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Market dynamics, innovation, and transition in China's solar photovoltaic (PV) industry: A critical review

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Abstract

China's photovoltaic (PV) industry has undergone dramatic development in recent years and is now the global market leader in terms of newly added capacity. However, market diffusion and adoption in China is not ideal. This paper examines the blocking and inducement mechanisms of China's PV industry development from the perspective of technological innovation. By incorporating a Technological Innovation System (TIS) approach, the analysis performed here complements the previous literature, which has not grounded itself in a theoretical framework. In addition, to determine the current market dynamics, we closely examine market concentration trends as well as the vertical and horizontal integration of upstream and downstream actors (74.8% and 36.3%). The results of applying the TIS framework reveal that poor connectivity in networks, unaligned competitive entities and a lack of market supervision obstruct the development of China's PV industry. Therefore, we maintain that inducement mechanisms are required to instigate learning-by-doing capacities, which may help

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overcome blocking mechanisms and offset functional innovation deficiencies. In addition, policy implications are proposed for promoting the development of the PV industry in China.

Keywords: Solar photovoltaic (PV); Technological Innovation System (TIS); Functional pattern; Blocking/inducement mechanisms

1. Introduction

The continuous depletion of worldwide fossil fuels has caused serious environmental and social concerns [1-3]. The development of renewable energy has been recognized as an important element for mitigating air pollution problems and promoting sustainable development [4]. Because of the advantages of solar photovoltaic (PV) power generation, PV power has long been acknowledged as a promising renewable energy technology with the potential to replace fossil fuel. The advantages for the environment include the ability of PV power to utilize abundantly available resources without creating emissions during its operation [5]. Currently, the technical potential of solar PV power has almost no limits. However, its economic potential, which is influenced by policies and regulations, often determines deployment trajectories [6].

Although solar PV power accounts for a small percentage of the global renewable energy flows, many countries are currently focused on its economic potential. As presented in Figure 1, the global cumulative capacity of solar PV power continues to rise. By 2013, almost 138.9 GW of PV power had been installed globally, which was capable of producing 160 TWh of electricity every year [7]. This burgeoning growth is partially connected to the plummeting costs of modules and batteries. In terms of local markets, solar PV power will likely reach grid parity in numerous urban areas in a matter of decades, especially in certain communities in the US, such as Los Angeles and Westchester [8].

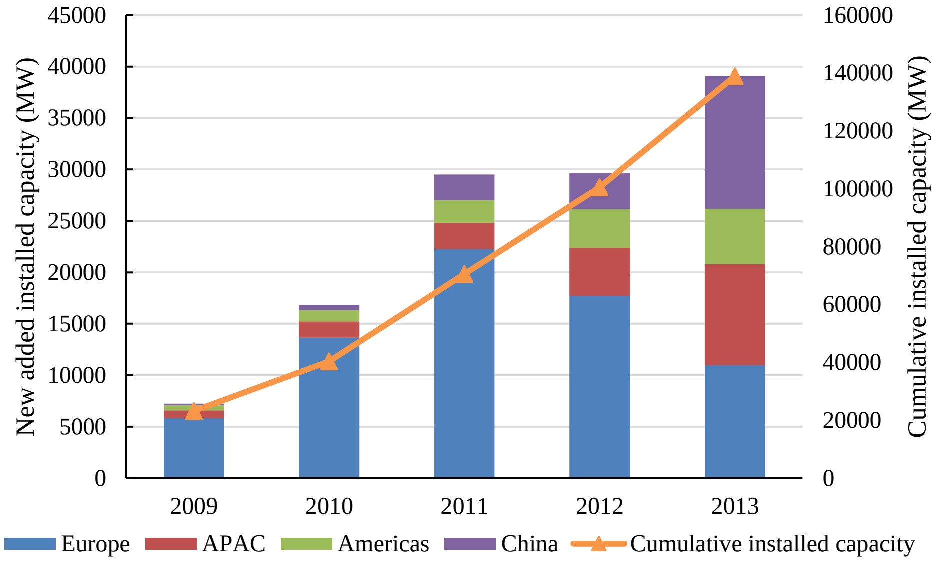

Figure 1 World cumulative PV installed capacity from 2009 to 2013

Data Resources: Global Market Outlook for Photovoltaic 2014-2018, European Photovoltaic Industry Association (EPIA)

Following worldwide trends, China’s newly installed PV capacity increased rapidly after 2012. In 2013, China achieved the world’s largest combination of solar PV installations, with 12.92 GW connected to the grid, and it was followed by Japan with 6.9 GW. From 2011 to 2013, the newly installed PV capacity of the Asia-Pacific (APAC) region, including China, was still exhibiting explosive growth (see Figure 1). However, the amount of installations in the European market decreased, particularly in Germany and Italy.

Manufacturing trends can partially explain the patterns of solar installations. PV modules are now mass produced, and the production of PV modules in large-scale fabrication facilities is one explanation for the declining costs [9]. China is a dominant manufacturer of PV modules and contributed more than 50% of world production from 2009 to 2013. Prior to 2009, major development programs were enacted to promote Chinese solar PV power for off-grid domestic uses [10,11]. In addition, China’s PV industry is facing issues related to the duplication of large-scale production. After experiencing anti-dumping and countervailing duties charged by the US and the EU, China’s PV industry is experiencing industrial restructuring and rapid market reconfiguration. Inherent industry development problems remain, such as severe capacity surpluses and domestic market under-development [12]. In addition, despite fairly considerable public support from the government, the rate of solar PV power diffusion in China remains slow and tedious [13].

These production-related effects, economies of scale, and sources of public largesse are not the only factors that influence the long-term potential for production [14]. Technological innovation is fundamental for increasing the efficiency of the renewable energy along with concomitant economic and environmental benefits [15], and it plays a decisive and extremely vital role throughout the development of the PV industry. The innovation process involves the research, development, and demonstration of solar PV technologies in the production stage as well as the demonstration and deployment of these technologies at the industrialization and commercialization stages [16]. From a life-cycle perspective, this process can be divided into two parts: research and development (R&D) and diffusion [15]. R&D during the early innovation stage can significantly promote core industrial technology progress and improve private sector investments. Therefore, R&D funded by the public sector has attracted increasing attention from many countries, which have started to formulate relevant policies [17]. Diffusion serves as a bridge between the laboratory and market. Successful diffusion must overcome many market uncertainties, such as cost, demand and infrastructure [18,19].

This paper aims to develop a critical review and technological innovation roadmap by analyzing the status quo and the blocking/inducement mechanisms of China’s PV industry. Many previous studies have identified obstacles in a piecemeal fashion without comprehensively examining the topic [20-23]. In mature markets, such as the US and the EU, supportive policies have become increasingly stable and market competition continues to promote technological innovation [24-26]. However, China remains at a unique development stage in which the industry faces the potential of expanding or contracting [27,28].

To assess these tensions and complexities, we utilize the concept of a Technological Innovation System (TIS) [29]. Such approaches have shown promise in assessing hydrogen and fuel cell innovation systems in countries such as Iran, the US, and Denmark [30, 31]. In addition, automotive natural gas, offshore wind and other clean energy technologies have also been assessed using the TIS approach to identify the incentives and blocking mechanisms of industry development [32-34]. Few previous studies have decomposed the industry supply chain [35-37], and such an analysis may be of great importance in China's PV industry. Overall, previous studies that have focused on the development of the solar PV industry have identified problems by analyzing the historical process and the status quo. A foundation of systematic analyses is missing in these studies; thus, the identified problems appear fairly tedious and complicated and may be involved in multiple dimensions that transcend policies, markets and future planning. In addition, China's PV industry has unique characteristics, and each industry link has different development states because of the market supply and demand and government incentives. This complexity can be identified and analyzed by utilizing a TIS framework.

2. China's solar PV industry: A critical overview

Because most PV technology improvements occur abroad, the development of China's PV industry is mainly dependent on duplicating production processes to provide low-priced products. Thus, considering the innovation system as an analytical construct is crucial. A general definition of a system is a group of components [38]. To identify these components within distinct industry chains, we argue in this section that the status quo is heavily influenced by entities in the public and private sectors.

2.1 Current status of China's solar PV power generation

2.1.1 Solar resources assessment in China

Solar resources are plentiful in China. The annual average radiation on a horizontal plane is 1492.6 kWh/m^2. At similar latitudes, the amount of solar radiation available in China is more than that in most European countries (yearly average irradiation ranges from 1200-1600 kWh/m2) [39,40]. However, radiation is not evenly distributed across the entire country. According to the Wind and Solar Energy Resources Center of the China Meteorological Administration, the amount of solar radiation is more than 1400 kWh/m2 in most parts of China, including the northeast, north, northwest and southwest areas. Figure 2 shows that the radiation level in the western portion of the country is much higher than that in the east. For example, the Tibetan Plateau and the Sichuan Basin have the largest and the smallest amount of solar radiation, respectively. However, the west area is a vast territory with a sparse population, which increases the difficulty of developing the photovoltaic power industry. Moreover, the electricity demand in the east continues to increase because of the higher population density and the faster economic growth. Therefore, power grid planning and different types of power generation represent a vital foundation for the consumption and deployment of PV power generation.

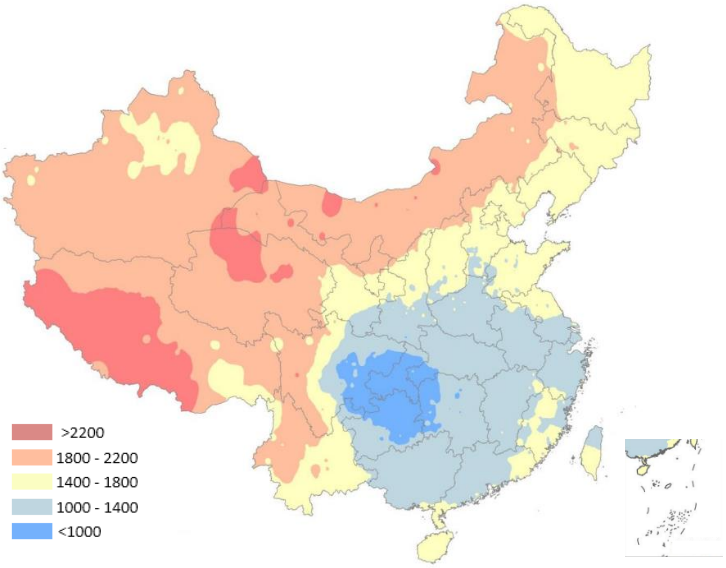

Figure 2 Distribution of China’s solar radiation under the optimal slope
Data resources: China wind and solar energy resources bulletin

2.1.2 Burgeoning domestic PV market

Compared with other developed countries, China’s PV industry had a relatively late start. However, in the past five years, China's presence in the PV world market has changed from nonexistent to vital. As shown in the Figure 3, the PV industry hardly existed in China before 2010. During the 12th Five-Year Plan of China, China’s market experienced rapid development and expansion. In 2014, the accumulative PV installed capacity reached 28.05 GW. Therefore, China’s PV market is prosperous and vigorous, although its development process has not been smooth. In 2012, the anti-dumping and countervailing duties charged by the US and the EU forced many of China’s PV enterprises in bankruptcy, and the restriction on commodity exports caused an overcapacity in the PV industry. In 2013, the Chinese government drafted more policies to improve the market access of PV products, such as polysilicon and PV modules. Therefore, the new installed capacity declined in 2014, and the pressure of overcapacity decreased to some extent.

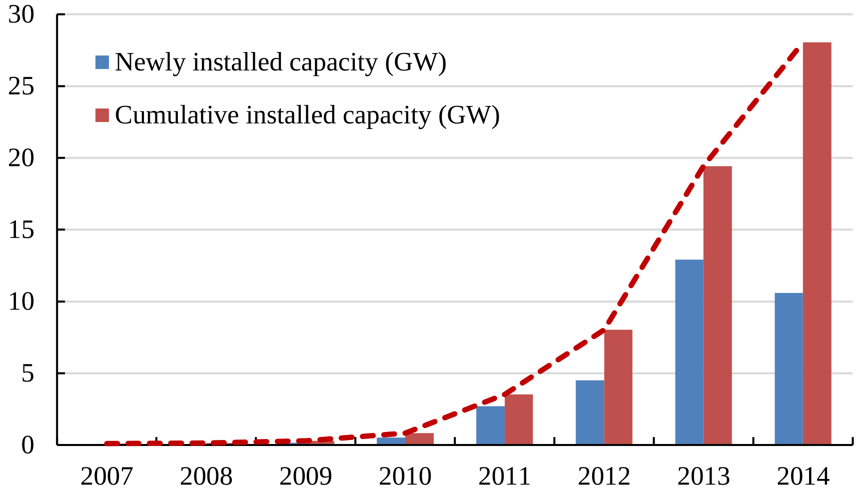

Figure 3 2007-2014 China's newly increasing and accumulative PV installed capacity. Data resources: China Photovoltaic Industry Alliance (CPIA); National Energy Administration, China

2.2 Characteristics and evolution of PV technology in China

In PV power systems, the PV module is the main device that coverts sunlight into direct-current (DC) electricity, and the relevant processes include capital equipment production, silicon manufacturing, cell manufacturing and installation [41]. Polysilicon production and solar cell manufacturing are the core technologies in an integrated PV system. The former is the key raw materials in cell manufacturing, and the latter directly determines the conversion efficiency of the PV modules.

2.2.1 Polysilicon technology

Polysilicon is a highly pure form of silicon that is produced by a chemical purification process. After constant refinement and innovation of the production process, three core polysilicon technologies have been derived: the improved Siemens process, the thermal decomposition of silane and the fluidized bed. These technologies have been blockaded by several enterprises in the US, Germany and Japan for a long time. Compared with international enterprises, China’s polysilicon production technologies, which mainly consist of the improved Siemens process, have experienced gaps in the production process and energy consumption and Chinese producers have the lowest utilization rates worldwide [42]. Because of the anti-dumping and countervailing duties charged by the US and the EU, the Chinese government began to introduce supportive policies to encourage corporations to improve the production processes for the original technology and import other technologies, such as silane fluidized bed technology. Such policies represent a vital method of reducing production costs, improving resource utilization and decreasing carbon dioxide emissions [43].

2.2.2 Solar cell technology

The conversion efficiency of solar power generation mainly depends on the solar PV cell. Three types of PV cells have been generated thus far. Crystalline silicon cells were the first generation of solar cells, and they have dominated most markets worldwide because of their high conversion efficiency and low manufacturing costs. The second type is thin-film solar cells, which are composed of flexible material that can be applied to build integrated PV systems [44]. Compared with crystalline silicon cells, thin-film solar cells have a lower cost. Before 2010, the production cost of crystalline silicon cells was higher than that of thin-film solar cells. Therefore, many enterprises shifted production to the thin-film solar cells, which accounted for 16.5% of the entire solar cell market in 2009. However, since 2009, the market share has declined because of the low conversion efficiency [45]. The third generation are new types of solar cells that include dye-sensitized solar cells, organic solar cells, etc. The new solar cells have generated breakthroughs in key technologies; however, they are still in the laboratory research stage and have not begun production at commercial quantities to allow them to compete with crystalline silicon cells.

Overall, continuing innovations and development in crystalline silicon solar cells is the key for future development in China because they have a large-scale production potential and can reduce PV production costs.

2.3 Policy framework and relevant impact on the PV market

2.3.1 Policies at the national level

In 2009, China promoted the concept of strategic emerging industries, and solar PV technology was identified as a critical branch of these industries. Since then, the Chinese government has drafted a number of supportive policies to narrow the gap between the PV industries in China and the more advanced countries and achieve emissions reductions. As shown in Figure 4, these policies can be divided into two categories: subsidies according to installed capacity or initial investment (2009-2013) and subsidies for electricity generation (after 2013).

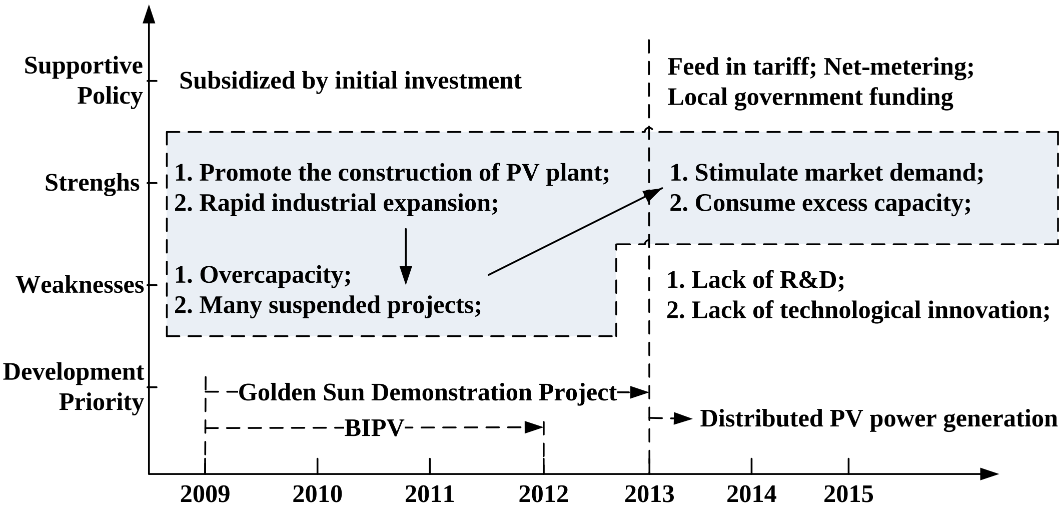

Figure 4 Development process for PV supportive policies

(1) Subsidy policy for initial investment

Before 2013, the main subsidy for PV power generation was awarded according to the initial required investment and the installed capacity of the PV project. The main supportive policies and development priorities were the Golden Sun project and Building Integrated Photovoltaic (BIPV) projects. In July 2009, China’s Ministry of Finance, Ministry of Science and Technology and National Energy Administration jointly launched the “Golden Sun Demonstration Project”, which is a policy to support the PV industry. This policy represents the first time China subsidized PV projects by installed capacity. This policy included planning for the PV installed capacity and the amount and scope of subsidies for the following 3 years. Detailed provisions were also included, such as for key equipment to be included in PV power systems and technical standards used to incorporate the project into the power network. Over the 3 years after the implementation of the Golden Sun Demonstration project, the subsidies expanded to include additional aspects, including raw material production and accessory products. Many PV power generation projects were built under this policy, including grid-tied projects, industrialization demonstration projects and BIPV projects.

The Golden Sun demonstration project promotes the large-scale construction of PV plants and the burgeoning domestic PV industry. Rapid industrial expansion has led to China becoming the world's most important PV producer. However, unforeseen issues complicated the industry development.

- Frequent problems occurred in the project approval process, subsidy payment and project supervision. The Golden Sun subsidy policy for initial investments encourages investors to reduce the cost of the power plant, which leads to reduced improvements to the quality of power plants. Many projects were not successful after receiving the subsidy.
- Import limits set by the US and the EU and numerous suspended PV projects led to a serious overcapacity in China's PV market. In an attempt to profit, many enterprises continuously lowered the prices of PV products, although the intense market competition forced these enterprises into bankruptcy.

Therefore, the government abolished the relevant subsidies of the Golden Sun project in 2013 and sought supportive polices for the sustainable development of the PV industry.

(2) Subsidy policy for distributed PV power generation

In August 2011, China's National Development and Reform Commission announced the first nationwide feed-in tariff for PV projects. The feed-in-tariff for relevant PV projects is 1.15 RMB yuan/kWh. Because of the rapid development of the global PV industry, the Chinese government has recognized that the distribution of PV power generation is the crucial factor for improving market demand, consuming excess capacity and promoting healthy industrial development.

Since 2013, the Chinese government has enacted supportive policies to promote the application of PV power generation. For example, the National Development and

Reform Commission drafted the price leverage policy. Based on solar energy resources in various provinces and PV power system construction costs, the country is divided into three areas, and the benchmark price for solar feed-in tariffs in these areas is 0.90, 0.95 and 1.00 RMB yuan/kWh. In addition, the net-metering subsidy for distributed PV power generation is 0.42 RMB yuan/kWh. Although technical standards are also involved in these policies, explicit requirements for R&D and innovation have not been set. Furthermore, the technical standards are not consistent with the actual market environment. For example, the efficiency of monocrystalline silicon and polycrystalline silicon cells was set to more than 20% and 18%, respectively; however, thus standard is higher than that of most products in China’s PV market. Therefore, most of the subsidy policies for distributed PV power generation still belong to demand-pull policies, and few technology-push and government-led incentives are available.

2.3.2 Policies at the provincial level

After national departments announced a series of policies, many provincial and municipal governments began to pay attention to the emerging PV industry. As shown in Table 1, local governments have focused on policy support for distributed PV power generation. These areas are mainly located along the eastern coast, and they are suitable for developing distributed PV power systems because of the high population density. Under these policies, PV projects are mainly subsidized in two ways. The first method is a power generation subsidy, and the specific instruments include feed-in tariffs and net metering. Net metering is set for a period of 3-5 years and does not conflict with state subsidies. Feed-in tariffs are usually set in intervals with the electricity price, which decreases gradually as the year progresses. The second method is subsidies according to the initial installed capacity, which is mainly used for PV plants. Certain areas have adopted both methods of promoting the development of PV power generation, such as in Jiangxi. A number of the leading PV product manufacturing enterprises are located in Jiangxi Province. The subsidies have also promoted the rapid development of these manufacturing enterprises.

Table 1 Summary of the provincial PV subsidies

Subsidy	Province/City	PV plant	Distributed PV
Subsidized by power generation (RMB yuan/kWh)	Shandong	1.20	0.05①
	Shanghai	0.30	0.25①
	Hebei	0.15	1.3 (2014)② 1.2 (2015)②
	Jilin	0.15①	
	Hunan	0.20①	
	Zhejiang	0.10①	
	Jiangsu	1.25 (2013)②; 1.20 (2014)②; 1.15 (2015)②	
Subsidized by initial installed capacity (RMB yuan/W)	Anhui/Hefei	3	
	Henan/Luoyang	0.1	
	Shaanxi	1	
Both methods③ (RMB yuan/W, RMB yuan/kWh)	Jiangxi	First stage: 4 Second stage: 3	0.2
	Guangdong/Dongguan	0.25	0.1

① The subsidy instrument is net metering based on state subsidies of 0.42 RMB yuan/kWh;

② The subsidy instrument is feed-in tariffs, and the price is for each year;

③ The unit is RMB yuan/W for the PV plant and RMB yuan/kWh for the distributed PV.

In addition, PV technology policies for poverty alleviation have been adopted by certain provinces in central China. These subsidies are aimed at PV projects in rural areas, such as a distributed PV power generation system built on farms and PV plants built on barren hillsides and agricultural facilities. These policies promote the application of PV power generation based on the actual conditions in China, and they resolves problems related to power shortages and poverty in remote areas.

3. Characteristics and problems associated with China’s PV market development based on an industry chain analysis

3.1 Analysis of the PV industry chain characteristics

Certain TIS function patterns can be observed throughout the development path of the PV market, such as market formation, resource mobilization and entrepreneurial experimentation. To analyze the influence of these factors on the promotion of PV power generation, it is crucial to map the entire PV industry chain and its features. As shown in Figure 5, the upstream industry (silicon purification and wafer production), the midstream industry (PV panel and PV module production) and the downstream industry (PV power systems) constitute the entire PV industry chain. Each link of the industry chain has its own features that are primarily determined by the market competition conditions. The major factors include market size, competition mode, barriers to entry and product differentiation.

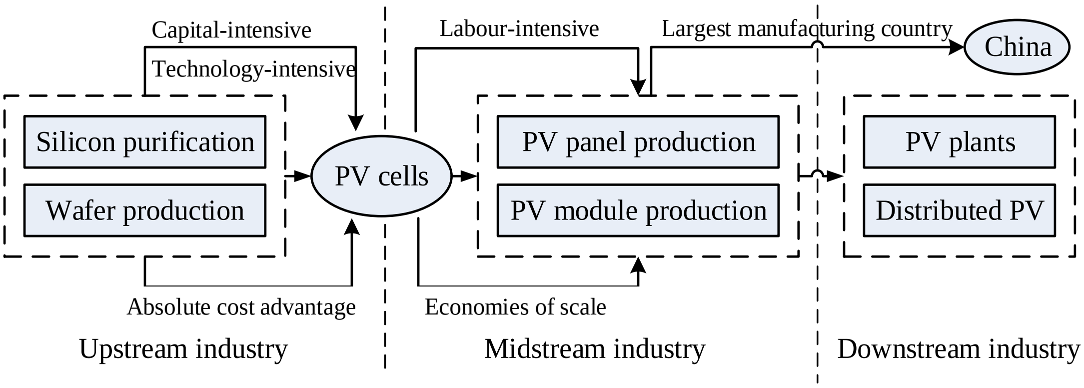

Figure 5 Structure and features of the PV industry chain

3.1.1 Upstream supply chain

In 2014, China’s polysilicon production reached 130,000 t, which accounted for 43% of the global polysilicon production, and the total capacity of polysilicon enterprises reached 156,000 t. The number of enterprises in operation has increased to 18 from the 8 enterprises operating in 2012. As shown in Table 2, the production of the top four enterprises accounted for 74.8% of the total production. The market concentration rate, CR_4 (74.8%)[1], is at a relatively high level, which indicates that there is a group of leading enterprises in China’s PV industry that control the market resources. In the emerging PV industry, the power monopoly can promote technological innovation by enterprises, and the leading enterprises can fully exploit R&D resources and undertake R&D risks.

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[1] $CR_4 = \sum_{i=1}^{4} X_i \,/\, \sum_{i=1}^{N} X_i$
X_i: production of *i* enterprises, *N*: the total number of enterprises in the industry.

Table 2 Top 10 polysilicon producing enterprises in 2014

Enterprises (polysilicon production)	Production (t)	Percentage (%)
Golden Concord Holdings Limited (GCL)	65500	50.38%
Tebian Electric (TBEA)	16000	12.31%
China Silicon (SINO-SI)	9500	7.31%
Chongqing Daqo New Energy	6300	4.85%
Yichang CSG Polysilicon	4700	3.62%
OPISI Silicon	4500	3.46%
Asia Silicon (BVI)	4500	3.46%
Rene Solar	4500	3.46%
Jingyang Energy	3000	2.31%
DunAn Group	3000	2.31%
Total production	13000	

Data resources: collected from solarzoom PV solar website <http://www.solarzoom.com/article-62091-1.html>.

The upstream industry is a technology-intensive and capital-intensive industry (Figure 4), and the absolute cost advantages create barriers to entry into the upstream industry. The core technology for polysilicon production is still controlled by foreign enterprises. In recent years, China has attempted to break through the technical barriers and improve its own production process. However, the purity of the available polysilicon is still lower than that of the products from other enterprises in the US or Germany. Currently, the leading enterprises should continue introducing advanced technologies and improving the production process and work to incorporate the downstream enterprises. Inter-firm technology spillover is significant for production because it provides a direct contribution to production efficiency improvements and changes in prices [46].

3.1.2 Midstream production processes

In the midstream industry, the main products include solar cells and PV modules. China has the largest manufacturing industry for PV cells and modules in the world. In recent years, China's PV market has been highly dependent on international markets, especially the European market. In 2012, the amount of exports to the EU accounted for 67% of the total exports. However, the anti-dumping and countervailing duties charged by the US and the EU represented huge obstacles to the export of China's PV products. Thus, Chinese PV enterprises began to focus on Asian countries, including

Japan and Korean. As shown in Figure 6, exports to Asia accounted for 54.50% of the total exports in 2014 and exports to the EU accounted for 19.60%.

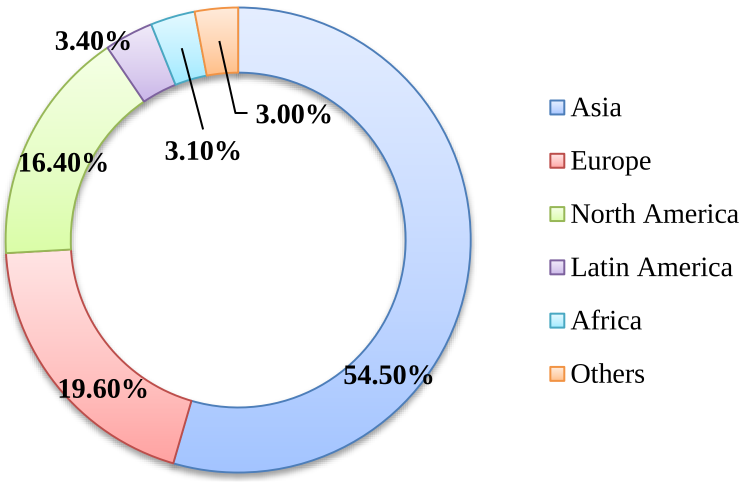

Figure 6 Export ratio of China’s PV modules in 2014

Data resources: collected from the China Power website <http://www.chinapower.com.cn/article/1288/art1288417.asp>

In the domestic market, the total production of China’s PV modules reached 35 GW in 2014. The midstream industry is a labor-intensive industry, and a barrier of scale economy occurs in this industry link. The leading enterprises can fully exploit the scale economy to lower the product cost. As shown in Table 3, the top five companies in production rankings led the market of PV modules in the most recent three years. Yingli Solar ranked first in 2012 and 2013. Trina Solar ranked third in 2012 and second in 2013. These leading enterprises have relied on technological progress to overcome the anti-dumping and countervailing duties policies.

However, based on China’s strategic emerging industry policies, local governments have encouraged many new corporations to enter this industry link because the threshold of PV module production is lower than that of the other links; thus, enterprises can profit in a short period. Over-enthusiastic investments lead to low market concentration rates. As shown in Table 3, the CR_4 is only 36.3%. The investment mode prevents technological innovations and technology efficiency improvements. Similar products cause low price competition and overcapacity, which hinders the development of the leading enterprises. As shown in Table 3, the production percentages of the last five enterprises are at less than 5%. These enterprises do not easily engage in technological innovation, and they rely on economies of scale.

Therefore, certain enterprises have begun to adopt different development strategies since 2014. For example, Yingli Solar aims to change from a PV module manufacturer to an energy solution provider, thereby moving to the downstream industry. Canadian Solar Inc.; ReneSolar, Ltd.; and Jinko Solar Co., Ltd. Have focused on expansion to the overseas market.

Table 3 Top 10 PV module producing enterprises in 2014

Enterprises (Module production)	Production (MW)	Percentage (%)
Trina Solar Limited	3700	10.6%
Yingli Green Energy Holding Company Limited	3300	9.4%
Jinko Solar Co., Ltd.	3000	8.6%
Canadian Solar Inc.	2700	7.7%
JA Solar Holdings	2300	6.6%
Hanwha SolarOne, Ltd.	1420	4.1%
ReneSolar, Ltd	1200	3.4%
Hareon Solar	940	2.7%
Zhongli Talesun Solar Co., Ltd	700	2.0%
China Tomorrow (CHNT)	700	2.0%

Data resources: collected from the solarzoom solar PV website <http://www.solarzoom.com/article-62091-1.html>.

3.1.3 Downstream applications and installations

In the downstream industry, the PV applications include grid-connected PV power generation systems, PV plants, etc.; thus, it is a technology-intensive industry. In this portion of the chain, investors are still relatively small in China, although it represents the highest revenue in the whole industry chain. A capital barrier prevents entry into this industry. Before 2013, most investors were large state-owned enterprises that had enough capital strength to invest in PV projects, which were mainly national demonstration projects. Many of these projects were only in the pilot-testing phase and did not provide residential power. In 2014, a number of polysilicon and PV module production companies began to enter the downstream industry. As shown in Table 4, the installed capacity of the top four enterprises reached 20% of the total installed capacity in 2014.

Table 4 Top 5 EPC producing enterprises in 2014

Engineering Procurement Construction (EPC)	Installed Capacity (MW)
Tebian Electric Apparatus Sun Oasis (TBEA)	834
Shanghai Solar Energy Science & Technology Co., Ltd.	700
Guodian Solar Co., Ltd. (GD Solar)	650
Astronergy Solar, the Chint Group	400
Zhongli Talesun Solar, Zhongli Sci-Tech Group	350
Others	9976

Data resources: "Chinese Suppliers Continued to Lead the Solar PV Module Market in 2014", *PV Integrated Market Tracker* from Information Handling Services (IHS).

3.2 Functional pattern analysis of the PV TIS

Based on the above analysis of the PV industry chain, it is worth noting that China's PV market has overcome its trade conflict issues. However, an innovation systematic analysis identified certain policy problems. The first step of the TIS analysis is to investigate the function patterns (e.g., market formation, entrepreneurial experimentation, etc.) and ascertain the degree to which the functions are filled in the TIS [38].

(1) Market formation

Market formation experiences three phases, nursing, bridging and maturing [38]. China's PV industry has experienced rapid development in the polysilicon and PV module production portions of the supply chain. However, when considering the PV industry chain as a whole, the market is still a "nursing market" that has not generated healthy competition, which is supported by the following qualitative evidence.

- Limited electricity generation: the electricity generation share of PV power is less than 0.5% of the total power generation in 2014[2]. The size of the PV market is limited.

- Unspecific demand: potential customers have not been identified and the market demand is not specific. Most users, including households, workshops and office buildings, will likely adopt the costly PV.

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[2] Data are collected from Chinese Xinhua website <http://news.xinhuanet.com/2015-02/15/c_1114383284.htm>

- Unfavorable competition: Compared with the cost of coal power generation, the levelized cost of PV power generation is higher. In addition, China's PV products do not present sufficient performance differences.

(2) Entrepreneurial experimentation

In the development process of a TIS, uncertainties can obstruct the enterprises from benefitting from investments in technological innovation. These uncertainties mainly include "efficiency gaps" [47]. By mapping the number and variety of new entrants, complementary technologies and other factors, entrepreneurial experimentation can reduce the efficiency gap and avoid market failure [33, 36]. Representative features in the industry chain indicate that China's PV market does not accomplish the functional pattern of entrepreneurial experimentation.

- Inadequate complementary technologies: as discussed in section 2.2.1, all of China's PV enterprises have adopted the improved Siemens process as the main technology for polysilicon production. And after importing advanced technologies from foreign enterprises, these enterprises likely will not improve upon production engineering

- Too many new entrants: the degree of industrial concentration, CR_4, is low, which means that too many new entrants have flooded the mid-stream industry because of encouragement by local governments. However, the amount of PV module exports decreased from 22.77 billion dollars in 2011 to 12.78 billion dollars in 2012[3]. Overcapacity has seriously obstructed entrepreneurial experimentation.

- Single forms of PV enterprises: in 2012, most of the developers in the down-stream industry were large-sized state-owned enterprises. In 2013, private enterprises entered the market (Table 4). However, state-owned property still dominated the industry. Simplification of EPC enterprises does not encourage entrepreneurial experimentation.

(3) Resource mobilization

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[3] Data are collected from China Photovoltaic Industry Alliance (CPIA)

In the technological diffusion of a TIS, market resources must be mobilized [48]. These resources include financial capital, complementary assets, human capital, etc. For China's PV industry, human capital has played a key role in lowering the cost of relevant products. However, for TIS development, financial capital has received little attention, and two main reasons are outlined below.

- Low capacity utilization: the capacity utilization of PV modules and polysilicon was less than 60% and 50%, respectively, in recent years. Currently, attracting investments and obtaining seed capital for PV enterprises have been problematic [22].
- Obstacle of coal-fired power: the existing structure of power generation in China, which excessively relies on coal-fired power, is difficult to change in the short term [49], and coal is still desired, even by energy consumers [50]. In addition, the high cost and low technical efficiency hinder the mobilization of financial capital despite the implementation of subsidies by the Chinese government.

Overall, strengthening financial innovation is an effective method of mobilizing financial capital. Based on sophisticated systems of asset assessment, governments should allow enterprises to finance PV projects, which are currently limited to five state-owned power companies.

4. Mapping the functional patterns of the solar PV TIS

4.1 Relationship between blocking mechanisms and functional patterns

Based on a functional pattern analysis of the PV TIS, China's emerging PV industry presents a number of limitations. As shown in Figure 7, these limitations indirectly block TIS development, which obstructs the implementation of the relevant supportive policies and represents the main reason for the slow development of China's PV industry. Therefore, from the perspective of technological innovation, it is vital to identify these blocking mechanisms to promote a self-sustaining PV industry [51,52]. The main blocking mechanisms consist of the following three aspects.

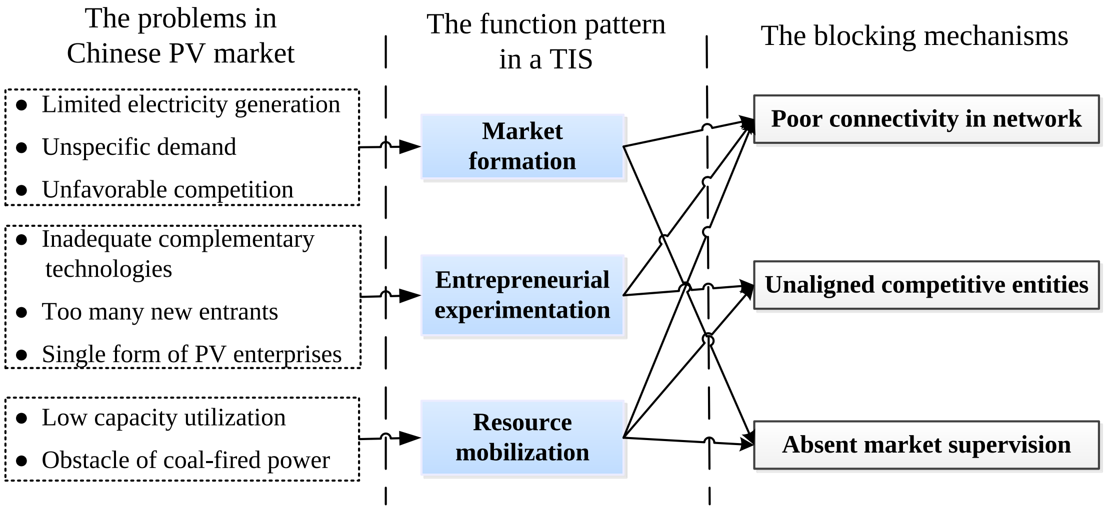

Figure 7 Relationship between function patterns and blocking mechanisms

(1) Poor connectivity in networks

In China, poor connectivity between actors (enterprises, academic institution, public sectors, financial institutions, etc.) in the PV industry leads to a technology blockage from R&D to diffusion, which represents the main reason why the Chinese PV market is still in the nursing stage. As shown in Figure 7, three weak function patterns in the PV TIS jointly lead to the blocking mechanism. However, the most important relationship between the function and the blocking mechanism is entrepreneurial experimentation because the connectivity between actors is structured by enterprises that are considered the core of the network. An analysis of entrepreneurial experimentation indicates that enterprises cannot obtain support from academic institutions, which is exemplified by the lack of complementary technologies. The high number of new entrants indicates that the industry is misled by the public sector. Moreover, misleading assumptions related to support, including subsidies, reduce the sustainable development of the PV system in the long term. Therefore, PV enterprises cannot easily obtain seed capital and investments, which reduces the utilization of financial capital; this finding is supported by previous studies.

For China’s PV industry, the value of R&D support schemes constitutes only 1% of the value of deployment or investment support. Direct R&D support cannot be targeted to the relevant actors and cannot facilitate feedback from the network among researchers, producers and users [53]. Therefore, deployment policies are not associated with the R&D of PV technologies, which causes a block between the public R&D subsidy and private activity expenditures [54-56].

(2) Unaligned competitive entities

Enterprises seeking to obtain revenue quickly cause an unbalanced industrial structure and disorderly market competition. Unaligned competition is caused by a limiting “resource mobilization” function. However, resource mobilization is an indirect and external factor. Specifically, low capacity utilization is caused by underutilization of resources throughout the industry chain, and coal power generation is an external blocking factor.

Therefore, entrepreneurial experimentation directly obstructs the alignment of enterprises in different industry links. Too many enterprises in the midstream PV industry duplicate the production processed, and these industries do not cooperate with the enterprises upstream and downstream in the industry, which causes overcapacity.

Leading enterprises that have attempted to achieve institutional alignment to lower production costs and improve process productivity have survived the trade conflicts. For example, during the period of anti-dumping and countervailing duties in 2013, Yingli Green Energy Holding Company Limited (Yingli Solar), which is the largest enterprises of PV modules production, cooperated with the leading polysilicon production enterprise, Golden Concord Holdings Limited (GCL Group). This cooperation integrated the optimal resources in the industry chain, which ensured a lower cost of production and shipments of the respective products. However, Wuxi Suntech Solar Power Co., Ltd (Suntech) has maintained a high production capacity since 2006 and achieved the greatest number of PV modules shipments in the world in 2010. However, Suntech did not partner with other enterprises in the PV industry chain, and it was forced into bankruptcy in 2013 because of overcapacity and low-price competition.

(3) Absent market supervision

The subsidy policies introduced by public sectors have not promoted the large-scale application of PV power generation in recent years, and one of the main reasons is the absence of market supervision, which obstructs the formation of competitive markets.

Therefore, the most important characteristics of the relationship between the function pattern and the lack of market supervision originates from the “market formation”.

First, supportive policies can theoretically reduce the disadvantages of high production costs, although the implementation of these policies is complicated, which leads to low PV power generation. For example, the renewable energy subsidy procedure covers many public sectors, including the national sector, provincial departments, power grid corporations, etc. The default time is usually 6-18 months. These complicated procedures cannot guarantee the proper operations of PV projects.

Second, unspecific standards, including grid-connected operations and system maintenance and management decrease the consumer awareness and preferences for PV power generation, which directly leads to unspecific market demand

Third, distributed PV power generation, which is the priority of China’s supportive policies, is less than 3 years old. China’s PV enterprises prefer to participate in the upstream or midstream industries rather than the design of PV power generation systems for users. If most of the PV enterprises cannot meet a specified market requirement or expand the customer market, the market supervision implemented by the public sectors will not be optimized under actual operations, which will block the “resource mobilization” of the PV market.

4.2 Inducement mechanism analysis based on learning-by-doing

4.2.1 R&D stage

In the PV industry, the two core technologies polysilicon production and PV module (solar cell) production are still lacking in technological R&D and innovation. For polysilicon technologies, China lags behind the US, Germany and other developed countries because of its short period of development. Improvements to technology may be achieved via learning-by-copying strategies and not technological innovation [15]. Under this approach (Figure 8), public sectors should encourage enterprises to import foreign advanced production technologies and imitate the production processes. To imitate these processes, enterprises should cooperate with research institutions to improve the fabrication process. From a long-term perspective, the gradual improvement of fabrication processes can contribute to the unique core technology of the associated enterprises and stable cooperation.

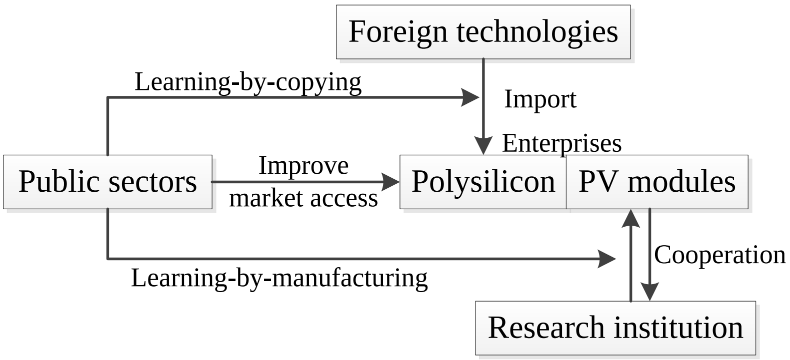

Figure 8 Inducement mechanisms in the R&D stage

Various industry sectors must adapt the different learning-by-doing methods. For PV modules (solar cell) technologies, China’s products have the significant advantage of low cost. And the incident photo-to-electron conversion efficiency has considerable room to improve compared with other clean technologies. Therefore, learning-by-manufacturing is consistent with the current status of the midstream industry (Figure 8). Although enterprises should improve the fabrication process when duplicating the manufacturing steps and apply the innovations achieved by research institutions to actual production, governments should also promulgate relevant regulations to improve access to manufacturing processes according to the actual production of the enterprises. An orderly market will guarantee that the leading enterprises can obtain sufficient revenue and focus on efficiency improvements, which represents the core factor for cost reduction.

Overall, the inducement mechanisms in the R&D stage can promote the construction of a cooperative network in the PV industry in which enterprises are the core actors. Moreover, the manufacturing experience of the enterprises will help the public sector form relevant market supervision regulations.

4.2.2 Deployment stage

Deployment is the second important stage of TIS development and represents the weakest part of China’s PV industry. Most of China’s PV products are dependent on exports to the developed countries and are not applied in the domestic PV system. The overcapacity caused by trade conflict obstructs technological progress and delays the deployment of PV power generation. Learning-by-doing also includes additional mechanisms, such as learning-by-operating and learning-by-implementing [15,57,58]. Demonstration projects subsidized by governments or financial institutions can provide relevant application experience to enterprises before the industrialization of the products.

Learning-by-operating may be helpful for the "entrepreneurial experimentation" function of TIS by providing corporate workers with system installation experience, which will guarantee power distribution reliability and more efficient PV power system operation. As shown in Figure 9, certain standards, such as those for grid-connected technology and product performance, can be developed in practical applications. Public sectors or grid corporations may utilize these standards to supervise other demonstration projects and form relevant regulatory policies.

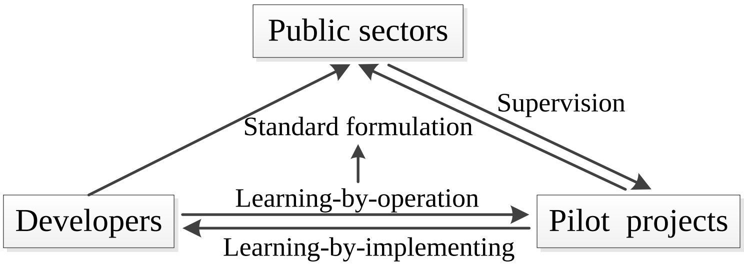

Figure 9 Inducement mechanisms in the market deployment stage

Learning-by-implementing can promote the alliance of enterprises. For example, combining distributed PV power systems, energy storage and micro-grid technology will help reduce voltage instability and increase operating rates; thus, it represents a method for achieving lower levelized PV power generation costs. The developers of PV projects will cooperate with these technology companies to increase operating rates and lower the actual delivery price of energy [59]. Learning-by-implementing will also feed back into the R&D stage of the PV TIS and promote the large-scale application of PV power generation in the future.

4.2.3 Market diffusion stage

All of the production components of the PV industry are interconnected. For example, trade conflicts limit the exportation of PV modules. However, the enterprises for polysilicon production are not sensitive to this problem and maintain the original production scale, thereby leading to overcapacity, which is a direct cause of business failures.

Based on the above analysis of blocking mechanisms, PV enterprises should focus on industry alliances or industrial clusters [60,61]. The leading enterprises in the midstream industry that present advantages of technology and scale should integrate the resources of small-scale enterprises and join with other enterprises in the industry chain to build an information sharing platform [49]. This platform will be helpful for reducing the unnecessary duplication of production, understanding the users' needs and lowering the operation costs. In addition, the cluster method will promote mutual learning and complementary advantages between enterprises, which will lead to the success of the market diffusion stage of technological innovation.

5. Policy implications

The objective of TIS analyses is to provide practical strategy guidance that can help policy producers (and other analysts) identify the key policy issues and industrial development pathways. Therefore, certain policy issues are specified from the above analysis of the blocking and inducement mechanisms and designed to remedy the poor functionality of China's PV TIS and harness innovation in the PV industry.

(1) Promote cooperation

In terms of connectivity, the Chinese PV market is still in a nursing stage. Promoting innovation and increasing cooperation will inspire the different actors in the PV market and establish a stable innovation network, which is exemplified in the combination of industry-university-research operational units with enterprise investments. Although the mode has been applied in other industries for many years, China's PV industry, which represents an emerging industry, does not have such an innovation chain. In reality, enterprise investments generally produce homogeneous products and university research findings are difficult to validate through industrialization. Moreover, financial institutes are also reluctant to take on this type of risk. To remedy the poor TIS functionality, the Chinese government or leading PV enterprises should promote innovation in the chain towards cooperation. In this innovation chain, the main body (i.e., leading PV enterprises) must seek cooperation with universities and funds from financial institutes while also identifying the lead users in a target group. Thus, R&D and market diffusion are linked through a cooperation network.

(2) Establish industrial clusters

Unaligned competitive entities lead to poor TIS functionality, including entrepreneurial experimentation and resource mobilization. Thus, unbalanced industrial structures also cause overcapacity, low-price competition and other supply-demand contradictions. To integrate the entire PV industrial chain, industrial clusters must be established. The analysis of the inducement mechanisms at the market diffusion stage indicate that enterprises at the different industry levels should integrate into one group or cooperate with each other. Important information will be shared in the group, such as product yields, production cycles, costs, etc. According to this information, enterprises can set production schedules to meet the market demand and increase their profits while avoiding unnecessary production and increasing capacity utilization, which will help strengthen the "resource mobilization" functionality.

In addition, the industrial clusters contain social capital and state-owned property. This group includes various types of PV enterprises and will prevent new small-scale enterprises that aim to lower the price of the PV product and profit within a short period from entering the market. This is also helpful for entrepreneurial experimentation.

(3) Deepen electric power system reform

In 2014, the Chinese government proposed the reform of the electric power system with the goal of introducing competition to China's electric power market and accelerating the breakup of the grid companies' monopoly. Deepening the reform will promote renewable energy consumption and remedy the lack of market supervision.

First, the new electricity trade mechanism proposes that users can directly buy power generated via renewable energy from the suppliers. In addition, the grid companies must guarantee that these power generation systems for renewable energy will be preferentially connected to the power grid. Compared with wind power and small hydropower plants, PV power generation is currently the main renewable energy that can be applied in urban buildings and controlled by users. Therefore, PV power generation will be accepted by more users via new electricity trade mechanisms. Second, certain new power grid forms will be proposed to relieve transmission and distribution pressures, such as the smart-grid and micro-grid forms. These new grids are beneficial to the consumption of PV power generation in distributed power supplies.

(4) Introduce financial innovation tools

In the deployment stage of the PV TIS, learning-by-operating and learning-by-implementing are the two main inducement mechanisms. Strengthening these two inducement mechanisms is important for transforming China's PV industry step from the current nursing phase into a bridging market. Therefore, financial innovation tools should be employed to increase domestic enterprise profits and stimulate market applications. In the preliminary stage of the project construction, PV power plants should be implemented as a limited asset. PV developers can obtain the value of the assets by a third party by raising capital from investment banks. Social capital investments in PV pilot projects are beneficial because they can promote learning-by-operating strategies. These financial strategies are currently allowed by state-owned power enterprises. In the operation stage of the PV power system, subsidy tools can help PV enterprises obtain benefits that include electricity sales and renewable energy power generation subsidies. The rapid capital accumulation will increase the opportunities for the enterprise to finance and invest in technological R&D.

6. Conclusions

China's solar PV industry has experienced rapid development over the past few years and has relied on a strategy that includes production duplication and low-priced products exported to foreign markets. However, a wave of anti-dumping and countervailing duties charged by the US and the EU in 2012 hindered China's PV industry. Overcapacity and marginal rates of technological innovation have become significant concerns. Although the Chinese government has introduced many supportive policies to promote large-scale PV power generation applications, the market remains suboptimal.

To identify the essential issues and the development path of China’s PV industry, this paper investigated market dynamics and industry development trends, and our analysis identified an array of blocking mechanisms and inducement mechanisms. A description of the main features of the PV industry, including the power generation, core technologies and supportive policies, was performed to identify the developmental advantages of China’s PV industry, which include abundant solar radiation and a large installation manufacturing base. In addition, certain inherent and serious problems are investigated in this emerging industry, such as the technological gap between the quality of domestic and foreign products, which is compounded by misguided supportive policies and subsidies. To comprehensively identify these issues, this study analyzed the characteristics of China’s PV market dynamics from the perspective of industry chains enmeshed within the larger TIS. We found that China’s solar PV market is still in the nursing stage of market formation. Inadequate complementary technologies, rapidly evolving new entrants and inconsistency between financing flows and industry structures lead to poor functionality and a lack of entrepreneurial experimentation. In addition, low capacity utilization and a strong commitment to coal-fired power are further obstructions to accelerated resource mobilization.

The above investigation of market dynamics, innovation, and transition in China’s solar photovoltaic (PV) industryindicates that the three most serious threats facing the industry are (1) poor connectivity in innovation networks, (2) unaligned competitive entities and (3) a lack of market supervision. Moreover, the inducement mechanisms are identified, and a learning-by-doing strategy is described. The different methods of learning-by-doing are suitable for the different industry levels base on the industrial characteristics. However, whether solar PV technologies will thrive or fail in the domestic market remains uncertain.

Acknowledgments

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