compared to the export market. Export also became problematic due to trade litigations [G-F5], resulting in a sharp drop in the growth rate of Chinese PV output [C-F1]. In this period, in the supply chain of the Chinese PV manufacturing sector, different industries seemed to be heading in different directions. While the polycrystalline silicon industry [C-F1] began to be restrained by the central government [C-F7], the solar cell and module industries [C-F1] still enjoyed easy access to financial resources from central and local government [C-F6]. In the meantime, some PV machinery manufacturers started to export self-developed manufacturing equipment to other developing countries [C-F3], which may indicate the beginning of the transformation of the Chinese PV manufacturing sector (see Fig. 9).

Obviously, compared to foreign market size, current Chinese PV market is still at its infancy stage. However, there are signs in the domestic market indicating the gradual formation of a mature PV innovation system. Moreover, the rise of Chinese PV innovation system in the past decade, induced by explicit influences of external contextual factors on the Chinese PV TIS and strong internal dynamics, has also been validated by interview results.

The effects of external contextual factors on Chinese PV TIS are twofold. On the one hand, four interviewees engaged in technology development (AT1, AT2, AT3, and AT4) highlight the essential role of turn-key production lines from western countries, especially Germany, which significantly facilitated the production of PV modules. On the other hand, most interviewees (AT1, AT2, AT3, AP2, and E1) view the rapid growth of PV market in Europe as the most important cause for large-scale expansion of Chinese manufacturing capacity of PV products in a short period.

As regard to the internal dynamics in Chinese PV TIS, interviewees AT1, AT2, AT4, and E1 all mentioned the accumulation of technological competence as a key factor that explains the rise of Chinese PV industry. However, universities and research institutes do not play a key role since their interaction with the industry is very limited (AT1, AT2, AT3, AP1, and E1). Moreover, the important role of local governments is recognized by interviewees AT1, AP1, AP3, and E1. In pursuit of rapid economic growth and local employment, local governments compete to provide favorable policies for PV manufacturers, such as easy access to financial capital, low-cost land use, and low cost electricity supply. This strong local support, induced by a strong national policy program, has attracted many entrepreneurs to enter into PV industry. Finally, two interviewees (AP2 and E1) highlighted that the Chinese PV advocacy coalition has become much more influential when PV industry has become more mature. This led to increasingly favorable institutional conditions.

4. Analysis and conclusions

The story of the success of China's PV industry on the global market started as early as 1980s, although the real acceleration did not occur until 2004. The industrialization process of the PV industry and the establishment of global dominance took place in less than 10 years.

Three factors *external* to the Chinese PV TIS were of crucial importance. Firstly, China changed its economic policy and permitted private enterprise [C-F1] and, related to this, the country became a WTO member. Secondly, the technology transfer from western countries to China was substantial, and Germany played an important role in this [C-F2, G-F3]. In search of a large market for their products, western firms helped the Chinese install PV installations and enhance their competences. Moreover, these firms delivered turn-key production lines. Thirdly, the large European market [G-F5] for PV in combination with the availability of turn-key production lines [C-F2] triggered Chinese entrepreneurs to enter this new industry. The turn-key production lines are a typical feature of this innovation system. Only modest technological competences are needed to run a PV factory. The high-tech capabilities and knowledge are embedded in the production lines and can therefore easily be transferred. It is the late entrance of China into the PV sector that helped make these types of dynamics possible. As a result of this late entrance, well-working turn-key production lines were available.

In addition to these external factors, there are strong *internal* dynamics in the Chinese PV TIS that explain the rapid growth of the sector. Entrepreneurs entered the innovation system because of the high expectations of profitable business opportunities. However, it was the Chinese central government that in several policy plans highlighted the importance of renewable energy for the long-term future of China. In this way, activities in the PV sector were legitimized and local governments used this legitimacy to facilitate PV entrepreneurs with cheap capital, land, and institutional advantages, which in turn led to more entrepreneurs entering the innovation system. In the meantime, technological competence was also acquired by means of investment in R&D, but due to the weak connection between knowledge organizations (universities and research institutes) and PV manufacturers, for a long time most of the technology was imported from abroad. While the central government highlighted the importance of PV in terms of climate and energy security, local governments mainly saw PV as an industrial opportunity and a way to increase local employment and tax revenues.

In addition, even though Chinese PV solar cell manufacturers preferred to import turn-key technology from abroad, the development of technological competence also played an important role in the rise of the Chinese PV industry, and this is reflected particularly in the rise of Chinese manufacturing of PV machinery for c-Si solar cells. The development of PV machinery involved high-tech capabilities and knowledge that for many years had been monopolized by a few western manufacturers of PV machinery. In this context, it is remarkable that several Chinese traditional machinery manufacturers managed to turn to PV and develop and produce various PV manufacturing modules, mainly in the field of c-Si solar cells and, furthermore, at a far lower price.

With the rapid rise of the Chinese PV manufacturing sector, it is the domestic market for PV that is the missing link which makes the PV innovation system complete. The small size of the domestic market is mainly due to the weak lobby network around PV, which is believed to be a common institutional problem in China. Moreover, the export-oriented focus did not help to create a strong Chinese PV innovation system. However, in recent years local governments have started to join the lobby network. This seems to be successful, and has led to the beginning of a Chinese PV market with the implementation of an FIT scheme.

Therefore, in approximately 10 years, as a late entrant, the Chinese PV manufacturing sector has managed not only to catch up, but also to become the world leader in the PV industry. Considering the increasing importance of this sector for the Chinese economy, the Chinese PV industry has gradually become one of the pillars of the Chinese manufacturing sector. Especially because of its high-tech capabilities and its great contribution to local employment and tax revenue, the PV industry seems to be receiving more attention from the Chinese central and local government.

In terms of theory development, this paper has shown that it is highly useful to explicitly take different context factors into account, echoing recent calls for conceptualizing contextual structures and interaction dynamics by the major transitions scholars [33,115,116]. In this paper, we have simplified both the context of the Chinese PV innovation system to Chinese industrial policy in general and the influence of the global PV TIS. Although this may be a simplification, we believe it sheds sufficient light on important interaction mechanisms and offers sufficient explanations for the development of this industry.

While this study has attempted to thoroughly uncover the interactions between the Chinese PV innovation system and some context systems in the innovation trajectory of PV in China, it has some limitations that can be improved by further research. Firstly, the role of local factors in the innovation and transitions process has been highlighted in this study but we did not specify the link with existing actor structures. A recent study argued that TIS actors, networks and institutions are embedded in structures that pre-exist in a specific territory, and the local embeddedness has impact on the formation of an innovation system [33]. This spatial orientation is important since it may explain why industrial clusters emerge and develop in one city or region but not in another; and how to identify the spatially differential routes of transitions in a specific territory. Secondly, this research is unable to emphasize the interactions between TIS and relevant neighboring sectors. In this study, we observed that entrepreneurs moved into the PV industry from related sectors, however, a thorough analysis of the impact of related sectors on a focal innovation system is still lacking.

Acknowledgments

The authors are extremely grateful to the eight interviewees who unreservedly shared their knowledge with us. This work has been supported by the National Natural Science Foundation of China (Project nos. 71073041, 71273073 and 71472057), the National Soft Science Research Program of China (Project no. 2012GXS4D080) and the Research Fund for the Doctoral Program of Higher Education of China (Project no. 20122304110026).

Appendix A. List of Interviews

See Table A1.

Table A1
List of interviews that have been carried out.

Symbol	Type	Institute	Nationality	Interview information
AT1	Academics at technology	Shanghai Jiao Tong University	China	2014.01.26, 43′, by phone
AT2	Academics at technology	Chinese Academy of Sciences	China	2014.01.27, 32′, by phone
AT3	Academics at technology	Nankai University	China	2014.01.29, 47′, by phone
AT4	Academics at technology	Utrecht University	the Netherlands	2014.01.29, 37′, face to face
AP1	Academics at policy	Chinese Academy of Sciences	China	2014.03.10, by email
AP2	Academics at policy	North China Electric Power University	China	2014.03.13, 28′, by phone
AP3	Academics at policy	Tsinghua University	China	2014.03.17, 27′, by phone
E1	Entrepreneur (CTO)	anonymous	China	2014.03.14, 44′, by phone

References

[1] IEA. World energy outlook.Paris, France: IEA Publications,; 2013.
[2] Masson G, Latour M, Rekinger M, Theologitis I-M, Papoutsi M. In: Winneker C, editor. Global Market Outlook for Photovoltaics 2013–2017. European Photovoltaic Industry Association; 2013.
[3] RED, Nowak S, Gutschner M, Gnos S, Rinke T. Technology Roadmap Solar photovoltaic energy (Division IsRE). Paris, France: IEA Publications,; 2010.
[4] PV pvXchange. module price index; 2014 ⟨http://www.pvxchange.com/priceindex/Default.aspx?template_id=1&langTag=en-GB⟩.
[5] Zheng C, Kammen DM. An innovation-focused roadmap for a sustainable global photovoltaic industry. Energy Policy 2014;67:159–69.
[6] Wolden CA, Kurtin J, Baxter JB, Repins I, Shaheen SE, Torvik JT, et al. Photovoltaic manufacturing: present status, future prospects, and research needs. J Vacuum Sci Technol A: Vacuum Surf Films 2011:29.
[7] Lund PD. How fast can businesses in the new energy sector grow? An analysis of critical factors Renewable Energy. 2014;66:33–40.
[8] Bloomberg; 2011a ⟨http://www.bloomberg.com/news/2011–08-15/evergreen-solar-seeks-bankruptcy-protection-with-debt-of-486–5-million.html⟩.
[9] Bloomberg; 2011b ⟨http://www.bloomberg.com/news/2011–12-14/german-solar-stock-pioneer-solon-plummets-on-insolvency-filing.html⟩.
[10] Bloomberg; 2011c ⟨http://www.bloomberg.com/news/2011–10-17/solyndra-judge-denies-u-s-request-to-put-trustee-in-charge-of-bankruptcy.html⟩.
[11] CPIA. 2011–2012 China Photovoltaic Industry Development.Beijing: China Photovoltaic Industry Alliance,; 2012.
[12] Jäger-Waldau A. PV Status Report 2013.Belgium: Publications Office Of The European Union,; 2013.
[13] Jäger-Waldau A. PV Status Report 2003.Italy: Office For Official Publications Of The European Communities,; 2003.
[14] Jäger-Waldau APV. Status Report 2008.Belgium: Office For Official Publications Of The European Communities,; 2008.
[15] Schultz S. Twilight of an industry: bankruptcies have German solar on the ropes. Spiegel International Online; 2013: ⟨http://www.spiegel.de/international/business/q-cells-bankruptcy-heralds-end-of-german-solar-cell-industry-a-825490.html⟩.
[16] Utterback JM. Mastering the Dynamics of Innovation.Boston: Harvard Business Press,; 1996.
[17] Klepper S, Simons KL. Industry shakeouts and technological change. Int J Ind Organ 2005;23:23–43.
[18] Klepper S, Simons KL. Technological extinctions of industrial firms: An inquiry into their nature and causes. Ind Corp Change 1997;6:379–460.
[19] Klepper S, Miller JH. Entry, exit, and shakeouts in the United States in new manufactured products. Int J Ind Organ 1995;13:567–91.
[20] Editor. Chinese ‘Anti’ voice, the legislation of European ‘Anti-dumping’ on PV need to be cautious. Solar Energy; 2012:23–26 [Chinese version].
[21] Zhang S, Andrews-Speed P, Zhao X, He Y. Interactions between renewable energy policy and renewable energy industrial policy: A critical analysis of China's policy approach to renewable energies. Energy Policy 2013;62:342–53.
[22] Zhao ZY, Zhang SY, Hubbard B, Yao X. The emergence of the solar photovoltaic power industry in China. Renew Sustain Energy Rev 2013;21:229–36.
[23] Zhao ZY, Zhang SY, Zuo J. A critical analysis of the photovoltaic power industry in China – From diamond model to gear model. Renew Sustain Energy Rev 2011;15:4963–71.
[24] Grau T, Huo M, Neuhoff K. Survey of photovoltaic industry and policy in Germany and China. Energy Policy 2012;51:20–37.
[25] Lei XP, Zhao ZY, Zhang X, Chen DZ, Huang MH, Zheng J, et al. Technological collaboration patterns in solar cell industry based on patent inventors and assignees analysis. Scientometrics. 2013;96:427–41.
[26] Wu CY, Mathews JA. Knowledge flows in the solar photovoltaic industry: Insights from patenting by Taiwan, Korea, and China. Res Policy 2012;41:524–40.
[27] de la Tour A, Glachant M, Ménière Y. Innovation and international technology transfer: the case of the Chinese photovoltaic industry. Energy Policy 2011;39:761–70.
[28] Hekkert MP, Suurs RAA, Negro SO, Kuhlmann S, Smits REHM. Functions of innovation systems: a new approach for analysing technological change. Technol Forecast Soc Change 2007;74:413–32.
[29] Bergek A, Jacobsson S, Carlsson B, Lindmark S, Rickne A. Analyzing the functional dynamics of technological innovation systems: a scheme of analysis. Res Policy 2008;37:407–29.
[30] Poole MS, Van de Ven AH, Dooley K, Holmes ME. Organizational Change and Innovation Processes, Theories and Methods for Research. Oxford University Press,; 2000. p. 406.
[31] Abbott A. Some comments on sequence analysis and optimal matching methods in sociology: review and prospect – reply to Levine and Wu. Sociol Methods Res 2000;29(1):65–76.
[32] Abbott A. Sequence analysis: new methods for old ideas. Ann Rev Sociol 1995;21:93–113.
[33] Bergek A, Hekkert MP, Jacobsson S, Markard J, Sandén B, Truffer B. Technological innovation systems in contexts: Conceptualizing contextual structures and interaction dynamics. Environ Innov Soc Trans 2015;16:51–64.
[34] Truffer B, Coenen L. Environmental Innovation and Sustainability Transitions in Regional Studies. Reg Stud 2012;46:1–21.
[35] Negro SO, Hekkert MP. Explaining the success of emerging technologies by innovation system functioning: the case of biomass digestion in Germany. Technol Anal Strateg Manag 2008;20:465–82.
[36] van Alphen K, van Ruijven J, Kasa S, Hekkert M, Turkenburg W. The performance of the Norwegian carbon dioxide, capture and storage innovation system. Energy Policy 2009;37:43–55.
[37] Hillman KM, Sandén BA. Exploring technology paths: The development of alternative transport fuels in Sweden 2007–2020. Technol Forecasti Soc Change 2008;75:1279–302.
[38] Hellsmark H, Jacobsson S. Opportunities for and limits to academics as system builders – the case of realizing the potential of gasified biomass in Austria. Energy Policy 2009;37:5597–611.
[39] Wieczorek AJ, Negro SO, Harmsen R, Heimeriks GJ, Luo L, Hekkert MP. A review of the European offshore wind innovation system. Renew Sustain Energy Rev 2013;26:294–306.
[40] Gosens J, Lu Y. From lagging to leading? Technological innovation systems in emerging economies and the case of Chinese wind power Energy Policy. 2013;60:234–50.
[41] Suurs RAA, Hekkert MP. Cumulative causation in the formation of a technological innovation system: the case of biofuels in the Netherlands. Technol Forecast Soc Change 2009;76:1003–20.
[42] Wieczorek AJ, Hekkert MP. Systemic instruments for systemic innovation problems: a framework for policy makers and innovation scholars. Sci Pub Policy 2012;39:74–87.
[43] Weber KM, Rohracher H. Legitimizing research, technology and innovation policies for transformative change. Res Policy 2012;41:1037–47.
[44] Johnson A, Jacobsson S. Inducement and blocking mechanisms in the development of a new industry: the case of renewable energy technology in Sweden. In: Coombs R, Green K, Richards A, Walsh V, editors. Technology and the Market Demand, Users and Innovation. Cheltenham: Edwar Elgar Publishing Ltd; 2001. p. 89–111.
[45] Hekkert MP, Harmsen R, de Jong A. Explaining the rapid diffusion of Dutch cogeneration by innovation system functioning. Energy Policy 2007;35:4677–87.
[46] Praetorius B, Martiskainen M, Sauter R, Watson J. Technological innovation systems for microgeneration in the UK and Germany - a functional analysis. Technol Anal Strateg Manag 2010;22:745–64.
[47] Haase R, Bielicki J, Kuzma J. Innovation in emerging energy technologies: A case study analysis to inform the path forward for algal biofuels. Energy Policy 2013;61:1595–607.
[48] Hudson L, Winskel M, Allen S. The hesitant emergence of low carbon technologies in the UK: The micro-CHP innovation system. Technol Anal Strateg Manag 2011;23:297–312.
[49] Hultman M, Yaras A. The socio-technological history of hydrogen and fuel cells in Sweden 1978–2005; Mapping the innovation trajectory. Int J Hydrog Energy 2012;37:12043–53.
[50] Lai X, Ye Z, Xu Z, Husar Holmes M, Henry Lambright W. Carbon capture and sequestration (CCS) technological innovation system in China: Structure, function evaluation and policy implication. Energy Policy 2012;50:635–46.
[51] Carlsson B. Internationalization of innovation systems: a survey of the literature. Res Policy 2006;35:56–67.
[52] Binz C, Truffer B, Li L, Shi Y, Lu Y. Leapfrogging in infrastructure. Conceptualizing leapfrogging with spatially coupled innovation systems: the case of onsite wastewater treatment in China. Technol Forecast Soc Change

2012;79:155–71.
[53] Jacobsson S, Bergek A. Transforming the energy sector: the evolution of technological systems in renewable energy technology. Ind Corporate Change 2004;13:815–49.
[54] Negro SO, Hekkert MP, Smits RE. Explaining the failure of the Dutch innovation system for biomass digestion—A functional analysis. Energy Policy 2007;35:925–38.
[55] Van de Ven Andrew H, Polley DE, Garud R, Venkataraman S. The Innovation Journey. Oxford: Oxford University Press,; 1999.
[56] Wieczorek AJ, Negro SO, Harmsen R, Heimeriks GJ, Luo Lin, Hekkert MP. A review of the European offshore wind innovation system. Renew Sustain Energy Rev 2013;26:294–306.
[57] Vasseur V, Kamp LM, Negro SO. A comparative analysis of Photovoltaic Technological Innovation Systems including international dimensions: the cases of Japan and The Netherlands. J Cleaner Prod 2013;48:200–10.
[58] Binz C, Truffer B, Li L, Shi Y, Lu Y. Conceptualizing leapfrogging with spatially coupled innovation systems: the case of onsite wastewater treatment in China. Technol Forecast Soci Change 2012;79:155–71.
[59] Wang CG. Overview of land-use of solar cell in China. Energy of China 1983:26–8 [Chinese version].
[60] AT2. Institue of Semiconductors, Chinese Academy of Sciences, China. Pers comm, by phone, 27/01/2014. Utrecht, The Netherlands.
[61] Lin AZ, Wang SC. Progress of PV generation in China. Solar Energy. 1999:7–8 [Chinese version].
[62] Kong L. Problems of market standardization of PV generation in China. Energy of China 1996:47–8 [Chinese version].
[63] Shao WS. Review of private economy for 30 years. People's Tribune 2008:10–2 [Chinese version].
[64] CPG. Interim Regulations on Private Company. Central People's Government; 1988 [Chinese version].
[65] Cui RQ, Huang Y, Sun TT. Problems and Prospects of Photovoltaic Development in China. Energy Eng 1999:1–3 [Chinese version].
[66] AT3. College of Electronic Information and Optical Engineering, Nankai University, China. Pers comm, by phone, 29/01/2014. Utrecht, The Netherlands.
[67] AT1. Institue of Solar Energy, Shanghai Jiao Tong University, China. Pers comm, by phone, 26.01.14. Utrecht, The Netherlands.
[68] China · Jinglong. ⟨http://www.jinglong.net/news/JinglongEvents/JinglongEvents.html⟩. viewed in 2014 [Chinese version].
[69] UNFCCC: ⟨http://unfccc.int/essential_background/items/6031.php⟩. viewed in 2014.
[70] NSTC. The outline of new energy and renewable energy (1996 – 2010). National Science and Technology Commission; 1995 [Chinese version].
[71] NPC. Electric Power Law. National People's Congress; 1996 [Chinese version].
[72] Peng F. Interview with chairman&CEO of 'Trina Solar' Jifan Gao. Sol Energy 2008:48–50 [Chinese version].
[73] E1. One of the main PV manufacturers, China. Pers comm, by phone, 14.03.14. Utrecht, The Netherlands.
[74] MOST, NDPC. Guide to high-tech industrialization key field of current priority. National Development and Plan Commission, Ministry of Science and Technology of the People's Republic of China; 1999 [Chinese version].
[75] Yuan GL. Open the treasure of solar power, development of 'Yingli Green Energy'. Sol Energy 2006:57–8 [Chinese version].
[76] BJX. WTO in raining for ten years, PV in Hebei province being the master of Chinese PV industry); 2011. ⟨http://guangfu.bjx.com.cn/news/20111124/325233.shtml⟩ [Chinese version].
[77] Zi J. Xiaofeng Peng: If China never be a member of WTO. China.org.cn; 2011 [Chinese version].
[78] AP2. School of Economy & Management, North China Electric Power University, China. Pers comm, by phone, 13.03.14. Utrecht, The Netherlands.
[79] NETC. The 'Tenth Five-Year Plan' of new energy and renewable energy industry (2011 – 2005). National Economy and Trade Commission; 2001 [Chinese version].
[80] Zhao YW. PV window. Sol Energy 2002:20–1 [Chinese version].
[81] Editor. Domestic renewable energy news. Sol Energy 2007:58–60 [Chinese version].
[82] Xu WX, et al. 20 Kw PV roof grid-connected generation system. Sol Energy 2005:24–6 [Chinese version].
[83] Ma SH. The 'China-Germany Western PV Village Program' in the stage of system installation. Sol Energy 2004:11 [Chinese version].
[84] Ma SH, et al. Implement mechenism and progress of 'Western PV Villiage Power Station' project. Sol Energy 2006:51–4.
[85] AT4. Copernicus Institute of Sustainable Development, Utrecht University, The Netherlands. Pers comm, 29.01.14. Utrecht, The Netherlands.
[86] Editor. PV power station in Qinghai province begins. Energy Eng 2002:39 [Chinese version].
[87] De S. PV window. Sol Energy 2002:27 [Chinese version].
[88] Wang CG. Basic technology request for the 'Delivering Electricity to Countryside Program'. Solar Energy. 2002:4–5 [Chinese version].
[89] NDPC. The regulation of engineering construction of "Electricity to Countryside" program. National Development and Plan Commission 2002 [Chinese version].
[90] BMU. Renewable Energy Sources Act (Erneuerbare-Energien-Gesetz EEG) (Federal Ministry for the Environment NCaNSB). Bonn: Erneuerbare-Energien-Gesetz Federal Law Gazette,; 2004. ⟨http://www.erneuerbare-energien.de⟩.
[91] Zhao YW. The research report of development of Chinese PV industry (2006–2007). Sol Energy 2008:6–13 [Chinese version].
[92] IEA. National Survey Report of PV Power Applications in China. International energy agency co-operative programme on photovoltaic power systems: IEA; 2012.
[93] Wang CG. Development and challenge of Chinese PV industry. Sol Energy 2008:6–10 [Chinese version].
[94] NPC. Renewable Energy Law. National People's Congress; 2005 [Chinese version].
[95] AP1. School of Management, Chinese Academy of Sciences, China. Pers comm, by email, 10/03/2014. Utrecht, The Netherlands.
[96] AP3. Laboratory of Low Carbon Energy, Tsinghua University, China. Pers comm, by phone, 17/03/2014. Utrecht, The Netherlands.
[97] Rigter J, Vidican G. Cost and optimal feed-in tariff for small scale photovoltaic systems in China. Energy Policy 2010;38(11):6989–7000.
[98] Ma SH. Suggestions of enacting step tariff to facilitate PV generation in China. Energy of China 2004:31–4 [Chinese version].
[99] Zhang S, Andrews-Speed P, Ji M. The erratic path of the low-carbon transition in China: Evolution of solar PV policy. Energy Policy 2014;67:903–12.
[100] MOF, MOST, NEA. Notice on the implementation of 'Golden Sun Demonstration Program'. 2009 [Chinese version].
[101] MOF. Interim Measures of solar PV building financial subsidy funds management. 2009 [Chinese version].
[102] MOF, MoHURD. On accelerating the implementation of solar PV building applications. 2009 [Chinese version].
[103] LZ. Chu The forty-eight institute, 'Turnkey Project' strenghten the competitiveness of PV manufacturing. 2009 [Chinese version]: ⟨http://o.cena.com.cn/Article/yaowen/xinzhongguochengli/2009–09-29/20090929101029_22328.shtml⟩.
[104] MIIT. The 'Twelfth Five-Year Plan' of Solar PV Industry. Ministry of Industry and Information Technology of the People's Republic of China; 2012.
[105] Peng F. The establishment of 'Chinese PV Industry Alliance'. Sol Energy 2010:42–3 [Chinese version].
[106] CPG. Decision to accelerate fostering and developing strategic emerging industry. Central People's Government; 2010 [Chinese version].
[107] Zhang T. The unexpected FIT for PV might make a big turn to Chinese PV market. Solar Energy 2011:22–3 [Chinese version].
[108] NDRC. Notification of improving the policy of PV generation FIT. National Development and Reform Commission; 2011 [Chinese version].
[109] Ruan XD. Foreign emerging market analysis for Chinese PV company. Solar Energy. 2012:44–8 [Chinese version].
[110] Editor. Hunan solar cell screen printing equipment firstly "marry" to the United Arab Emirates. Screen Printing Industry 2010:49 [Chinese version].
[111] Editor. Hebei new energy giant firstly exports special equipment overseas. The World of Power Supply 2011:57 [Chinese version].
[112] Bao JW. The conclusion of 'Anti-dumping and anti-subsidy' from U.S. is settled. Sol Energy 2012:25–6 [Chinese version].
[113] CPNN. The 'PV Generation Promotion Alliance' is set up, fighting back on U.S. 'Anti-dumping and subsidy'. cpnn.com.cn; 2012 [Chinese version].
[114] NEA. The 'Twelfth Five-Year Plan' of solar PV generation. National Energy Administration,; 2012 [Chinese version].
[115] Coenen L. Engaging with changing spatial realities in TIS research. Environ Innov Soc Trans 2015;16:70–2.
[116] Gosens J, Lu Y, Coenen L. The role of transnational dimensions in emerging economy 'Technological Innovation Systems' for clean-tech. J Cleaner Prod 2015;86:378–88.