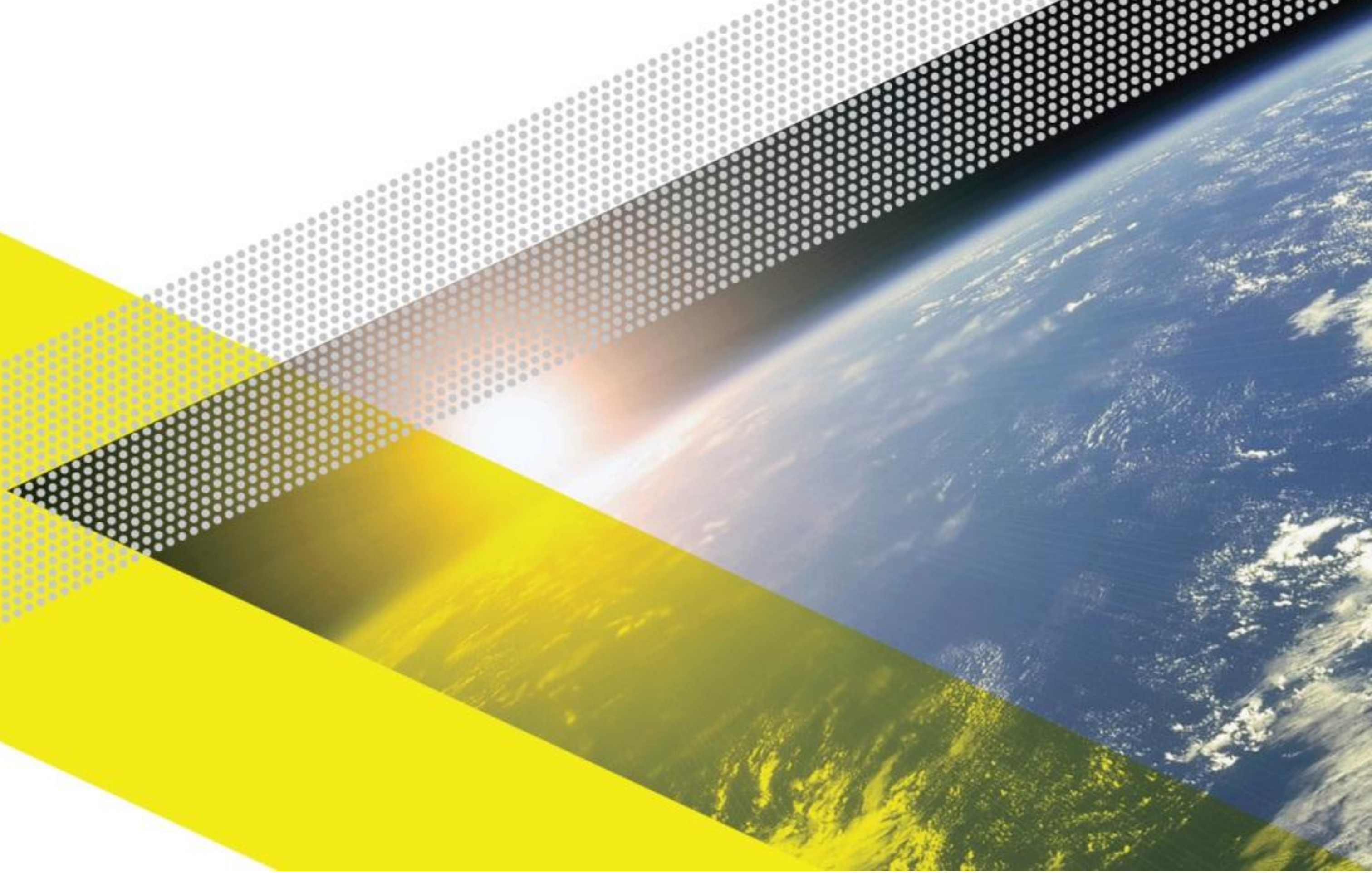
Climate Technology & Development
Case study:

Innovation and Technology Transfer Across Global Value Chains: Evidence from China's PV Industry

Kelly Sims Gallagher
Fang Zhang
Tufts University

July 2013



Acknowledgement

The authors would like to thank the members of the Climate Technology and Development team for their valuable comments and insights, as well as CDKN for their support of this project and case study and BP, whose support enabled much of the underlying research.

This case study has been drafted as part of the project Climate Technology and Development, funded by CDKN and coordinated by ECN, which examines the conditions for innovation for climate-compatible development for different categories (the emerging industry, the rising middle class, the base of the pyramid) in developing countries. This report is registered under ECN project number 5.1633.

Climate & Development Knowledge Network

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Executive Summary

China's success as a rapid innovation follower in the infant PV industry has surprised many observers. This paper explores how China inserted itself into global clean energy innovation systems by examining the case of the solar PV industry. It decomposes global PV industry value chains, and further determines the main factors shaping PV technology diffusion. Chinese firms first entered PV module manufacturing through technology acquisition, and then gradually succeeded building their competitiveness and technological capabilities by utilizing a vertical integration strategy, as well as local interactive learning networks. The main drivers for PV technology development and diffusion in the global innovation system are global market formation policy, a global mobilization of talent, optimal manufacturing capacity, and vertical integration of value chains in China. The development trajectory of the PV industry in China indicates that innovation in cleaner energy technologies is a combination of global and national innovation processes, and that effective global coordination of PV innovation systems along the global PV value chain is significant for global clean energy development.

Main messages for policy:

- Predictable market formation policy is required for PV industrial development in both developed and developing countries.
- National policies may benefit from global harmonization.
- Free trade in clean energy technologies should be promoted.
- International interventions are needed to facilitate cross-border investments, trade, and labour mobility, as well as international R&D cooperation. Clean energy innovation is no longer a national process, but a globalized process.
- Open markets rather than protectionism will accelerate the diffusion of PV technologies.
- R&D support in developing countries should be emphasized as part of the clean energy innovation system in developing countries.
- If overcapacity occurs, let the market take care of the surplus supply.

1

Research background

The explosive growth of a photovoltaics (PV) industry that started in the 2000s has come as a surprise to many observers. In 1999, there was less than 700 MW PV installed capacity globally. More than 32.4 GW of PV were installed in the world in 2012, which brought the cumulative PV installed capacity to 102 GW (EPIA, 2012) as shown in Figure1. The average growth of the annual newly installed PV capacity has amounted to 49.5% per year since 2000. Meanwhile, the price of PV modules has also rapidly decreased by 20% per year during the last 30 years. In late 2011, factory-gate prices for crystalline-silicon PV modules fell below the $1.00/W mark. This is moving towards the benchmark of $1.00/W installed cost for PV systems, which is often regarded in the PV industry as marking the achievement of grid parity for PV (Yang, 2010; Bazilian, et al, 2013).

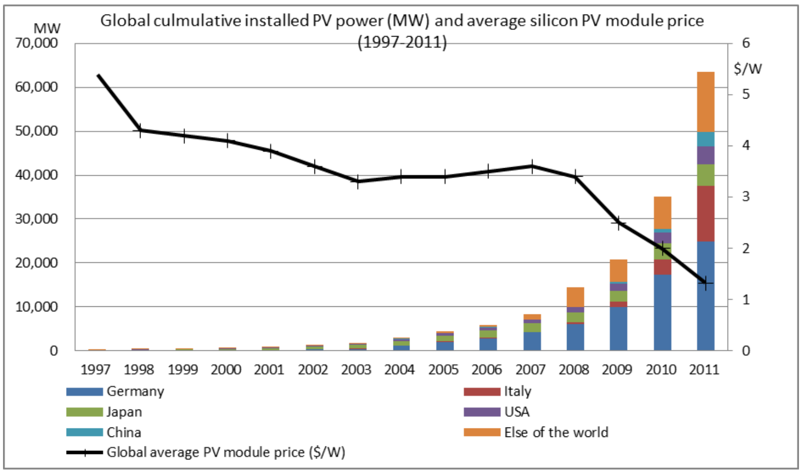

Figure 1: **Global cumulative installed PV capacity and average silicon PV module price from 1997-2011**
Data sources: IEA (2012); SEMI (2012); Mints (2011).

Another surprise for many observers is China's success as a rapid innovation follower in the PV industry. China entered the global PV industry in 2001 when the global market was just emerging. In only 6 years, China surpassed Japan and became the largest solar cell producer in the world, even though there was no domestic market in China at the time (see Figure 2). In 2011, China produced more than 20 GW of solar modules, accounting for 60% of global production, but only about 2 GW were installed in China. The traditional Chinese strategy for emerging industries is to adopt an import-substitution approach where the "infant industry" would produce for the Chinese market first with some government protection, and then gradually begin to export when the firms reach an international level of competitiveness. The emergence of the Chinese PV industry took a quite different trajectory, however.

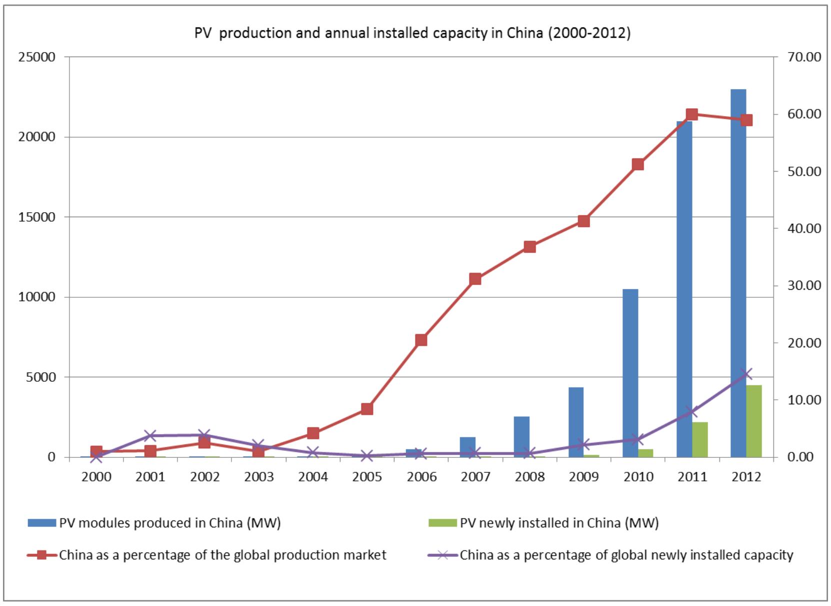

Figure 2: **PV production and annual installed capacity in China (2000-2012)**
Data source: China's Solar PV website; SEMI (2012), etc.

Against this background, this paper will explore four main questions: (1) How did China insert itself into the global PV innovation system? (2) What were the main strategies the Chinese PV industry used to build its technological capability and competitiveness? (3) What were the main factors driving PV technology transfer to China? (4) How could China "leapfrog" in the PV industry? (5) What kinds of policy should be developed to promote technology capacity building in China's PV industry?

2

Literature review and research framework

2.1 Energy innovation system and knowledge learning

Innovation is not just "invention" or "R&D" but rather a set of processes that as a whole should be thought of as a system (Carlsson and Stankiewicz, 1995). It is strongly affected by the social system, including different actors, networks, and institutions (Rogers 1995). The idea of an energy technology innovation system (ETIS) was developed more recently (Grubler et al. 2012), and it applies the systems approach to energy innovation. The key elements of the ETIS include all aspects of energy systems (supply and demand); all stages of the technology development cycle; as well as all innovation processes, feedbacks, actors, institutions, and networks (Gallagher et al. 2012).

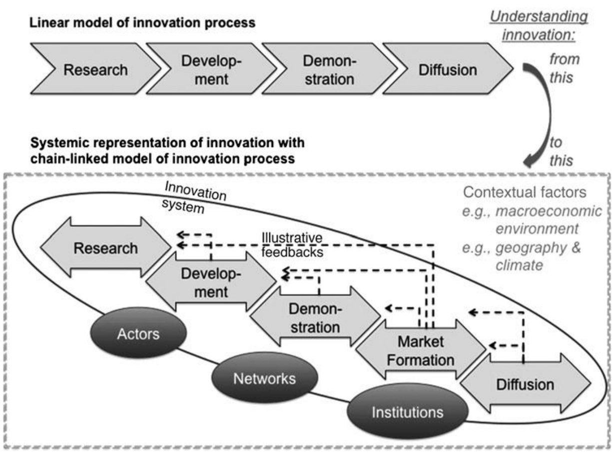

Figure 3: The evolution of thinking on innovation process
Sources: Grubler et al. 2012; Gallagher et al, 2012.

The systemic approach emphasizes that innovation is a collective activity involving many actors and knowledge feedbacks and that innovation processes are influenced by their institutional settings and corresponding incentive structures, including the market as well as government. Technological innovation is characterized by multiple dynamic feedbacks between different stages of the process (Grubler, 1998). For energy technologies, the feedback process from application experience to redesign and engineering has been particularly important (Grubler, 2008).

The ETIS is a sectoral innovation system, with emphasis on technical change within the energy system. It can be applied to both national and global levels of analysis. The solar PV innovation system is part of the wider ETIS, and this innovation system is truly global, with PV technologies being developed and deployed in numerous countries around the world.

2.2 Technology transfer

Clean energy technology transfer is a key process of the global energy innovation system (Grubler et al. 2012; Gallagher et al., 2012). The transfer of technical knowledge from firms in one country to firms in another country is fundamental to the process of technological capacity building. International technology transfer covers hardware transfer, such as tooling for factories, and intangible asset transfer, such as product design and the capability of manufacturing a product (Grubler, 1998). The transfer of technology without supplemental intangible knowledge needed to accompany the hardware may detract from the lasting effectiveness of the technology transfer (Fu and Zhang, 2011). As innovation is costly, risky, and path-dependent, most innovation activities are largely concentrated in a few developed countries. A common strategy among latecomer countries has been to obtain technology through a technology transfer from a country that has already developed advanced technology, and this was how China acquired its solar PV technology.

Technology transfer is also fundamentally a process of learning (Martinot, et al. 1997). A complete and successful technology transfer would mean that innovation could now be achieved at the receiver's side. The ability for a complete technology transfer to occur is dependent on the degree of technological knowledge transferred and the recipient company's ability to learn and adopt an externally-sourced technology (Cohen and Levinthal 1990). Knowledge can include know-what, which is required for learning-by-using equipment or products; know-how, such as knowledge needed to operate and maintain machines and facilities, which is learning-by-doing; and know-why, which includes understanding the principles underlying the development and manufacture of products (learning-by-searching) (Garud, 1997).

There are various strategies through which technology can flow from transferor to transferee (Able-Thomas, 1996), including trade in equipment, foreign direct investment (FDI), joint ventures, licensing agreements, R&D cooperation, turnkey contracts, outward FDI, as well as international conferences, papers, and labour mobility (Lewis, 2005; Cui, Wang and Zou, 2011; Gallagher, 2014). Conventional technology transfer mechanisms such as trade, FDI, and licensing were important for industry formation and take-off, but when these sectors began catching up, a range of other mechanisms became increasingly important, including endogenous technology creation, global R&D networks, and the acquisitions of Western firms. Table 1 provides a typology of mechanisms for the cross-border flow of cleaner energy technologies.

Table 1: **A typology of mechanisms for the cross-border cleaner energy technology transfer**

Mechanism	**Variation(s)**	
Turnkey contracts	Could include contracts with foreign providers for installation and/or operation of technology	Conventional mechanisms ↓
Equipment or goods trade	Imports of equipment or other technologies from foreign providers	
Licenses		
International strategic alliances or joint ventures	Can be formalized as joint venture	
Foreign direct investment to invest in or purchase a domestic firm, or to establish a new wholly-owned firm in foreign country	Could be wholly-owned, or a joint venture with contract provisions related to transfer of technology to the joint venture	
Migration of people for work or education	Could be entrepreneur, financier, consultant, or a formal full-time employee who has worked or been educated in another country	
Contract with a foreign research entity where IP is to be shared or wholly owned by the investor	Could be a contract with a university lab, a government lab, or a for-profit firm	
Collaborative R&D	Research partnerships with foreign entities with shared IP arrangements	Unconventional mechanisms
Purchase of a foreign firm to acquire technology (M&A)	Could be a merger with a foreign firm	
Open sources	Including exhibitions, conferences, books, papers, patent documents	
Bi- or multi-lateral technology agreements among governments	Could include private participation, may include support for capacity building or "tied aid"	

Source: Adapted from Gallagher (2014).

Many factors may shape technology diffusion. The first one is the domestic market. Technology providers are more easily attracted by the prospect of large and stable demand. A large market allows technology businesses to build a significant production scale and achieve lower production costs as a result of economies of scale and technological learning curves (Wei, 1995; Stern, 2007; Lewis, 2005). It also provides scope to develop a wide portfolio of low-carbon technologies. Countries with a small demand would instead be expected to have a narrower portfolio, focused in the technologies where they have significant competitive advantages (Pueyo et al., 2011).

The second factor is public policy. Experience in China, India, and Brazil has shown that in addition to a large demand, successful technology transfer was a response to governments' strong signals and incentives favouring low-carbon growth (Lewis, 2007; Ockwell et al., 2008; Zhang et al., 2009). Gallagher (2014) clarifies four kinds of public policy in the global diffusion of clean energy technology: (1) domestic manufacturing or industrial policy; (2) technology or innovation policy; (3) export promotion policy; and (4) market formation policy. She emphasizes that the lack of market demand in China inhibited Chinese firms from developing and deploying gas turbine technologies, and as a result, they are now decades behind their American, European, and Japanese competitors. By contrast, a strong demand market abroad for PV contributed to the ability of Chinese PV firms to export their products.

The third factor is the complementary assets of the players (Derick, et al., 2010; Lewis, 2007). Complementary assets are defined as infrastructure or capabilities needed to support the successful commercialization and marketing of a technological innovation (Teece, 1986; Rothaermel and Hill, 2005). Incumbents can deal with outer competition together with their downstream assets, if these complementary assets are necessities for the new competitors, which increase their bargaining power with new entrants (Rothaermel and Hill, 2005).

Fourth is the globalization of science and technology. The globalization of science and technology increases the international mobility of technology and human resources. The extent of the global reach of a firm's innovative activities can also play an important role in its technology development strategy. Comparing the differences of growth trajectory between Suzlon from India and Goldwind from China, Lewis (2007) concluded that the establishment of a global learning network was the key factor for the rapid rise of Suzlon.

Other factors identified in the literature include: the competition faced by supplier firms, industry characteristics, the size of the supplier firm and its foreign manufacturing experience, the strategy of the supplier firm, the existence of a supplier's affiliate in the host country, and recipient firm characteristics (Baranson 1967 and 1970; Hall and Johnsonk 1970, Wagner 1979, Stobaugh 1984, Telesio 1984, Farok 1985, Pavitt 1985, Davidson and Fetridge 1985).

2.3 Value chain analysis

The value chain describes the full range of activities undertaken by an enterprise or group of enterprises to bring a product or service from conception through different phases of production, delivery to final consumers, and final disposal after use (Kaplinsky and Morris, 2002; World Bank, 2006). During the 1990s, value chain analysis became widely used, particularly as a consequence of the writings of Michael Porter (Porter, 1985; 1990) and an influential book by Womack and Jones who referred to value chains as the "value stream" (Womack and Jones, 1996). The value chain in Porter's view is an analytical tool to identify the links between actors and functions of a firm that may serve to create value for customers (Porter, 1985).

Value chains have become increasingly internationally segmented due to the globalization process; the production and processing of one product is often carried out by different enterprises in other countries (Faße, Grote, and Winter, 2009; Kaplinsky and Morris, 2002). With the increasing interdependence and functional integration of the world economy, value chain analysis must be expanded to cover global commodity chains. Global value chain analysis is recognized as a useful practical and policy tool to cast more light on international relationships between actors and activities involved in creating goods and services in the global economy (Gereffi, et al. 2001).

The traditional use of value chain analysis is to explore the segmentation of profits and the power relationships between various actors. It is also used to analyse the distribution of environmental costs and benefits, referring to “greening the value chain” (Faße, et al., 2009; Irland, 2007; Boons, 2002; Bolwig and Gibbon, 2009). Increasingly, global value chain theory and technology transfer theory have been synthesized to explain industrial development and innovation in developing countries in the context of increased globalization and transnational inter-firm linkages (Altenburg, 2006; Gereffi, 1994, 1999; Gereffi & Kaplinsky, 2001; Pietrobelli & Rabellotti, 2007; Morrison, et al. 2008). Linkages across the value chain can play a crucial role in accessing technological knowledge and supporting the developing country producers’ learning and innovation activities. Forward and backward linkages may induce voluntary and involuntary knowledge transfer from multinationals to local suppliers and customers (Barba Navaretti and Venables, 2004; Narula and Zanfei, 2005; Castellani and Zanfei, 2006).

2.4 Analytical framework

Analysis of the PV industry in China to date has been mainly to investigate technology transfer and understand the energy innovation system (Fu and Zhang, 2011; Tour, et al. 2011 Gallagher 2014). In this paper, we will introduce the perspective of value chain analysis and synergize it with these prior perspectives. There are two main functions of value chain analysis. First, it provides a way to bridge the national and global innovation systems since the production and processing of one product is often segmented and carried out by different firms in different countries (Saliola and Zanfei, 2009). Second, value chain analysis helps us to focus on the full spectrum of related activities, and not only on the final manufacturing involved in PV production. The full spectrum includes R&D, demonstration, the acquisition of capital equipment, and distribution and marketing, which are increasingly significant in the PV industry. Third, the global value chain emphasizes the nature of the relationships among the various actors involved, and their implications for development.

Thus, we consider value chain relationships as a process interaction between national and global energy innovation systems involving different forms of knowledge transmission and development. We assume that the development of China’s PV industry was affected by technology transfer as well as the interactive learning process along the value chains. Next, we review the PV industry’s development in China and further analyse the drivers behind the learning process.

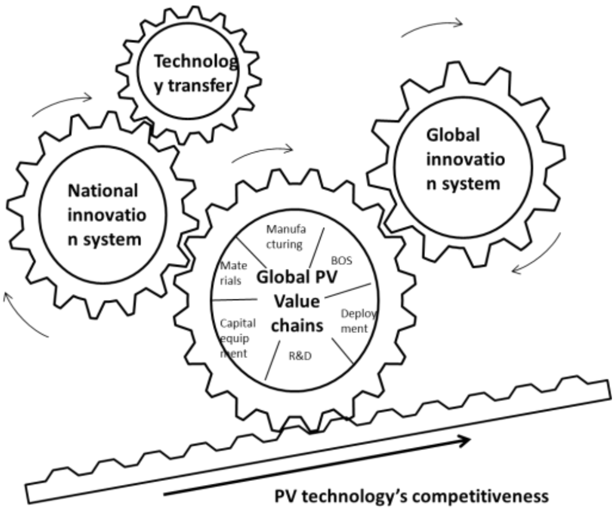

Figure 4: **The function of value chain analysis**

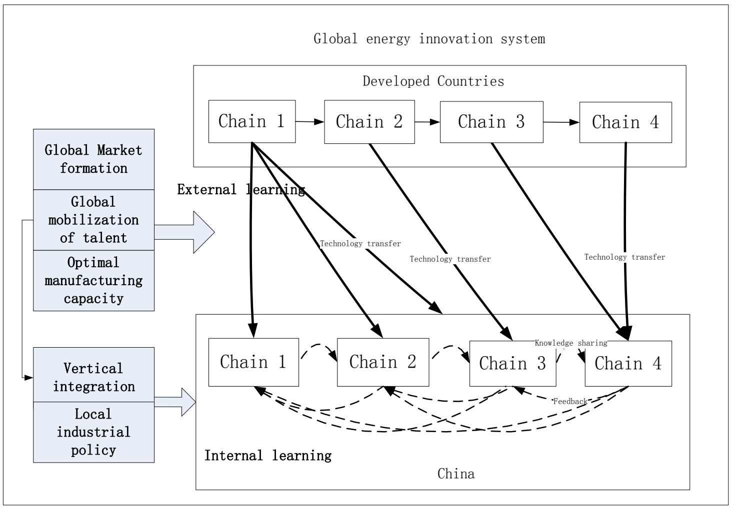

Figure 5: **Analytical framework**

3

The decomposition of the global solar PV value chain

3.1 Definition of PV technology

PV technology has long been acknowledged as a clean energy technology with vast potential. It uses PV cells to convert the planet's most abundant and widely distributed sunlight into electricity. Inside each cell there are layers of a semi-conducting material. Light falling on the cell creates an electric field across the layers, causing electricity to flow. No pollution is emitted during the operation of the PV cell, although there are environmental impacts during the production stage. There are mainly four kinds of PV technology applications: consumer products, distributed PV off-grid, distributed grid-connected, and centralized solar PV power stations (EPAI, 2011).

There are currently three generations of PV technologies. The first one is crystalline silicon PV. The average conversion efficiency of multi-crystalline PV is 14% to 15%, while mono-crystalline PV cells can almost reach 20%. Crystalline silicon PV technology currently takes 80% of the global market because of its high conversion efficiency and its extensive manufacturing base. The next generation is thin film PV, which deposit thin layers of PV materials on low-cost substrates like glass, stainless steel, or plastic. Thin film is significantly cheaper to produce, but it currently has much lower efficiency levels - between 6% and 12%. Thin film PV currently accounts for less than 20% of global solar production. The third generation of PV technology includes concentrator photovoltaics, organics, and other technologies that have not yet been commercialized at large scale. In this paper, we mainly focus on the crystalline silicon PV technologies.

The global potential of solar energy power is huge. On average, each square meter of land on Earth is exposed to enough sunlight to generate 1,700 kWh of energy every year using currently available technology. It is estimated that the total solar energy that reaches the Earth's surface could meet existing global energy needs 10,000 times over (EPIA, 2011).

3.2 PV industry value chain

There are two PV value chains. The first one is more narrow, beginning with polysilicon production to ingot, wafer, cell, and finally to modules. Looking only at the cell production does not encompass the whole picture of the PV value chain, however. Capital equipment, which is used to produce the polysilicon and PV cells, as well as complementary system components, such as inverters, balance of system (BOS) components, system designs, and installations equipment are also significant pieces of the PV industry. The extended value chain includes the capital equipment production and system component manufacturing, and it breaks the PV industry into six main separate value segments, as shown in Figure 6 (EPIA, 2011; Kirkegaard et al., 2010; Zhao, 2011).

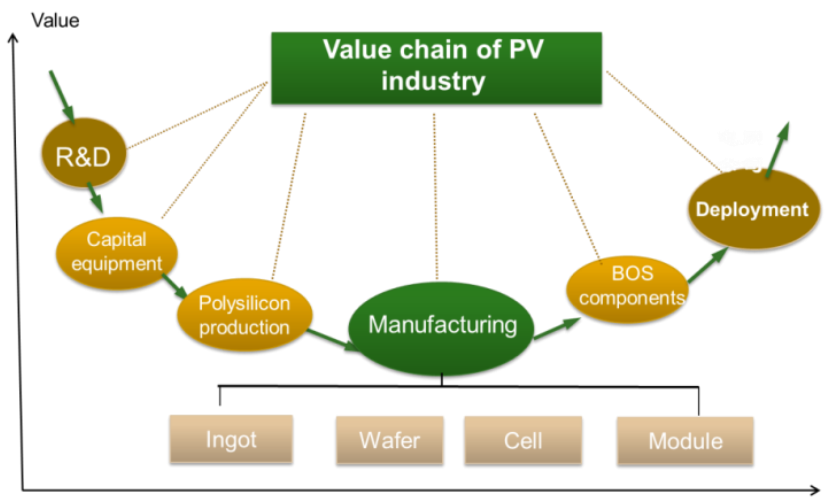

Figure 6: **Example of a PV industry value chain**

- **Research and development (R&D)**: The aim of R&D is to develop basic, general, or specific technologies related to PV technology, including its production equipment and process. The R&D process is knowledge intensive and risky, but if it succeeds, the profits are huge.
- **Capital equipment production**: Capital equipment is used to produce polysilicon, cells, and modules in the PV industry, including the furnace for polysilicon purification, chemical and gas suppliers, abrasives and equipment for cutting wafers, pastes, and inks for cells, encapsulation materials for modules, and specialized measurement equipment for use in production.
- **Polysilicon production**: Polysilicon production converts metallurgical-grade silicon to the polysilicon that can be used for solar cells. Polysilicon production is always capital and energy intensive, and it also requires high-tech equipment and much process know-how.
- **Module manufacturing**: PV module manufacturing mainly takes four steps: casting silicon into ingots; slicing the wafer from the ingot block; turning the wafer into a cell through etching and polishing, cleaning, diffusion, antireflective coating and screen printing; and finally soldering cells together into modules.

- **Balance of system (BOS) components**: The system components, excluding the PV modules, are referred to as the BOS components, mainly including solar panel mounting equipment, PV charge controllers, PV current monitoring devices, inverters, cables and wiring, connectors, overcurrent protection, combiner boxes, grounding hardware, and lightning protection equipment. Among them, the inverter is the most significant component of the BOS.
- **PV Deployment**: PV deployment, which refers to the integration of the PV system and the delivery of solar electricity to customers, is the final destination of the PV industry. The deployment process includes system design, system installation construction, operation and maintenance (O&M), and repair services.

In general, higher value exists on the two sides of the value chain, while the middle manufacturing chain needs less specific knowledge and skills, creating less added value. In the PV value chain, the upstream chain (R&D, capital equipment, and polysilicon production) and downstream chain (BOS components and deployment) create more value and achieve higher profits. The solar panel manufacturing process adds less value and earns fewer profits (Su, 2013). For example, in China in 2006, the silicon producers achieved 50% gross profit. In the manufacturing process, however, ingot and wafer producers only earned 18% profit, solar cell producers 22%, and modules producers 9% (Li 2009).

3.3 Distribution of global PV value chains

Initially local firms in American and European pioneer markets dominated the whole PV industry. However, many segments of the solar PV value chain have experienced fast globalization since 2000 through technology transfer and new market entrants from developing countries. Until now, the highly technology-intensive R&D and capital equipment segments were still mainly located in Europe, the United States, Japan and South Korea. Polysilicon production used to be dominated by firms from Europe, the United States, and Russia, but China has already emerged into this field through technology acquisition from Russia and its own technology R&D. In the manufacturing process, even though Japan, Germany, and the United States are still significant producers, China, Taiwan, and other Asian countries have become the main players in the manufacturing segment. In 2012, more than 58% of global PV modules were produced in China. In the downstream segments, Japan, Germany, and the United States still dominate since PV deployment is mainly located in these places. However, China and India rapidly broadened their domestic PV markets during the late 2000s. In 2012, China became the second largest PV installed country. Figure 7 illustrates the global distribution of the PV value chain.

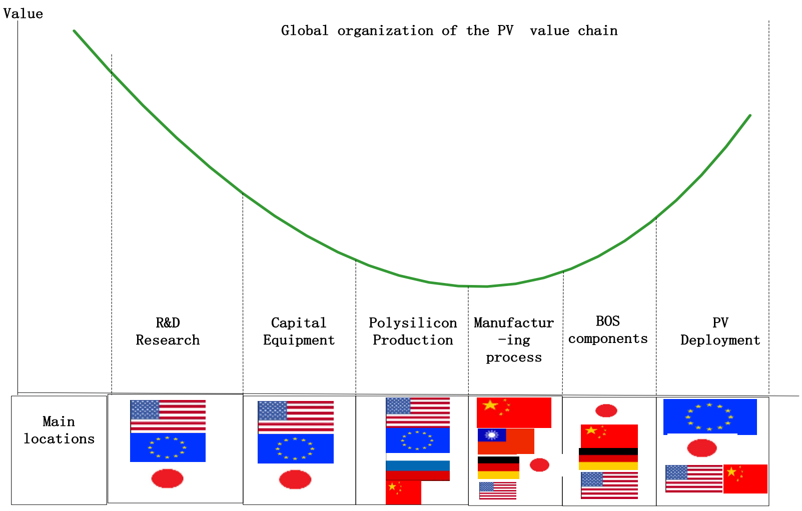

Figure 7: The global distribution of the PV value chain

Data sources: author analysis based on data from IEA (2012), EIPA (2011), SEMI (2012).

Table 2 shows the top 10 actors in the global PV value chain, which provides a more vivid picture of the distribution of value. In the R&D segment, the top 10 patent assignees are mainly from Japan, the United States, and South Korea; in the capital equipment field, European, American and Japan firms dominate. Applied Materials (USA), Centrotherm (Germany), Roth & Rau (Germany), and GT Solar (USA) are the main global providers. However, JGST from China emerged as one of the top 100 capital equipment providers, even though its market share is quite small at less than 2% of the global market in 2012. The situation in the polysilicon segment is similar. China dominates the manufacturing segment, which is cell production and module production. In 2011, three Chinese firms were in the top 10 global cell producers and five Chinese firms were in the top 10 global module producers. China's PV cells and modules production accounted for 47% and 54% of the global market that year. Additionally, firms from Germany, the United States, and Japan continue to be competitive players in these segments. In the balance of system (BOS) field (e.g. PV inverter production), firms from Europe dominate, largely due to the fact that most PV modules have been installed in Europe until recently. In the final deployment segment, Germany, the United States, and Japan continue to be the main market for PV deployment. Until 2011, nearly 70% of the installed PV capacity was still in Europe, but China and the United States are both gradually increasing their PV deployment. In 2011, China was the third largest country in newly installed capacity, surpassing Italy in 2012 to become second only to Germany.

Table 2: **Top 10 actors in the main global PV value chains**

Ranking	R&D: Patent assignees (2010)	Capital equipment providers (2011)	Polysilicon producers(2010)	Manufacture: Cells production （2011）	Manufacture: Modules production (2011)	BOS manufacturing : inverter producers	Deployment: Newly installed capacity in 2011	Deployment: cumulative installed capacity in 2011
1	Canon KK (Japan)	Applied Materials (USA)	Hemlock Semiconductor corporation (USA)	First Solar (USA)	Suntech (China)	Power-One (Germany)	Italy, 31.6%	Germany,36.7%
2	Sharp KK (Japan)	Centrotherm(Germany)	Wacker Polysilicon (Germany)	JA Solar (China)	First Solar(USA)	Siemens(Germany)	Germany 26.4%	Italy，18.6%
3	LG Electronics Inc(South Korea)	MeyerBurger(Swiss)	OCI Company (South Korea)	Suntech (China)	Yingli (China)	Advanced Energy (USA)	China 9.5%	Japan,7%
4	Samsung Electronics Co Ltd (South Korea)	GTAT (USA)	GCL-Roly Energy Holdings Limited (China)	Yingli (China)	Trina Solar (China)	Sungrow Power (China)	USA 5.6%	Spain,6.2%
5	Mitsubishi Co (Japan)	Schmid(Germany)	MEMC Electronic Materials Inc. (USA)	Trina (China)	Canadian Solar(Canada)	Danfoss Solar Inverters (Denmark)	France 5.3%	USA, 6.2%
6	Sumitomo Chem Co Ltd (Japan)	Komatsu-NTC (Japan)	Renewable Energy Corporation (Norway)	Motech(Taiwan)	Sharp (Japan)	Satcon (USA)	Japan 4.2%	China, 4.3%
7	Du Pont (USA)	Oerliko (Swiss）	LDK Solar Co. Ltd （China）	Gintech (Taiwan)	Jinko (China)	Elettronica Santerno (Italy)	Australia 2.5%	France,3.7%
8	Sanyo Electric Co Ltd (Japan)	APOLLO (USA)	Tokuyama Corporation (Japan/Malaysia)	NEO Solar Power	Sunpowe (USA)	AEG Power Solutions Germany	UK 2.5%	Belgium 2.2%
9	Appplied Materials Inc (USA)	RENA(Germany)	Kumgang Korean Chemical Company (South Korea)	Canadian Solar (Canada)	Hanwha Solarone(China)	Refu Electronik (Germany)	Belgium 1.9%	Australia 1.7%
10	Fujikura Ltd (Japan)	JGST(China)	Mitsubishi Materials Corporation (Japan)	Sun Power (Germany)	Kyocera(Japan)	Riello Eletronica (Italy)	Spain 1.4%	UK,1.1%
Else		Else 51%		Else 51%			Else 9.2%	Else 12.7%

Data sources: IEA (2012), EIPA (2011), SEMI (2012).

4

Technology transfer and China’s emergence in the global PV value chain

The solar power potential in China is huge, amounting to 19.5 million TWh per year. It is estimated that 1% of China’s continental area, with 15% conversion efficiency, could supply 29,304 TWh of solar energy. That is equivalent to 145% of world-wide electricity consumption in 2008 (EU, 2011). As a green and clean renewable energy technology, solar PV could help China overcome its energy security and GHG emission problems.

PV technology research and development started in China as early as in the United States and other countries. In 1958, China developed the first piece of mono-silicon cell, only one year behind the United States. At that time, solar PV research was mainly used in space applications, just like in other countries. Solar PV cells also started to be used in remote and rural areas beginning in the mid-1970s. Some solar cell manufacturers were established in Ning Bo and Kaifeng, but the production scale was extremely small, still less than 100 KW in the 1980s. In 1985, China started to import solar cell production lines from the United States, Canada, and other countries and gradually increased its production capacity to 4.5 MW per year. This was the scale of production capacity until 2002.

China’s actual involvement in the global PV market started in 2001, driven by a rapid increase in market demand in Japan and Germany. In 2002, Suntech established its first 10 MW PV module production line. The next year, Yingli Green completed its first 3 MW production line, which actually had been planned as a demonstration project of China’s Ministry of Science and Technology (MOST) in 1998, but was stalled by the uncertain domestic market and weak policy prospects. Later, LDK, Trina, JA Solar and more new Chinese entrants began to manufacture PV modules and rapidly expanded their production capacity driven by strong market expansion in Europe. The growth rate of China’s PV module production was 140% per year between 2005 and 2007, and in 2010, production capacity was increased to 20 GW.

Table 3: **Emergence of Chinese PV manufacturers in the global market**

Ranking	2006	2007	2008	2009	2010	2011	2012
1	Sharp	Sharp	Q-Cells	First Solar	Suntech	Suntech	Yingli Green
2	Q-Cell	Q-Cells	Suntech	Suntech	First Solar	First Solar	First Solar
3	Kyocera	Suntech	Sharp	Sharp	Sharp	Yingli Green	Suntech
4	Suntech	Kyocera	First Solar	Q-Cells	Yingli Green	Trina Solar	Trina Solar
5	Sanyo	First Solar	Kyocera	Yingli Green	Trina Solar	anadian Sola	Canadian Solar
6	Mitsubishi	Motech	Motech	JA Solar	anadian Sola	Sharp	Sharp Solar
7	Schott	Sanyo	Sanyo	Trina Solar	Hanwha Sola	SunPower	Jinko Solar
8	Motech	Solarworld	SunPower	SunPower	Kyocera	Jinko Solar	JA Solar
9	BP	Mitsubishi	JA Solar	Kyocera	SunPower	Hanwha Sola	SunPower
10	SUnPower	SunPower	3P/Mitsubish	Motech	SolarWorld	Kyocera	Hanwha Solarone

Data sources: PV Tech Website, Solarbuzz Website, EPIA, 2012, etc.

The main method used by Chinese emerging firms to acquire PV production technology from abroad was to import most if not all of the equipment to manufacture modules (Yang et al. 2003). This initial technology transfer process occurred with remarkably few barriers and with incredible speed.[1] One of the leading solar PV manufacturers imported 80% of the equipment for its solar cell production, mostly from Germany and United States. The recruitment of talent from abroad as well as R&D cooperation with foreign partners were also significant methods of knowledge acquisition in this industry. Many of the leaders of the Chinese PV industry were either educated or worked outside of China and returned to found or join new firms. The Chief Technology Officer at Yingli and CEO of Suntech both received doctorates at the University of New South Wales in Australia. As a result, Suntech works closely with the University of New South Wales. New South Wales professor Stuart Wenham is now chief technology official (CTO) of Suntech. Both the CEO and Vice President of JA Solar were trained in the United States. Trina Solar and DuPont agreed in 2012 to begin collaborating on R&D efforts to advance the efficiency and lifetime of solar cells and modules (Gallagher, 2014).

As a result of technology transfer, PV module production conglomerated in China (as shown in Figure 8). In 2007, China became the largest PV producer in the world surpassing Germany. The share of China's PV production in the global market rapidly increased after 2005, and more than 60% of PV modules were produced in China in 2011.

[1] United States, January 26, 2012.

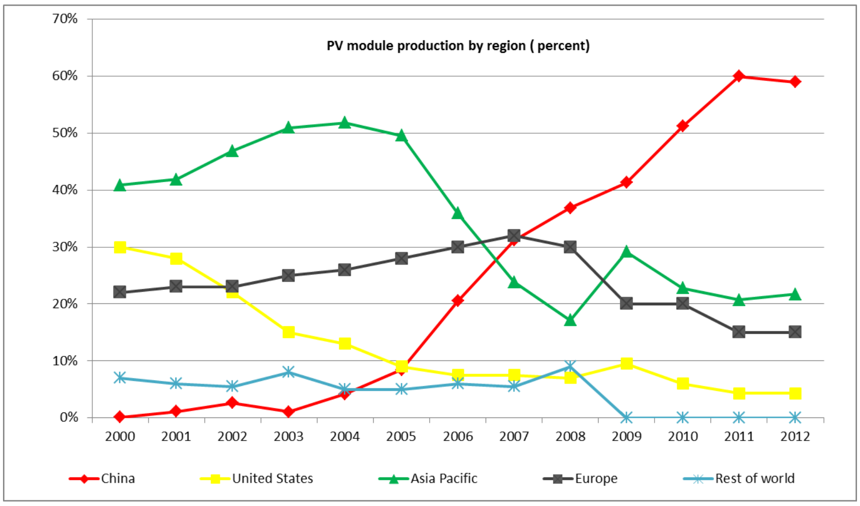

Figure 8: **The landscape of PV production**
Data sources: EPIA, 2012.

The technology innovation capacity in China has greatly improved. The top efficiency of a laboratory PV cell in China has reached 21%. Commercialized PV components and normal commercialized cells have efficiencies of 14-15% and 10-13% respectively. China has greatly reduced the production cost of solar PV cells, and consequently, the price of solar cells has decreased from the 40RMB/Wp in 2000 to 4.5 RMB/Wp in 2012 (IEA, 2012).

The global financial crisis since 2008 has greatly challenged the growth of the PV industry in China. To rein in their public expenditures, Germany, Spain, and Japan all reduced their support for PV deployment. Meanwhile, the rise of Chinese firms upset national politicians in other countries, who were worried about the loss of domestic clean markets and “green jobs,” as well as the potential leapfrogging of competitive emerging countries. As a result of suspicions that the Chinese government was unfairly subsidizing its firms, the Obama Administration announced a protectionist policy and imposed a minimum 31% tariff on solar panels imported from China in 2012, which rapidly caused a reduction of China’s PV exports to the United States. Similar protectionist policy was considered by Europe in 2013. The terrible weakening of global market demand pushed several Chinese PV manufacturers over the edge of bankruptcy.

The Chinese government started to ambitiously promote PV instalment in China in 2009 to compensate for the loss of foreign demand, and also because it was concerned about energy security and climate change. In late 2009, the National Energy Authority (NEA) raised the national target for solar energy from 1.8 GW to 20 GW by 2020, with 5 GW to be installed by 2015. Of the 2020 target, more than half of the installations are expected to be utility-scale PV systems. In 2010, the NEA released the 12^{th} 5-Year Plan (2011-2015) for Solar Power Generation and updated its target to install 35 GW of PV power by 2015 and 100 GW by 2020.

In 2009, China rolled out two national solar subsidy programs: the BIPV (building-integrated photovoltaic) subsidy program and the Golden Sun Program. The BIPV subsidizes RMB15/W for rooftop systems and RMB20/W for BIPV systems. The Golden

Sun Program subsidizes 50% of total investment in PV power generation systems and power transmission facilities in on-grid projects, and 70% for independent projects. In August 2011, China announced its first nationwide feed-in-tariff (FiT) for solar projects. The FiT established by the National Development and Reform Commission (NDRC) sets an on-grid solar power price of RMB 1.15/kWh (about US$0.18/kWh) for projects approved before July 1, 2012, and completed by year's end; and RMB 1.00/kWh (approximately US$0.16/kWh) for all others. According to the NDRC's consulting draft of PV generation price reform policy in March 2013, solar power generation rates are expected to decrease to 0.75-1 RMB/kWh for centralized grid-connected PV projects and 0.35 RMB/kWh for decentralized grid-connected PV projects due to the rapid reduction of PV module and system prices. Incentivized by these policies, the domestic PV instalment in China is increasing rapidly. In 2012, China displaced Italy and became the second largest market in the world for installed PV, trailing only Germany.

4.1 Vertical integration strategies to enhance competitiveness

Vertical integration is the main strategy for Chinese PV production firms to enhance their competitiveness. Most Chinese PV production firms first started PV production from module assembly, a sub-value chain in the production segment. The main patents had already expired and therefore did not serve as an effective barrier for new entrants. Then, Chinese manufacturers tried to enter into the polysilicon, ingot, and wafer segments through a vertical integration strategy (see Table 4). Yingli and Trina are perfect examples because they nearly cover the entire value chain from polysilicon production to PV deployment. Trina established its first PV module plant in early 2005 and then started to produce monocrystalline silicon later that year. In 2006, it expanded to wafer production and produced 28 MW by the end of that year. Besides manufacturing, Trina is also deeply involved in the downstream segments, producing system components and doing PV instalment and operation.

Table 4: **The Value Chains of the Top 5 PV manufacturers in China as of 2012**

Firms	Polysilicon	Manufacturing				Balance of system	Deployment
		Ingot	wafer	cell	module		
Yingli	√	√	√	√	√	√	√
Suntech			√				√
Trina	√	√	√		√	√	√
Jinko Solar	√	√	√	√	√		√
JA Solar			√	√	√		√

Data source: firms' websites and annual reports.

The most crucial vertical integration strategy used by Chinese PV manufacturers was the localization of polysilicon production. In 2005, silicon production in China only accounted for 0.5% of global production. The rapid growth of the PV industry led to a situation where, between 2004 and early 2008, the demand for polysilicon outstripped the supply. Prices for purified silicon started to rise sharply in 2007, and in 2008 prices for polysilicon peaked around $500/kg and consequently resulted in higher prices for PV modules. The shortage of polysilicon provision encouraged Chinese PV module producers to enter into this segment in order to ensure stable polysilicon supply, as well as to avoid market and price vulnerabilities. In 2010, about 140,000 metric tons of solar grade silicon production was reported, sufficient for around 20 GW, under the assumption of an average materials need of 7g/Wp. China produced about 45,000 metric tons, or 32% of the total, capable of supplying about 75% of domestic demand. The massive production expansions, as well as the difficult economic situation, led to a price decrease throughout 2009, reaching about $50-55/kg at the end of 2009, with a slight upward tendency throughout 2010 and early 2011. Japanese and German firms have been unwilling to transfer their technology to China, however, so polysilicon production in China is still more polluting and costly than foreign imports.[2]

Another strategy for vertical integration is to extend the business into the downstream segments. PV system integration and installation are the final steps and always need to happen near to or at the final location. Thus, these segments are still mostly dominated by local service providers and construction firms. While several significant developers such as Spain's Fotowatio and Iberdrola, integrated multinationals such as SolarWorld, and small- and medium-sized service providers such as Sgurr Energy do operate across borders, this segment of the value chain has the lowest degree of globalization to date.

With the growth of the Chinese domestic market, China's PV firms began to be actively involved in PV project engineering, construction and maintenance, as well as system design. The integration of the downstream value segment could enable the firms to increase their local market share. Meanwhile, the deployment process also helps the firms to get empirical knowledge and feedbacks about PV system operation, which enables the firms to engage in learning-by-using in the operation and maintenance of the systems. In the Chinese PV deployment market, however, standardization lags far behind global levels.

Chinese firms also have aggressively made strategic acquisitions and investments in foreign firms. For example, Suntech acquired MSK (a leading supplier of BIPV systems) to gain access to BIPV technology as well as to gain wider entry into the Japanese market. It acquired EI Solutions, a commercial solar systems integration company in the United States, as well as two investment funds to develop, finance, and own projects in the United States. Besides the market access, acquiring technological knowledge of system integration was also a driver behind these acquisitions and investments.

The first incentive for vertical integration is to increase profits, which could improve competitiveness. Since the middle 2000s, as more new firms entered, profits were rapidly reduced to 9% for the module firms (Hua Li, 2009). However, the profit margins for solar cell, wafer, and polysilicon production was still higher than for the module manufacturing as it required more complex technological knowledge and fewer new entrants rose in those chains (see Table 5). For the solar cell and wafer producers, their profit reached 22% and 26%. And the profit for the polysilicon production could even reach 50%. Vertical integration therefore had the potential to greatly increase profits.

[2] China, July 14, 2010.

For example, if the module firms added cell production, it would increase their profit from 9% to 25%; if it further integrated the wafer, their profit could be increased to 49% (see Table 5). Not surprisingly, Yingli Solar and Tianhe actively integrated cell, wafer, and polysilicon production into their firms after 2004. With higher profits, the manufacturers could reduce their prices and thus gain more competitiveness in the global market.

Table 5: **Profits for different value segments in China's PV industry in 2006**

Chains	Price	Added cost	Material cost	Profit	Profit rate
Module	4.25	0.67	3.2	0.38	9%
Solar cells	3.2	0.2	1.9	0.7	22%
Wafer	1.9	0.63	0.78	0.49	26%
Polysilicon production	0.78	0.31	0.08	0.39	50%
Cell – module	4.25	1.27	1.9	1.08	25%
Cell –Wafer-Silicon	3.2	1.54	0.08	1.58	49%
Module-cell-wafer-polysilicon	4.25	2.21	0.08	1.96	46%
Engineering, construction, and maintenance	3.05	1.8		11.25	41%
Whole value	12.04	4.31	0.08	7.65	64%

Data source: Hua Li (2009).

The second strategy is to ensure stable material supply and therefore obtain independence from the supplier. The world has abundant reserves of metallurgical-grade silicon, but its production is very capital and energy intensive and requires high-tech equipment. Historically, the silicon industry has been dominated by a handful of firms from Germany, the United States, and Japan, such as Hemlock, Wacker Chemie, REC, Tokuyama, MEMC, Mitsubishi, and Sumitomo. The technology concentration and rapid growth of demand caused a severe shortage of polysilicon between 2005 and 2008. As mentioned previously, most Chinese firms tried to establish their own polysilicon production capacity.

The third and fourth benefits of vertical integration are cost reduction and quality assurance. Firms can have more direct control over the quality of upstream materials or downstream complementary components. Fifth, vertical integration also allows for knowledge sharing between different value chains, which can help manufacturers rapidly adapt their production according to changes in the market.

Unexpectedly, vertical integration caused an unplanned production cluster and, effectively, a learning network in China. Module firms, such as Yingli Solar, always located these chains nearby, which could also reduce their transportation costs. The compact value chain also facilitated knowledge communication among engineers in different plants, which induced rapid process improvements in some firms. One executive proudly explained, "We imported similar equipment to foreigners, but we used it to cut thinner wafers than others. That's one process innovation we made."[3]

[3] China, August 12. 2011,

4.2 Case Study: Yingli Solar in China

Yingli Solar was established in Baoding, Hebei province in China in 1998. In that year, MOST in China engaged in solar power generation technology and planned to establish a 3 MW demonstration project, which was applied for by Yingli Solar. However, due to the hugely uncertain market, the project was not implemented until 2003.

In 2003, Yingli established a 3 MW module production capacity and in 2004, Yingli established its ingot, wafer, and cell production plants. In the same year, the cell products received certification from international tests, such as UL, IEC, and TUV, and so Yingli began to export to Germany. In 2006, Yingli continued to expand its production capacity, including a 95 MW ingot and wafer production capacity it had acquired, a 60 MW cell production capacity, and a 100 MW module capacity. In 2011, the overall production capacity reached 1.7GW.

With more entrants into the PV industry, the shortage of polysilicon became more and more pronounced. To ensure its silicon supply and reduce the cost of purchase, Yingli planned to establish its own polysilicon production facility since 2007 and finally started poliysilicon production in its Liujiu Plant in 2010. The initial production capacity of the Liujiu Plant was 400 MW, of which 100 MW was for polysilicon and 300 MW for monosilicon. The production capacity was increased to 1061 MW by the end of 2010.

Through vertical integration from polysilicon production to ingot, wafer, cell, and module production, Yingli avoided the vulnerability of price changes in the market. Meanwhile, vertical integration also greatly reduced polysilicon cost for Yingli and thereby increased its profit margins. What's more, Yingli co-located these segments, which also reduced transportation costs. The integration of the value chain also incentivized knowledge communication between engineers in different plants, which induced process improvements in Yingli overall.

Yingli Solar also established strategic technological collaborations with upstream and downstream suppliers. In 2009, Yingli cooperated on the Panda solar cell with the Energy Research Centre of the Netherlands and jointly developed the production line for the Panda with Amtech in the Netherlands. The Panda cell achieved 19% efficiency, and assembled modules using them achieved 16.5% efficiency.

Starting in 2009, Yingli set up several subsidiaries in the United States and Europe. In 2011, Yingli established an R&D research and sale service centre in Spain, which offers product value, test, and after sale services, which will guarantee the optimal quality of the PV modules in the European market. In the same year, Yingli also established the same R&D centre in San Francisco. The benefits are twofold: they are geographically closer to the main consumers of Yingli's final products, and it is easier for Yingli to grasp the latest technologies of solar cells in these technologically advanced countries.

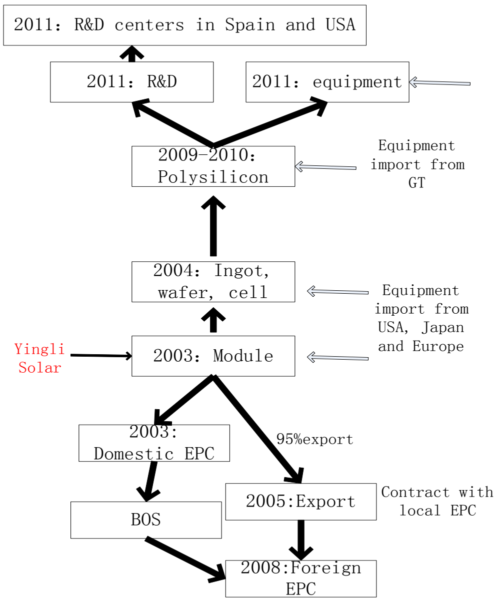

Figure 9: The growth of Yingli Solar across the value chain.

5

Drivers of PV technology innovation and transfer to China

5.1 Market formation policy

The birth of the Chinese solar industry was inspired by the burgeoning demand for solar PV in Europe, Japan, and the United States, and that demand was created by feed-in-tariffs in Europe, government-sponsored deployment programs like the Subsidy Program for Residential PV systems in Japan and renewable portfolio standards in the United States. While the Chinese government did not initially form a domestic market for solar PV, it soon recognized the need for it and established the Golden Sun demonstration program and then a feed-in-tariff for solar PV. New national and sub-national policies to address pollution, energy security, and global climate change created global markets for cleaner energy technologies beginning around the turn of the century. Firms can take advantage of these opportunities if they have the global perspective to see them. Policies in Germany, Spain, the United States, and China were particularly important for diffusion of solar PV technology.

Policy is often identified as the most important incentive for the deployment of clean energy technologies. In interviews, Shi Zhengrong, CEO of Suntech, asserted, “The number one barrier is policy. Well, it is cost, and therefore you need to have policy to create the market.” Dick Wilder of Microsoft was more specific, “The policy environment is important – principally the stability and the predictability. Especially when you are talking about large installations when the payback will take place over a long period of time, you want to be sure you have a regulatory environment that will be predictable while you are expecting to recoup your investment.” These quotations refer to market formation policies, and these policies need to be predictable, stable, and aligned if producers are to respond to them (Grubler et al. 2012).

5.2 The global mobilization of talent and information

Many of the leaders of the Chinese PV industry were educated outside China, worked outside of China, and returned to found or join new firms. One source claims that 61% of the board members of the three largest Chinese PV firms have studied or worked abroad, and notes that the CEO of Yingli studied abroad, as did six people in the management team at Trina Solar (de la Tour et al., 2011). With their sophisticated knowledge about technology, these leaders were able to make smart and careful choices about which technologies to buy from abroad, and what kind of equipment they needed for their manufacturing plants. Shi Zhengrong, CEO of Suntech, commented in an interview that one of his strengths was that he “can understand the technology” and therefore he knows what he needs to go out and buy. He said, “Buying is a great strategy for acquiring technology.” Suntech has both licensed technology and bought foreign firms outright. That being said, Dr. Shi asserted that technologically, their main strategy was “joint development” where they work with other universities or technology partners to develop technological solutions. Perhaps because they were educated abroad, these leaders also had a remarkably sharp global perspective on where the markets were for solar PV modules.

Additionally, the global education background also helps firms to operate global R&D cooperation. Most of the top Chinese firms have cultivated relationships with foreign research institutes or firms to conduct R&D in addition to acquiring firms outright. Similarly as Suntech, Yingli contracted with the Energy Research Centre of The Netherlands to improve the efficiency of mono-silicon cells, and the funding for this research cooperation is split with Yingli paying two-thirds and MOST the remainder. JA Solar signed an agreement with Innovalight, a firm based in Sunnyvale, CA, to co-develop solar cells with conversion efficiencies exceeding 20%, and also for Innovalight to provide silicon nanoparticle ink (Gallagher, 2014).

5.3 Manufacturing optimization in China

The main competiveness of China’s PV innovation system is firstly in its optimal manufacturing capacity. Labour costs are not a significant factor in the Chinese solar PV manufacturing industry since the manufacturing processes are highly automated, even in China. Several factors appear to be very important, starting with the flexibility of Chinese manufacturers. According to one foreign manufacturer, the speed at which the Chinese can react to orders and other changes in the marketplace is unrivalled. Part of this flexibility derives from the cluster effect of parts and components suppliers, most of whom are located in eastern China. Many ancillary equipment manufacturers are close by, and these firms are also able to turn on a dime and alter production as needed. Due to less-protective labour laws, the Chinese can also ramp production up and down in immediate response to the market, sending home workers if need be, and then rehiring when the market picks back up.[4] The Chinese manufacturer's attitude is always how to reduce costs[5]. In a speech at MIT in 2010, Suntech's Shi Zhengrong said that when he wrote the business plan for Suntech, he had no idea how much everything would cost, so he decided to estimate a 30% discount on everything. He was confident it could be done, and stated that his philosophy was "thoroughness." The early shortages of silicon also inspired Chinese firms to use it more efficiently.[6] One firm stated that they focused heavily on how to make the wafer thinner so as to use less silicon.[7] A different explanation for the ability of the Chinese to reduce costs in the manufacturing process more recently is the ruthless and fierce competition in the Chinese market. As in many other industries in China, success breeds copycatting, and many new firms tried to enter the marketplace after the initial successes of the major firms like Trina, JA Solar, Suntech, and Yingli. Local governments support these new firms in hopes of boosting job creation and local GDP. This phenomenon breeds "repetitive" production, as the Chinese call it. Estimates of the number of solar PV module manufacturers in China vary, but there are at least one hundred manufacturers, even though the top 10 biggest firms dominate the market. Still, the 2011-2012 downturn forced consolidation; by one account, 50% of Chinese manufacturers had suspended production as of December 2011 (Chang 2011).

5.4 Policy incentives from China's government

Although the central government was not focused on solar PV industrial development until the mid- to late-2000s, the provincial and local governments were quick to get behind the new solar firms in their jurisdictions, in hopes of creating local jobs and new industries. As one example, the city of Huai'an in Jiangsu Province provides a 50% refund in the real interest of loans used to purchase equipment for a factory, a refund equal to 0.05 RMB/kWh in electricity consumption for the first year, a refund of the land transfer fee, and a partial refund of corporate income tax for the first eight years (Grau et al. 2011). Later, after the Chinese manufacturers had already successfully brought the costs of solar PV down, the central government began to provide domestic market formation support through new policies.

As mentioned before, there are only three main market formation policies for solar PV today in China: Golden Sun, Solar Roofs, and Large-Scale On Grid PV. Some U.S. and German firms (most vociferously the German firm SolarWorld, which has a manufacturing facility in the United States) have argued that the Chinese government has unfairly subsidized its firms. There is no doubt that the Chinese firms received various kinds of support from the local governments especially including low interest loans and discounted land and electricity prices, and this was confirmed by interviews.[8]

4 United States, January 26, 2012.

5 United States, January 26, 2012.

6 United States, December 7, 2010.

7 China, July 19, 2010.

8 United States, January 26, 2012; China, July 19, 2010.

However, the U.S. government has also provided investment tax breaks, production tax breaks, and loan guarantees to many clean energy firms at the federal level, and it is not uncommon for further incentives to be provided at the local level as well. Clearly, governments in every country at the national, state, and local level are offering "carrots" to firms to locate and prosper there. The focus on subsidization may be distracting from more fundamental sources of Chinese competitiveness.

6

Discussion

6.1 Drivers for China's emergence as a fast innovation follower in the global PV industry

China first entered the PV module manufacturing chain of the global PV industry through technology acquisition and then gradually tried to build competitiveness through vertical integration of PV value chains. Vertical integration not only reduced cost and increase the competitiveness of the Chinese PV firms, but also created an effective learning network through clustering and interaction with actors, which in turn advanced the knowledge generation, transmission, distribution, and feedback in the PV innovation system. External global market formation policy, the global mobilization of talent, internal manufacturing optimization, and public incentives in China are the four main factors affecting the interaction between China's innovation system and the global innovation system. The development trajectory of the PV industry in China indicates that innovation in cleaner energy technologies can be a combination of global and national innovation processes.

6.2 China's contribution to the global clean energy innovation system

China's emergence as a global player in cleaner energy markets contributed to the globalization of these industries in several ways. Chinese students studied science and engineering at home and then went overseas to get educated technologically, and in so doing they acquired a global perspective. Some of these Chinese students stayed and contributed to foreign firms, such as China's current Minister of Science and Technology who worked at Audi in Germany for many years. Others took the knowledge they gained abroad and employed it in new industries in China. China's clean energy manufacturers have also contributed to remarkable reductions in the global cost of these technologies. Some have argued that these cost reductions are the result of illegal subsidization in China, but illegal or not, the costs have undoubtedly fallen at a rate that nobody expected. As a result, these technologies are much more accessible globally than they were only a few years ago. In other words, Chinese manufacturers have shifted the global supply curve, which has led to growth in global demand. Domestically, the Chinese clean energy market has grown 37% over the past five years, and has accounted for 20% of G-20 clean energy investment in 2011 (The Pew Charitable Trusts 2012).

6.3 The technology leapfrogging possibilities of China's PV industry in the global context

Technological development is cumulative, iterative, and derives from spill overs; so countries like China are able to pursue a catch up strategy. Often this catch up strategy does not only require extensive imports of foreign technologies through licenses, joint ventures, or other means, but also requires local energy technology learning, which plays the dual function of creating knowledge and promoting learning and absorptive capacity (Cohen and Levinthal, 1989; Aghion and Howitt, 1998). Through technology transfer and vertical integration, China has already accumulated and established its competitiveness in the manufacturing segment. However, in the two high value-added segments, China still lags behind, even though China has managed to enter into polysilicon production. Additionally, as the Chinese PV industry largely depended on the market abroad, international trade protectionism also challenges future technology transfer and leapfrogging in China.

7 Conclusions

Chinese firms first entered the PV module manufacturing segment of the global PV value chain, and then gradually tried to upgrade through vertical integration. The emergence of China's PV industry benefited from international technology transfer and internal effective learning through vertical integration across value chains, as well as process innovation and scaling strategies. The main drivers for PV technology generation and diffusion in the interaction between China's and the global innovation system are global market formation policy, a global mobilization of talent, optimizing manufacturing capacity, and vertical integration of value chains in China. The development trajectory of the PV industry in China indicates that innovation in cleaner energy technologies is no longer a national process but a global one.

The effective coordination of PV innovation systems along the global PV value chain and China's role as the green factory greatly reduced the costs of PV modules, which made PV technology nearly reach grid parity before the United States imposed import tariffs. Trade protectionism in clean energy innovation is likely to delay the innovation process and stall further cost reductions, which would impede the global clean energy transition and long-term GHG emission reductions. The findings indicate that harmonized global clean energy policies would accelerate future global clean energy development.

8

Messages for policymakers

Based on our findings, the following global and national policies are recommended to policymakers interested in stimulating the development of the solar PV industry as well as deployment of PV modules.

At the global level, the following interventions need to be considered:

- **Long-term market formation policy is required for PV industrial development.** The global scaling up of markets allows for a more rapid diffusion of technologies, and relatedly, a reduction in the costs of technology. In clean energy markets, "big is beautiful." With more commercial experimentation, the establishment of an industrial base, increasing standardization, and mass production to meet new demand, costs may fall through economies of scale and learning (Gallagher, 2014). The PV industry case shows that the scaling up of market formation in Europe, Japan, and the United States incentivized the global diffusion of PV technologies. China licensed foreign technologies, imported equipment, and exported panels to foreign markets, which in turn greatly drove down the cost of solar panels. The stability of the market formation policies may be more important than the size of the subsidy provided so that manufacturers can count on markets for the medium-to-long term.
- **National policies may benefit from global harmonization.** In the case of the PV industry, the cooperation and interaction of national innovation systems and the global innovation system along the global PV value chain was the fundamental driver for the rapid cost reduction of PV technology. Market standardization makes it easier for manufacturers to supply multiple markets and achieve greater economies of scale.
- **Promote free trade in clean energy technologies.** To further increase competitiveness of PV technology, policymakers should deepen the global cooperation process by keeping global markets for solar PV open in order to promote technology diffusion. Recent protectionist policies and trade conflicts not only slow the development of global markets for solar PV related goods and services, but could also provoke retaliation measures in other clean technology sectors. Such an outcome would not only harm the global trade system but also slow the effort to combat climate change.

- **International interventions are needed to facilitate cross-border investments, trade, and labour mobility, as well as international R&D cooperation**. Clean energy innovation is no longer a national process, but a globalized process. Global cooperation between private and public entities, industry and the academy, and among governments will contribute to the global clean energy innovation process.

At the national level, the following recommendations are made for consideration by policymakers:

- **Open markets rather than protectionism will accelerate the diffusion of PV technologies**. According to our analysis, China's strength in the PV industry came from its optimal manufacturing capacities and vertical integration strategy, not just substantial subsidization. Chinese entry in global PV manufacturing benefited the world in terms of improved consumer welfare, climate change mitigation, and reduced global PV prices. Though facing Chinese competition in the manufacturing chain, the United States and European countries still dominate in the high value-added segments of the global PV industry due to their strength in innovation and entrepreneurship, and gain even more from the price reductions and resulting increased market demand.
- **Stable and growing market formation policies are needed both in developed and developing countries.** There are two functions a market formation policy can serve. The first is to encourage private investment into technological development and deployment. The second is to encourage a global learning network among various stakeholders. Now that China has emerged as a PV manufacturing factory, it can further speed up domestic PV deployment through stronger market formation policies at home. And for developed countries, more ambitious clean energy strategies are also needed in home markets because policy uncertainties present a challenge to domestic manufacturing (Pew Charitable Trust, 2013).
- **R&D support in developing countries should be emphasized as part of the clean energy innovation system.** Human resource and R&D investments will not only increase the adaptive capacity in developing countries, but also increase developing country firms' confidence and bargaining power when they are buying foreign technology.
- **If overcapacity occurs, let the market take care of the surplus supply.** Overcapacity emerged in the Chinese PV industry in recent years, which contributed to the low prices offered by Chinese manufacturers. The low prices were already imposing discipline on the market before U.S. tariffs took effect.

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Author contact information:
Kelly Sims Gallagher and Fang Zhang
Tufts University
kelly.gallagher@tufts.edu
zhangfang0403@gmail.com
http://fletcher.tufts.edu/CIERP

Project contact:
Lachlan Cameron
ECN
T +31 88 515 4227
cameron@ecn.nl
www.ecn.nl