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Understanding the dynamics of global value chains for solar photovoltaic technologies

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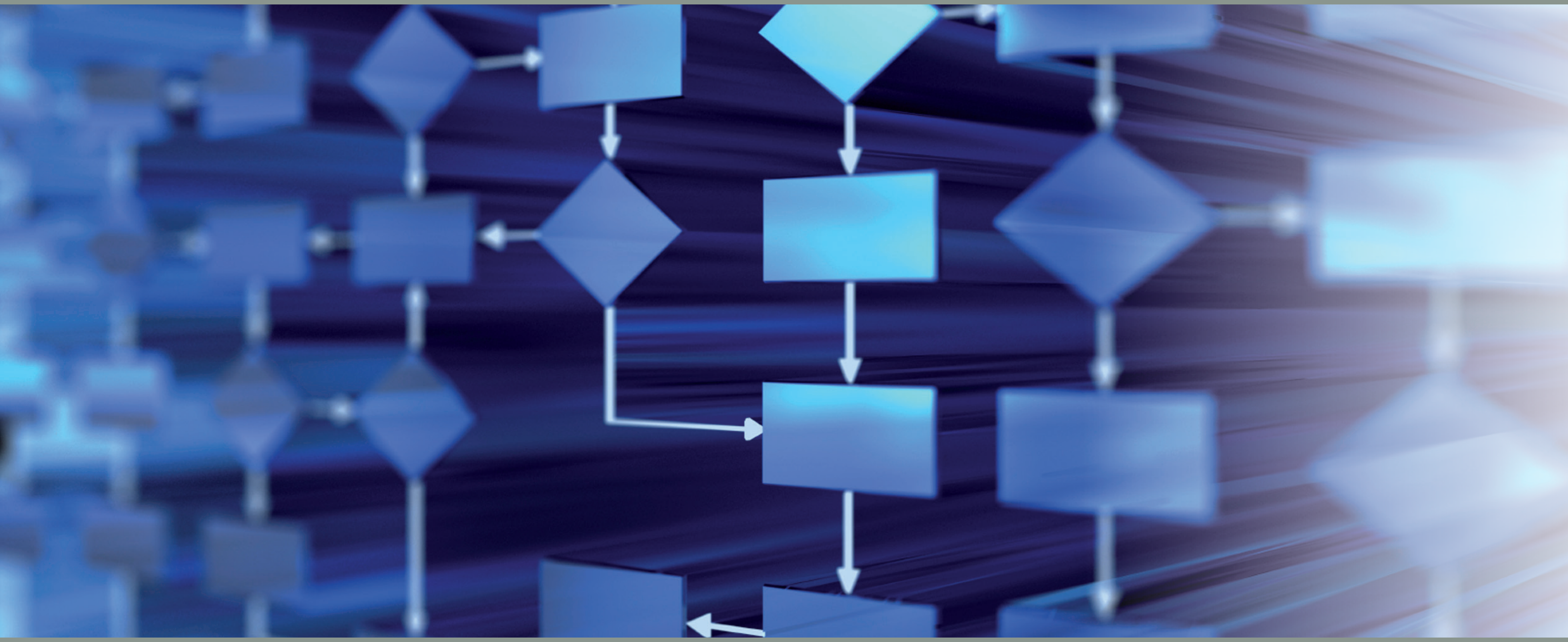

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Abstract

The solar photovoltaic (PV) industry has experienced a massive spatial shift in its global value chains over the last decade. This paper seeks to understand how this shift has occurred and its drivers, with a specific focus on the role of intangible assets and intellectual property (IP). While the value chain for solar PV technologies was initially concentrated in US, Germany and Japan (where the majority of patenting occurred), the technology transfer of production equipment to China through turnkey fabrication lines led to an 85% price drop since 2009. This established crystalline PV as the dominant 'product innovation' in solar PV and led major solar PV manufacturing firms to exit the market, inducing a geographical consolidation of manufacturing in China. In this market characterised by tight profit margins for surviving firms, innovation has focused on reducing production costs, rather than developing new products, leading to a decrease of patenting activity globally.

However, companies which survived the price collapse have increased their patenting activity recently, in particular in alternative technologies to the dominant design, suggesting a renewed interest in IP protection in these times of sectoral reshaping. While IP protection of intangible assets was not a key determinant in the success of Chinese companies, nor did it protect incumbent firms in developed economies from the competition of Chinese firms, it might well become a key ingredient for commercial success in the coming decades, if alternative technologies to crystalline PV cells finally make their way to the market.

Keywords: Solar photovoltaic; global value chains; process innovation; technology transfer; China; intellectual property.

JEL: O31, O33, Q40 and Q55.

Disclaimer

The views expressed in this article are those of the authors and do not necessarily reflect the views of the World Intellectual Property Organization or its member states.

1. Introduction

China now dominates the global solar photovoltaic value chain while, fifteen years ago, most of the demand and supply for PV systems were located in a handful of developed economies, in particular the US, Japan and Germany. This process has induced drastic price decreases (-85% since 2009) which allowed governments to reduce the subsidies provided downstream to solar power project developers (Lazard, 2016). Despite booming demand, it also led to the exit of several western and Chinese companies, and fierce competition between the survivors.

This paper seeks to understand how this spatial shift has occurred and its drivers, with a specific focus on the role of intangible assets and intellectual property. We also examine the role of innovation in the new competition regime.

The study is based on a review of the grey literature and academic studies – in particular, works by the authors (Carvalho, 2015, and De La Tour et al., 2011) – complemented by in-depth analyses of patent and industry data as well as by interviews of industry players, patent examiners and IP professionals.

In the first section, we describe the evolution of the value chain. We then examine the channels through which Chinese players have acquired the necessary knowledge and intangibles to enter the market. The last section deals with innovation. In particular, we examine the causes of the apparent decline of innovation in the recent period and the role that patents play in the new business environment that emerged from the major changes that the industry has recently been through.

2. The nature and evolution of international supply chains

2.1. The technology

Like many technologies, it was an incidental discovery that led to the initial development of solar PV as a niche technology for electricity generation. Russell Ohl, a scientist at Bell Laboratories in New Jersey, USA, discovered that shining light on a mono-crystalline material registered on a voltmeter[1] in the early 1940s (Perlin, 1999). Ohl was not the first scientist to discover a material that conducted electricity (known as the semi-conductive effect) when exposed to sunlight. The earliest noted incident was almost a century earlier by Edmund Becquerel in France, when he noted a similar effect when an electric current was produced when two metals immersed in a liquid were exposed to sunlight (Fraas, 2014). Though several scientists did manage to produce PV cells from different materials between the discoveries of Becquerel and Ohl, it was really the scientists at Bell Laboratories who developed the first crystalline PV cell (Fraas, 2014; Perlin, 1999).

There are now four different families of solar PV cells. First are wafer-based crystalline PV cells, which are further divided into either PV cells produced from a single crystal growth method (i.e. monocrystalline PV cells), or a cast solidification process that produces multiple, smaller crystals (i.e. multi-crystalline PV cells). The second category of PV cells are thin-film cells, which are produced by depositing very thin layers of semi-conductive PV material onto cheaper backing materials such as glass, plastic or stainless steel. Thin-film solar PV technologies have managed to commercialize alternative materials to crystalline PV, like

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[1] A device that measures electric potential (measured in volts).

cadmium telluride (CdTE) and copper indium gallium selenide (CIGS). Both crystalline PV and thin-film PV cells account for the majority of the terrestrial PV market, with crystalline PV accounting for over 90% of land-based PV systems (IEA, 2016b; SEMI PV, 2017).

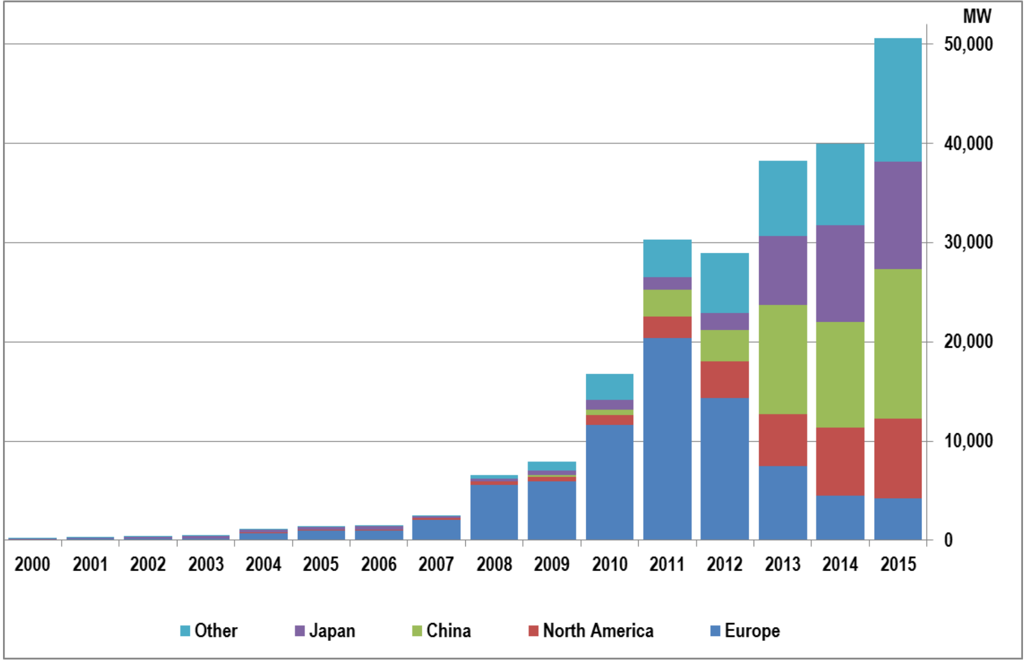
The next two families for PV cells are not yet commercialized, but do show promise. High efficiency cells (often referred to as Group III-V PV cells) are made from gallium arsenide (GaAs) on Ge substrates, and were first developed for space applications (IEA, 2016b; NREL, 2017a; Perlin, 1999). These PV cells can use either one PV cell (single p-n junction) or two types of PV cells (multi-junction) to capture a greater range of wavelengths of light, thereby increasing a cell's efficiency. Due to the high costs of materials and production of these PV cells, terrestrial systems involve using a single Group III-V PV cell which is mounted within a series of mirrored reflectors that concentrate sunlight onto the cell (a.k.a concentrated PV, or CPV). This device is then mounted onto a solar tracking device that ensures that the system conducts electricity for as long as possible. The final family of solar PV cells that is showing interest at the R&D stage are PV cells made from organic materials. Their potential lies in its dependence on low-cost materials and in the flexible nature of the material which implies the ability to be integrated onto multiple surfaces (NREL, 2017a), such as windows and other building surfaces. However, organic PV cells are generally still at the lab stage where researchers are largely working on ensuring these cells produce stable amounts of electricity.

High efficiency cells (multi-junction and single-junction cells) have achieved power conversion efficiencies that are much higher than the commercialized crystalline PV technologies, while certain types of thin-film PV cells that are not yet commercialized have now reached power efficiencies that are similar to commercialized crystalline PV cells (NREL, 2017a). However the difficulties for these technologies to come to the market are due to: (1) ensuring that these PV cells generate electricity reliably and stably in non-laboratory settings; and (2) that the production costs are below the current market prices for commercialized PV technologies in order to be cost-competitive. The latter reason is especially important in understanding why even high-efficiency cells, or organic cells that come from less expensive materials, will have a hard time competing against commercialized PV technologies even if these PV cells manage to overcome the initial challenge of performing in field settings. This challenge is due to the problems of scaling production to compete with crystalline PV – which was not theoretically the most attractive technology because its maximum theoretical efficiency is only 30%, which is much lower than lab-tested high efficiency cells which currently reach 50% efficiency (N.J.Ekins-Daukes, 2013; NREL, 2017b).

2.2. The demand

As shown in Figure 1, the demand for PV systems has experienced an exponential growth since 2000. In 2016, installations of new capacities increased by 34% on last year's installations, and the growth rate was even +126% in China. Until 2011, this growth mostly occurred in Europe. The demand is more evenly distributed since then, with China now being the largest market.

Figure 1: Market demand for solar PV installations (represented by annual PV capacity additions)

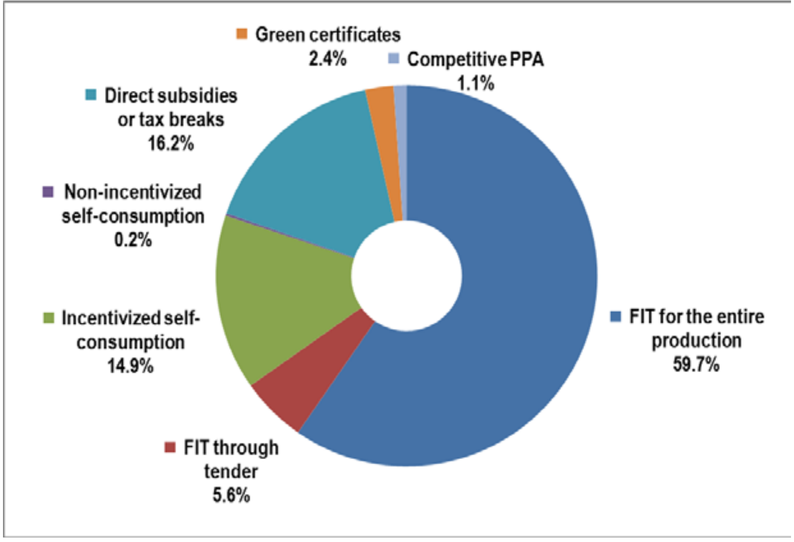


Source: IEA (2016)

The development of solar PV markets have been largely been driven by government support policies. Historically, regulators have mostly used feed-in-tariffs to accelerate investments. FITs still drive around 65% of the PV market in 2015 (Figure 2). This mechanism works by setting guaranteed prices at which grid operators are obliged to buy electricity from solar energy sources. Solar PV generated power is offered a higher price relative to other conventional sources, reflecting higher costs. Increasing cost-competitiveness of solar PV technologies have more recently allowed solar PV projects to engage in post-subsidy schemes, such as competitive tenders where solar PV developers submit bids to governments to develop power generation projects. The government then agrees to a power purchase agreement (PPA) to the winning bids. The decrease in solar PV prices has led some of these projects to be cost-competitive in markets with high electricity prices, leading to incentives to install solar generation for self-consumption.

PV systems can be used to provide electricity the size of conventional power plants – known as utility-scale generation. This utility-scale generation can act as a power plant generating electricity for the grid. Alternatively, large industrial plants, or other loads (e.g. data storage centers) can directly generate utility-size electricity from their own PV systems solely for their self-consumption, or offset some of the electricity supplied from the grid. Smaller-scale PV systems can be used for residential or commercial uses, and these too can be connected to the grid or be used solely for self-consumption (particularly in remote areas where grid infrastructure has yet to reach). Any PV system that is purely used for self-consumption needs to rely on batteries, or to be hybridized with other fuel sources, to ensure steady amounts of electricity are provided throughout the day. Table 1presents these different market categories.

Figure 2: Solar PV market incentives and enablers for 2015

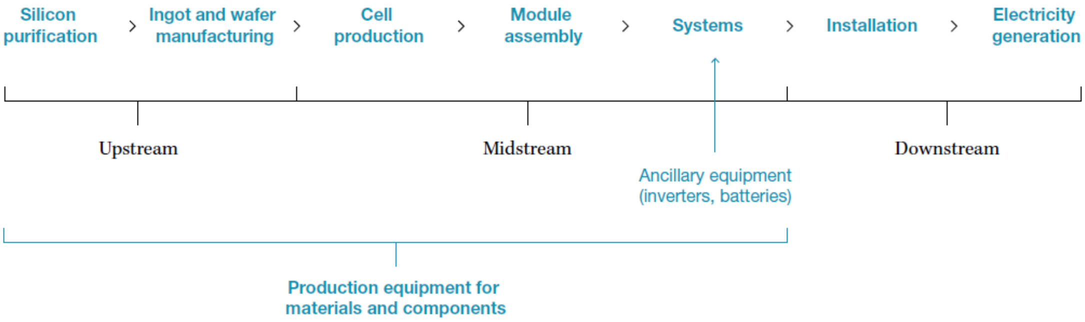


Source: IEA (2016)

Table 1: Categories of PV market types and applications

Categories	Applications	Grid-connected		Size of PV system	
		Grid-Connected	Off-grid	Utility	Distributed
Grid-connected, utility-scale generation	Power generators, industrial users	X		X	
Grid-connected, distributed energy	Residential & commercial buildings	X			X
Off-grid, utility- scale generation	Industrial users; remote communities	X			X
Off-grid, distributed energy	Residential & commercial buildings, including with remote communities; remote, niche applications (ranging from small calculators, to off-shore oil rigs, to space applications		X		X

Figure 3: Crystalline PV supply chain production stages



2.3. The supply

Figure 3 presents the supply chain of crystalline photovoltaics, the technology which accounts for over 90% of the PV market (IEA, 2016b; Schmela et al., 2016). The production process involves five main stages:

1. Silicon purification from silica (SiO2) found in quartz sand. The ultra-high purity required for the photovoltaic industry (> 99.999% pure) is obtained through heavy and highly energy-consuming chemical processes. Polysilicon is material not just used for crystalline PV, but actually for the semiconductor industry (used for microchips, etc.). However the demand of polysilicon for crystalline PV is so high that 90% of polysilicon production now goes to the PV industry (Schmela et al., 2016).

2. Ingot and wafer manufacturing. An ingot – a cylinder or a brick of silicon – is grown from the pure silicon. It can be a single crystal, called monocrystalline silicon or monosilicon, or multiple silicon crystals that are smaller; a material called polycrystalline silicon or polysilicon. Then, using a saw, ingots are sliced into thin layers called wafers. Secondary processes like polishing are involved.

3. Cell production. To form the cell, two differently doped wafers are assembled together to form a so-called p-n junction responsible for the photovoltaic effect, and the top and rear metal contacts are applied. Many treatments or modifications in the process can be applied to increase the efficiency.

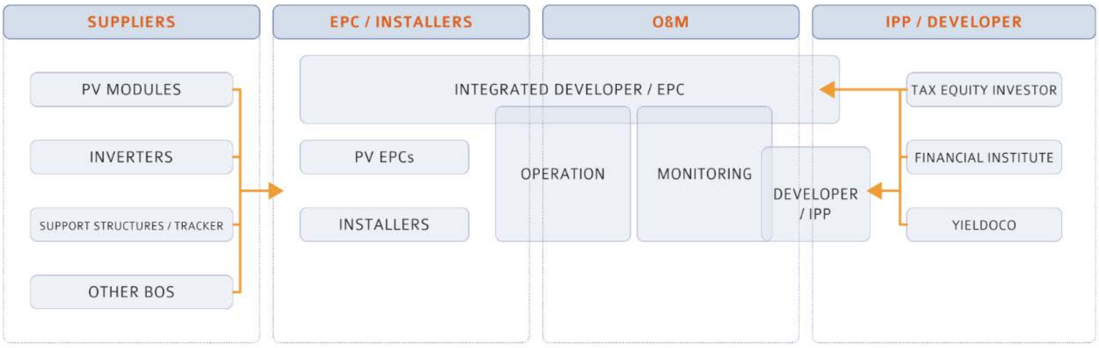
4. Module assembling. Cells are soldered together, the electrical junction being done by hand or automatically, and the cells are encapsulated in glass sheets to form a module which will be cooked in a laminating machine.

5. Systems. The modules are combined with complementary equipment (such as batteries or inverters) to deliver electricity to the loads (electricity consumption devices or to the electricity grid).

Importantly, these production steps rely on production equipment which has played a crucial role in the spatial transfer of technology in the PV industry.

The downstream parts of the supply chain focus on the market services involved with actually installing, operating, and financing PV systems (Figure 4).

Figure 4: Downstream: Providing demand-side services in developing solar PV markets



Source: IEA (2016)

The organization or the PV value chain has changed dramatically in the last decade, with a massive relocation of upstream and midstream activities to China and, to a lesser extent, to Taiwan (Province of China).[2] Until 2004, demand was largely concentrated in Europe where governments gave generous support for accelerating the deployment of PV capacities. This created powerful economic signals in countries with a strong semiconductor industry which initially became leaders in providing production equipment for crystalline PV technologies (Germany, Switzerland, Japan, and US). From 2015 onwards, China and Taiwan (Province of China) became leaders in midstream and upstream segments (wafers, ingots, cells and modules) while demand remains mostly located in Europe. They also entered the silicon market. This led to overcapacities, drastic price decreases from 2010 onwards and the exit of many western upstream and midstream firms. We will now describe this process in detail.

Upstream and midstream segments

Figure 5 presents the evolution of country market shares in the ingot, wafer, cell and module segments and demonstrates the success of Chinese firms which now supply more than 80% of the global market in most of these segments at the end of the period.

Though China did achieve dominance across most of the upstream and midstream parts of the crystalline PV supply chain by 2011, both developed and developing countries did manage to increase their production between 2005 and 2011 to meet a booming demand for PV systems. Germany, Japan, USA and India did triple their production capacities for upstream and mid-stream parts of the crystalline PV supply chain between 2005 and 2011 (Chase, 2014). Recall that the PV industry is booming – as an illustration manufacturing capacity of ingots and wafer grew by 9590% and 3991%, respectively, between 2005 and 2012 – and capacities are not only created in China. The growth is simply exponentially larger and faster in China.

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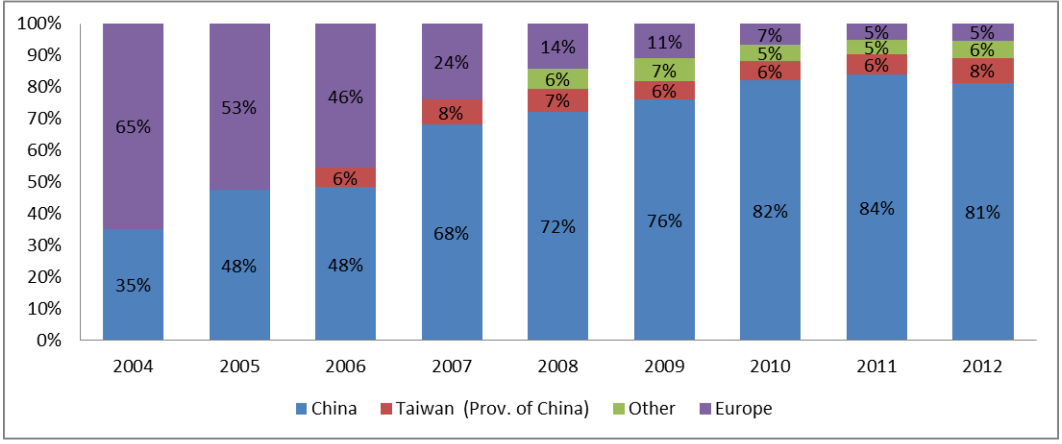
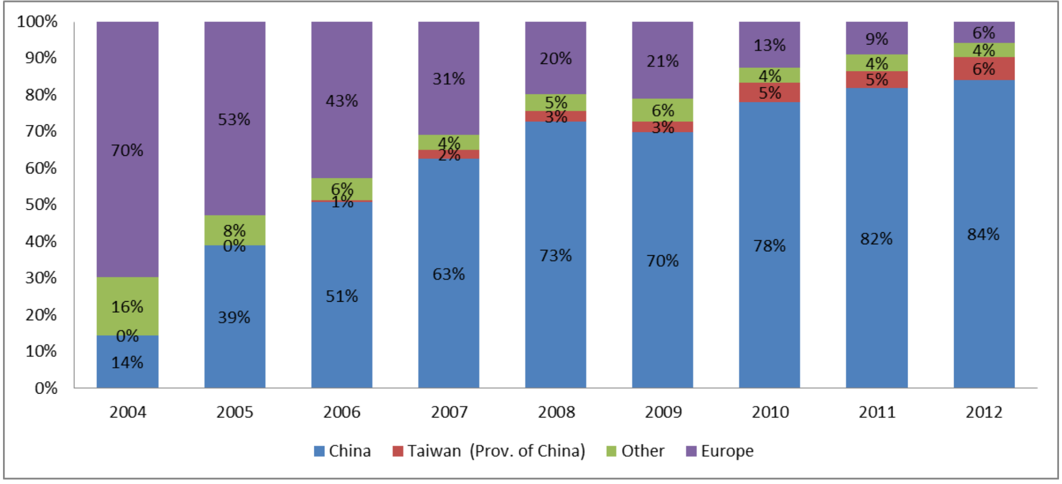
[2] See Chase (2014) and ENF (2012, 2013a and 2013b)

Figure 5: Distribution of manufacturing capacity in the different segments (% of global manufacturing capacity)

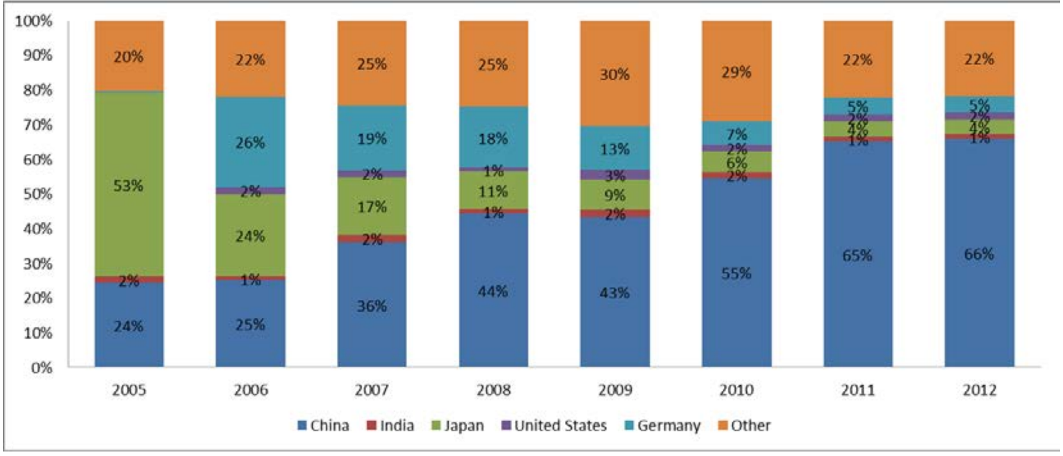
5a – Ingots (source: ENF, 2013b)



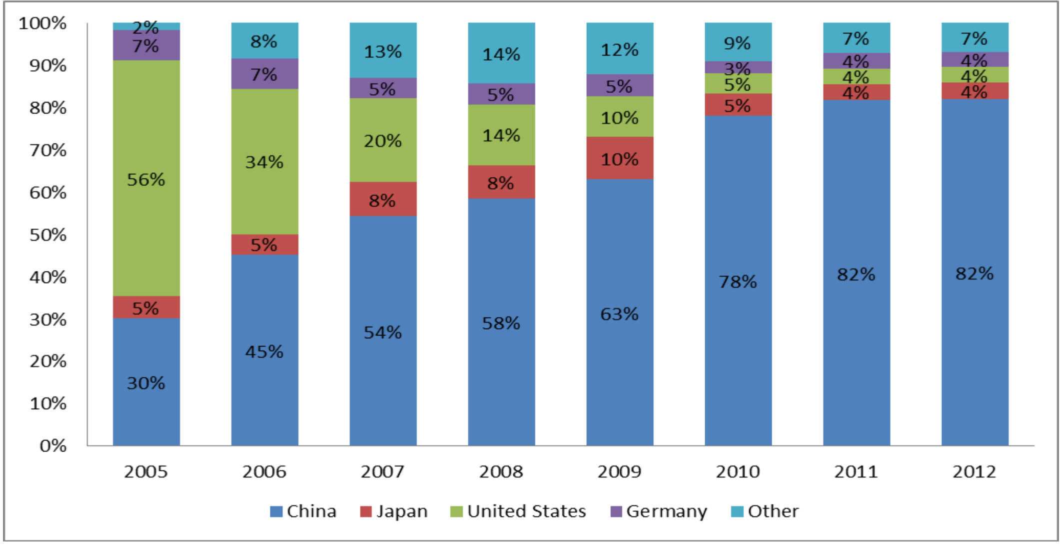
5b – Wafers (source: ENF, 2013b)



5c – Crystalline PV cells (source: BNEF, 2013)

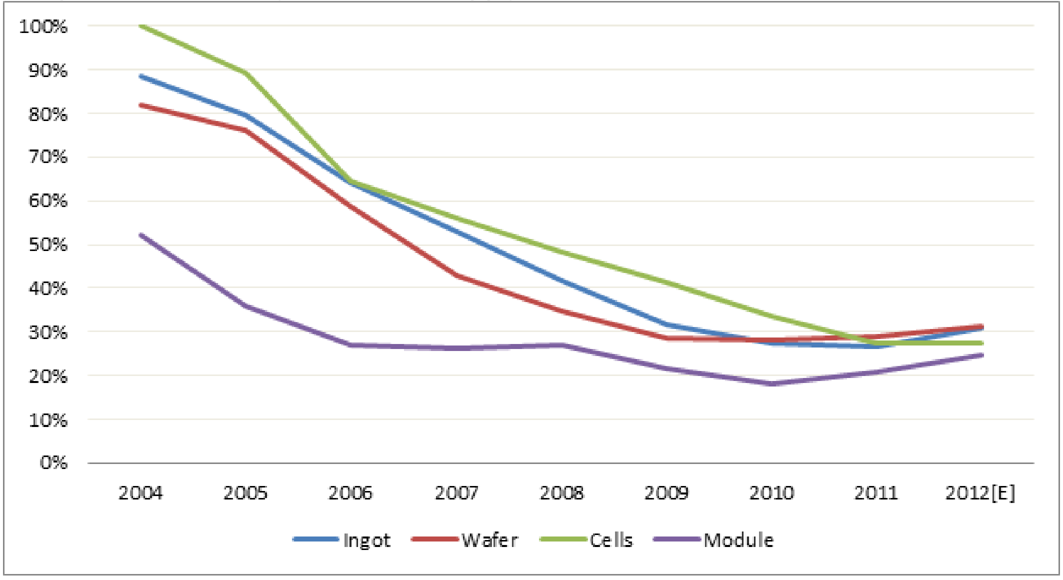


5d – Crystalline PV modules (source: BNEF 2013)



Market entry induced more competition as demonstrated by Figure 6, which shows the evolution over time of the market share of the top 5 producers for each year. In 2004, the different markets were oligopolies with the five largest players supplying most of the global production (between 80 and 100%, except for the module segment). In 2012, the share of top 5 producers was down to around 30% in the four segments.

Figure 6: Top 5 companies' market share for upstream and mid-stream components of the crystalline PV supply chain



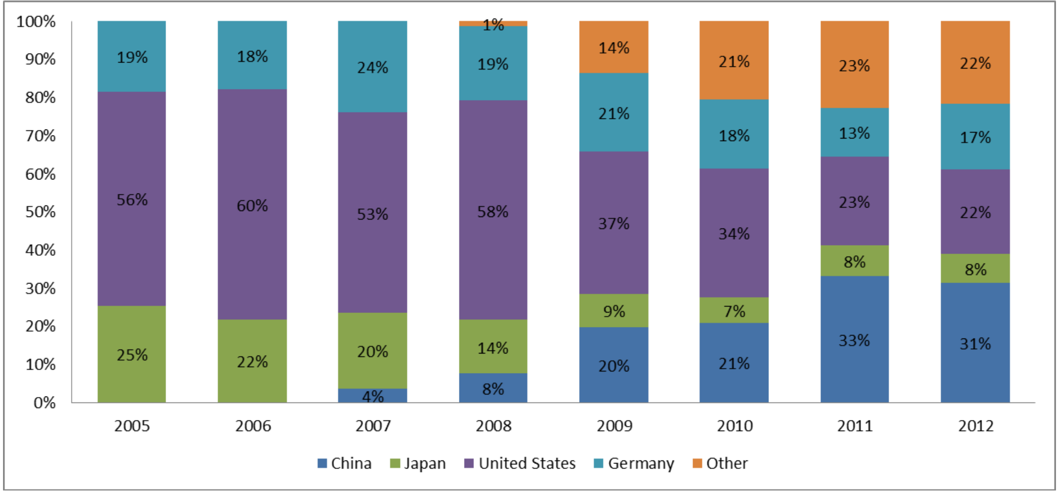
Source: ENF (2013a, 2013b)

Polysilicon production

In contrast with the other upstream and midstream segments, silicon purification requires advanced technologies and very specific know-how to control all the parameters of the chemical reactions, in order to be able to produce silicon at a competitive price. This may explain why Chinese firms were slightly less successful in this market although they represent around 30% of the global market in 2011 (see Figure 7 below). This increase in production brought down the price of polysilicon from its high of over $470/kg in 2008 to $25/kg in 2015 (IEA 2016c). These price decreases led to the closure of many plants, particularly in China, who did not have the cost structures to compete at such low prices for polysilicon (Chase, 2013). Nevertheless it should be noted that most of the polysilicon is produced and consumed for downstream players in China (ENF, 2013b).

IEA (2016c) notes that despite the continued level of overcapacity, new manufacturing plants for polysilicon production come online in the USA (e.g. Wacker Chemie) and South Korea (OCI). Opening new polysilicon plants was permitted by installing more cost efficient production equipment, that can maintain companies' profitability against other polysilicon competitors. Two major production processes are used for polysilicon production: the Siemens process and the fluidized bed reactor (FBR) process (SEMI PV, 2017). As the production of polysilicon is electricity-intensive, a large part of decreasing costs lies in improving the energy efficiency of these processes, with FBR processes being more efficient than the Siemens process. IEA (2016c) estimates that energy consumption improved by 7% per year between 2010 and 2015, going from 80kWh/kg to 55kwh/kg in that time period. Companies in USA, Canada and Norway are trying alternative and proprietary metallurgical processes to reduce energy and production costs of polysilicon as a way of competing against the decrease in spot market prices. Another way in which companies could reduce electricity costs was to locate plants close to places with low electricity prices.

Figure 7: Country distribution of manufacturing capacity of polysilicon (% of global manufacturing capacity)



Source: BNEF Database

Downstream: Installation and solar service business models

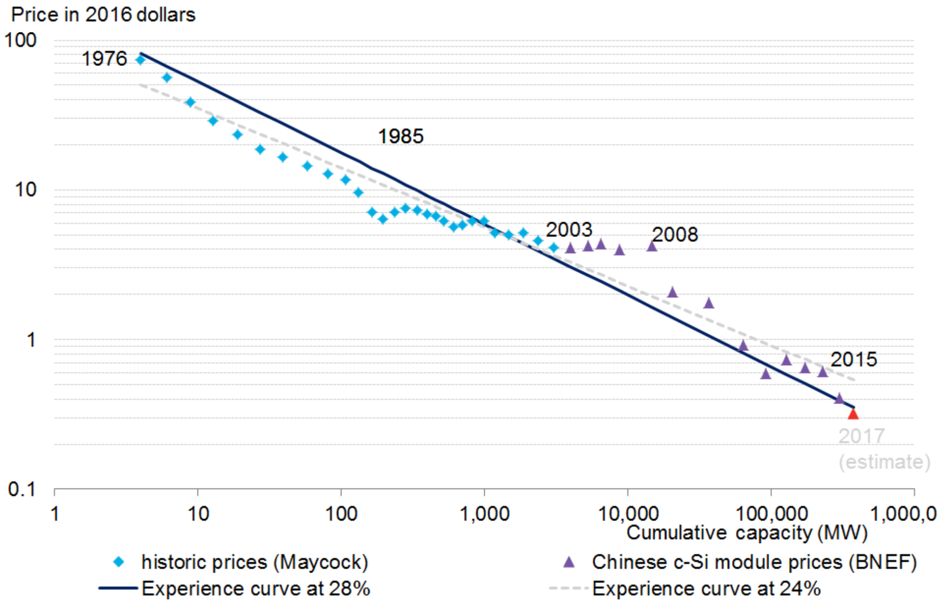
Solar PV manufacturers are increasingly moving to downstream parts of the supply chain involved with market development. This trend was initially observed during the financial crisis of 2008/2009, when orders for solar PV technologies were being cancelled due to the inability of solar PV project developers to obtain financing from banks (Chase, 2013). Prior to the crisis, most developers for solar PV projects obtained bank loans. Banks were willing to finance solar PV projects (along with other renewable energy projects) because the policy regimes provided price-guarantees for at least 20 years or more.

However the 2008/2009 financial crisis hit the liquidity of banks to provide loans to project developers, who then had to cancel their orders for solar PV technologies. Supply-side solar PV companies who had enjoyed high profits up to this time were facing cancellation of their orders, and could not re-sell them to other project developers. These supply-side companies that had strong balance sheets started moving downstream to project development in order to support demand for the upstream parts of their business. Currently, many upstream and mid-stream solar PV companies have consolidated with downstream parts of the market (IEA, 2016b).

2.4. Price history

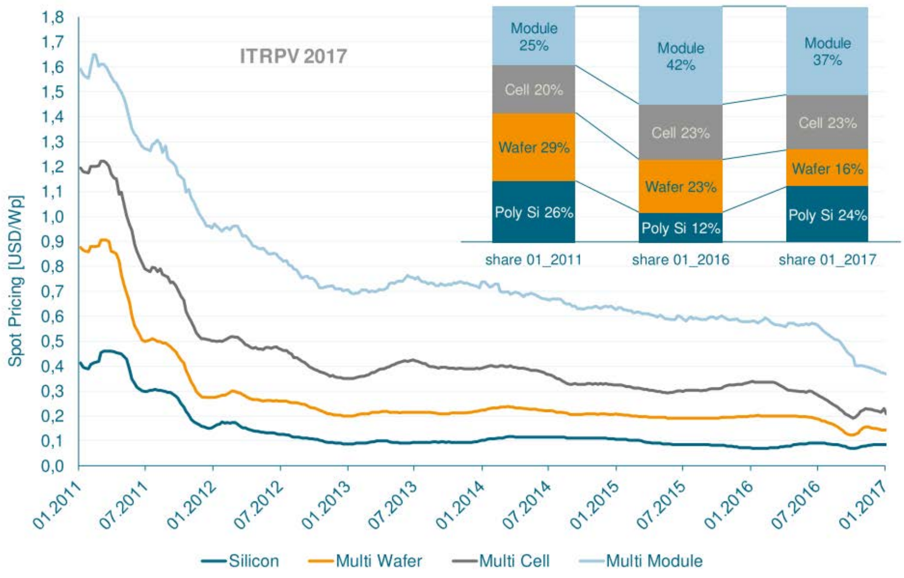
The dramatic decrease in costs of solar PV projects occurred from 2008 onwards (see Figure 8 below). BNEF (2016) estimates that solar PV module prices have decreased by over 80% between 2008 and 2015, with estimated price reductions of 26% for each doubling of capacity.

Figure 8: Solar PV module price reductions, 1976-2012 (USD/Watt)



Source: BNEF (2017)
Note: Prices inflation indexed to US PPI.

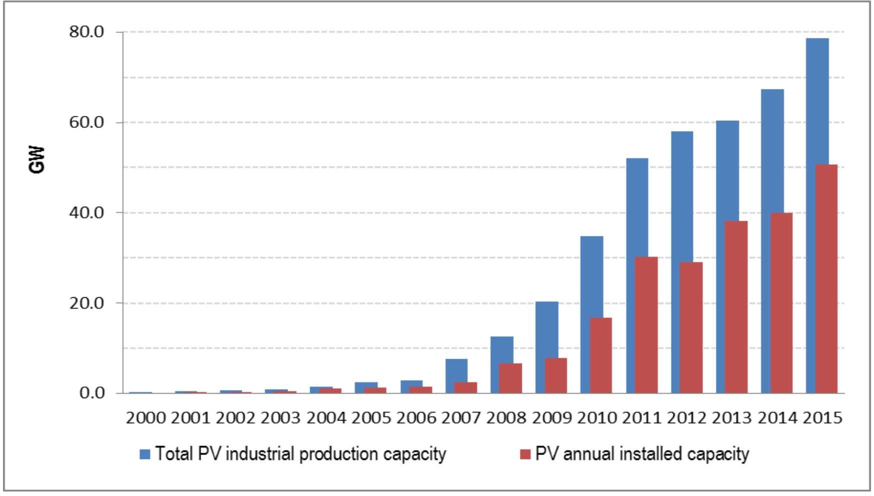
Figure 9: Percentage of Price of Multi-Crystalline PV systems attributed to individual components.



Source: SEMI PV (2017)

The recent decrease in prices concern all solar PV components (Figure 9). It is largely due to changes in scaling of production and the resultant oversupply of components (Figure 10), and to a lesser extent, improvements in production efficiencies. For example, innovation for ingots and wafer has been done through improving high level process innovations of the production equipment installed in factories. For ingots, this is done by growing larger sized crystals and improving the seed crystals needed to improve process time and increase yield (IEA, 2016b). Other production equipment improvements that can enable cost savings include improving the cutting of ingots into thinner wafers, reducing loss of unused ingot material (known as kerf), increasing recycling rates, and reducing consumables (IEA, 2016a; SEMI PV, 2017). Other process innovations involve finding ways to reduce the amount of metallization pastes/inks containing silver and aluminum, which are the most process-critical and most expensive non-silicon materials used in current c-Si cell technologies (SEMI PV, 2017).

Figure 10: Level of solar PV industrial capacity is greater than market demand



Source: IEA (2016)

2.5. Trade restrictions

Such price falls caused competitive pressures against American and European solar PV companies – who had enjoyed significant profits prior to 2008 – leading to an increase in bankruptcies and acquisitions in 2011 and 2012 (Wesoff, 2015).

As a result, solar PV manufacturing associations in both US and Europe petitioned their respective governments to impose tariffs against Chinese solar PV products (Ghosh, 2016). Their justification was that Chinese solar PV firms benefited from subsidized loans from their government that allowed them to not only set up their production facilities, but to sustain production even when market prices went below the costs of production (Goodrich, James, & Woodhouse, 2011). These justifications led to both the US and EU governments imposing anti-dumping duties against different Chinese crystalline PV products in 2012 and 2013 respectively. Both the US and the EU have extended these duties against Chinese solar PV products so that these duties are currently still in place (Schmela et al., 2016).

Furthermore, other countries who have set up market support mechanisms for solar PV have invoked local content requirements. Local content requirements require a certain percentage of technologies used for local PV markets to be sourced from local manufacturing facilities. These kinds of local content requirements exist in India, South Africa and Canada’s Ontario (though Ontario had to eventually revoke it following a WTO trade ruling) (Johnson, 2013)

Chinese firms have partially by-passed these trade barriers by setting up manufacturing plants in Malaysia, Thailand, India, Vietnam, the Netherlands, Germany and Brazil (Schmela et al., 2016). These manufacturing plants are used to serve the domestic markets in these countries, but also as export bases to other markets that currently have duties against them. The importance of political economy factors, such as how trade restrictions affect market access, can play an important role in geographical changes in the global supply chain.

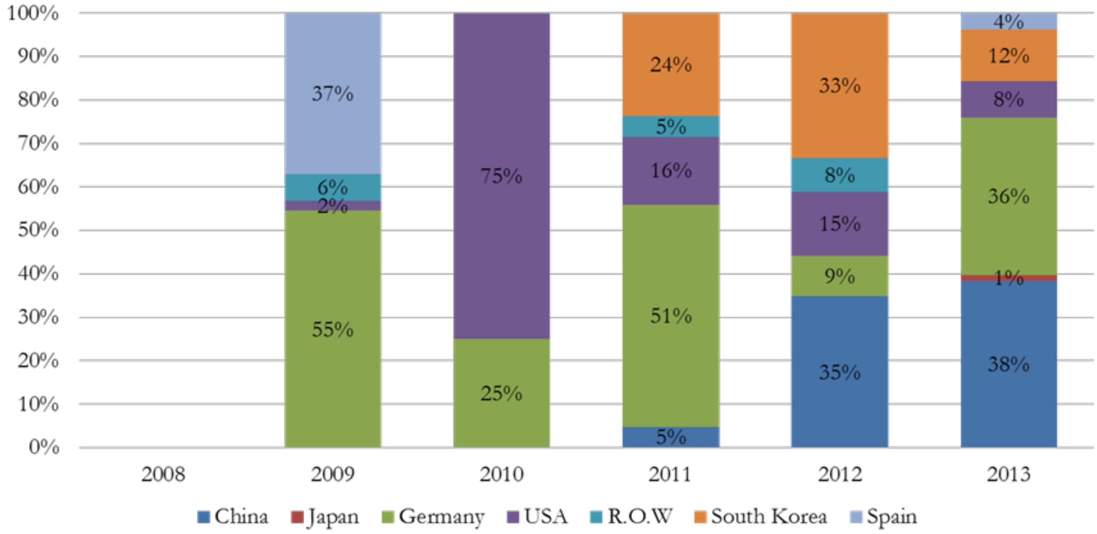
3. Value capture and the role of technology transfer

3.1. Value added

As can be expected from the trends presented in the previous section, the distribution of the added value of the PV value chain has drastically changed in the last decade. Before 2011, generous subsidies in Europe maintained prices well above production costs in all segments of the value chain (which can be seen in Figure 8 above). As a direct consequence, the relocation of most of the upstream and midstream activities in China that occurred during this period entailed a transfer of a significant share of the economic surplus to this country. Most of the downstream activities – which tend to be more profitable – remain located in industrialized countries, particularly in Europe.

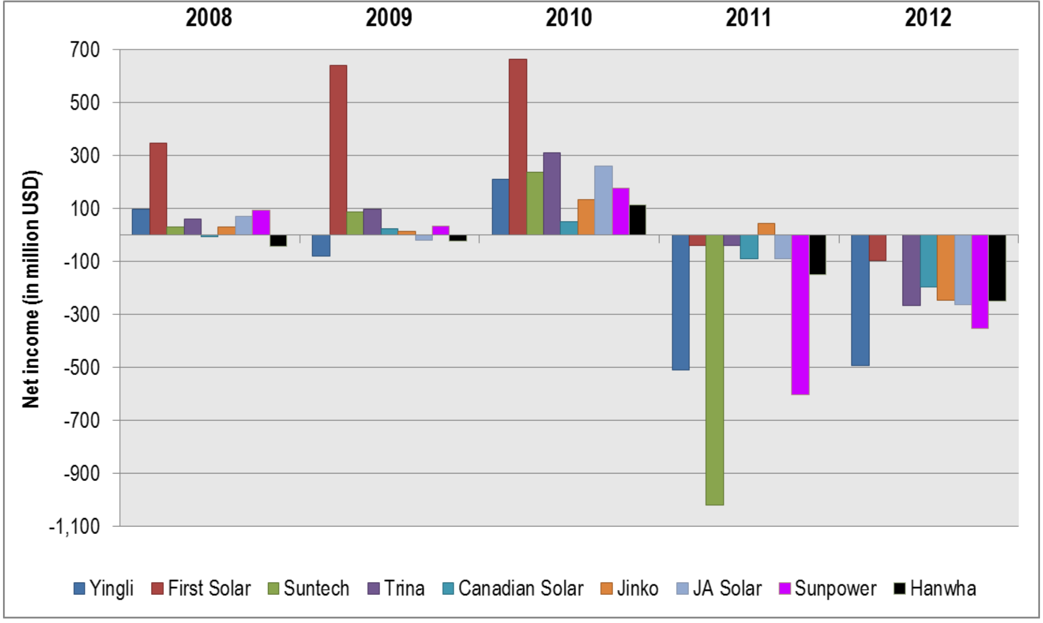
Following the price downturn in 2011, upstream and mid-stream players experienced decreased profit margins that made it difficult for companies involved in these parts of the supply chain to survive, leading to several bankruptcies of companies that could not compete against these price margins. Figure 11 shows the decommissioning of crystalline PV cell capacity over time and across countries. Figure 12 shows the evolution of the net profits of the top cell/module manufacturers between 2008 and 2012. As can be seen, all players started losing money in 2011. In 2012, Q-Cells, a major German-based cell manufacturers which led the market in most of the 2000’s, went bankrupt and was then bought by the Korean Hanwha. The Chinese leading PV firm Suntech also defaulted in 2013, leading to a complete restructuring of its activity.

Figure 11: Manufacturing capacity of crystalline PV cell (% of global manufacturing capacity)



Source: Carvalho (2015a)

Figure 12: Net income of key midstream manufacturers (2008-2012)



Source: SEC as in Zheng and Kammen (2014).

Since then, the situation is less severe, but still complicated. Table 2 displays the EBITDA margins of the major PV companies in 2015. Several companies operating in different segments (REC Silicon, Centrotherm Photovoltaics) continue to face serious difficulties. In general, midstream firms’ EBITBA margins fall short of the average in the semiconductor industry (26.5% for the S&P500 firms in 2015). Both IEA (2016c) and SEMI PV (2017) argue that the only ways in which companies in the upstream and mid-stream parts of the PV supply chain could survive is through high-level process innovations that could reduce the production costs of each material/component against their competitors operating in the same part of the supply chain, and thereby increase profit margins.

First Solar provides an interesting illustration. The company specialized in thin-film cells that account for a minor share of the market (7% in 2015) and is the most profitable midstream company (see table 2). What drives commercial success is being able to manufacture PV components below the market price of individual components in the value chain, and the production costs of competitors for the same components. This explains why First Solar is one of the most profitable and integrated PV firms in the industry, as their thin-film PV cell has power conversion efficiencies that are reaching crystalline PV levels (see Figure 16), and their production costs are substantially below the retail market prices for crystalline PV (see Figure 8). First Solar's ability to maintain such comparative advantage is through other companies not knowing how to reproduce the same product (a PV cell made from cadmium telluride materials) and using their specialized production equipment is based on maintaining its intellectual property rights. They were able to capitalize on the 'window of opportunity' to attract, scale and commercialize their technology when solar PV technology prices were high (Carvalho, 2015a).

Table 2: Profitability of major PV firms in 2015-2016

Company	Market segments	EBITDA margin
GCL-Poly Energy	Silicon / wafers / power projects	25% (2015)
Wacker	Silicon production / other chemicals	19.8% (2015)
REC Silicon	Silicon production	-4%(2015)
OCI Company	Silicon production / other chemicals	7.4% (2015)
First solar	Cells / modules / power projects	21.6% (2015)
Trina	Ingots / wafers / cells / modules	5.54% (2015)
JA Solar	Cells / modules	7.55% (2015)
Canadian Solar	Ingots / wafers / cells / modules / power projects	8.01% (2015)
Jinko Solar	Wafers / cells / modules / power projects	10.6% (2016)
SunPower	Cells / modules / power projects	6.36% (2016)
Applied Materials	Production equipment	25.2% (2016)
Centrotherm Photovoltaics	Production equipment	-10.7% (2015)
Sungrow	Inverter	10.6% (2015)
SMA Solar	Inverter	11.3% (2015)
SolarEdge	Inverter	10.3%(2015)

Source: Author's research on annual reports of companies

As previously explained and indicated in the second column of Table 2, several upstream and midstream players – GCL, First Solar, Canadian Solar, SunPower, Jinko Solar – have integrated downstream activities. Low market prices for upstream and mid-stream parts of the value chain actually mean that a greater part of the value has gone to downstream parts of the value chain involved with market development. Most financing for solar PV projects is through debt financing from banks, and therefore subject to interest rates (which account for a significant part of the solar PV project). Interest rates are determined not just by market risk, but also by technological risk – and therefore it becomes important for solar PV project developers to source solar PV technologies from recognised players, who are considered 'bankable' because they have demonstrated well-functioning technologies in the market, providing stable electricity generation, and project yields. One of the ways in which upstream and mid-stream companies have managed to maintain their brand is by moving downstream to project development to demonstrate how well their technologies function in the market, thereby building a so-called ‘Tier 1’ or ‘Tier 2’ brand.

Value-added by downstream activities however tend to decrease in the recent period due to changes in renewable energy policies. By far, FITs were the most common tool to promote the deployment of new PV capacities (see Figure 2). As the price is set by the regulator, the size of the rents crucially depends on the quality of its information about PV generation costs of electricity. Experience shows that regulators have regularly overestimated these costs as capacities actually installed have almost systematically exceeded the quantities that were initially planned to be commissioned. Regulators now tend to rely more on auctioning and competitive mechanisms such as competitive tenders for PPAs and auctioned FITs which erode the markups of project developers.

More generally, this shift towards auctioning mechanisms signals that PV is getting closer to competitiveness with conventional energy sources, in particular in regions with high solar radiation levels, and/or high electricity prices, and cheap project financing (i.e low interest rates). 2016 saw an impressive year, with Abu Dhabi and Mexico achieving some of the lowest bids for solar PV pricing contracts.

3.2. Technology transfer to China

What has been the role of intangible assets in the shaping of the PV value chain? Addressing this question primarily requires understanding how the Chinese upstream and midstream firms acquired the necessary knowledge to enter at different stages of the value chain.

De la Tour et al. (2011), Fu & Zhang (2011), and Wu & Mathews (2012) show that Chinese companies mostly acquired PV technologies by purchasing production equipment from international suppliers. From purified silicon to solar panels, products along the PV supply chain are very standardized. Market competitiveness mainly derives from the capability to manufacture products that satisfy a standard level of quality at an affordable cost. In this context, successful entry into each of the market segments requires access to state-of-the-art production technology. This in turn requires international markets for production equipment that are competitive. Pioneering Chinese firms were able to enter the market by purchasing production equipment from western providers (de la Tour et al. 2011, Wu & Mathews, 2012).

Production equipment companies for crystalline PV have initially come from companies that specialize in producing equipment for the semi-conductor and the electronics industry. These companies applied their technological capabilities in the semiconductor industry to produce equipment suited for manufacturing ingots, wafer, cells and modules. The semiconductor companies that have consistently been listed as the top companies in terms of early market-share and quality of equipment for solar PV production equipment have been US, Germany, and Japan-based (see Table 3). This enabled these companies to garner high value-added. According to Pew (2013), the net balance of solar PV trade in 2012 was $0.9billion in favor of the US over China, even though China’s trade volume for solar technologies was greater. This was largely due to American semiconductor companies selling production equipment to Chinese solar PV manufacturing companies.

The inflow of foreign technology in production equipment in China is illustrated by Figure 13, which shows the share of patent applications filed by foreign applicants at SIPO in production equipment and in other PV segments combined (silicon, ingots and wafers, cells, modules). Between 2004 and 2008, when Chinese companies became dominant in the global PV market, the share of patent applications filed by foreign applicants at SIPO in production equipment lied between 75% and 90%, indicating large technology transfer. In contrast, the proportion of patent applications filed by foreign applicants at SIPO in other segments of the PV industry was already lower than 50% from 2007 onwards. Besides the importing of equipment goods, the purchase of manufacturing equipment usually involves the transfer of complementary know-how through training sessions of engineers and technicians operating the production line. This in turn progressively enables PV manufacturers to adapt their production chain to local conditions – for instance, substituting some equipment with a cheaper workforce. Several of our interviewees moreover indicated that large PV manufacturers tend to develop partnerships with equipment suppliers, sharing know-how and feedback to improve the manufacturing process. Although they may include temporary exclusivity clauses, such partnerships make it possible for equipment suppliers to redistribute this know-how to other customers, thereby accelerating the circulation of knowledge across the industry.

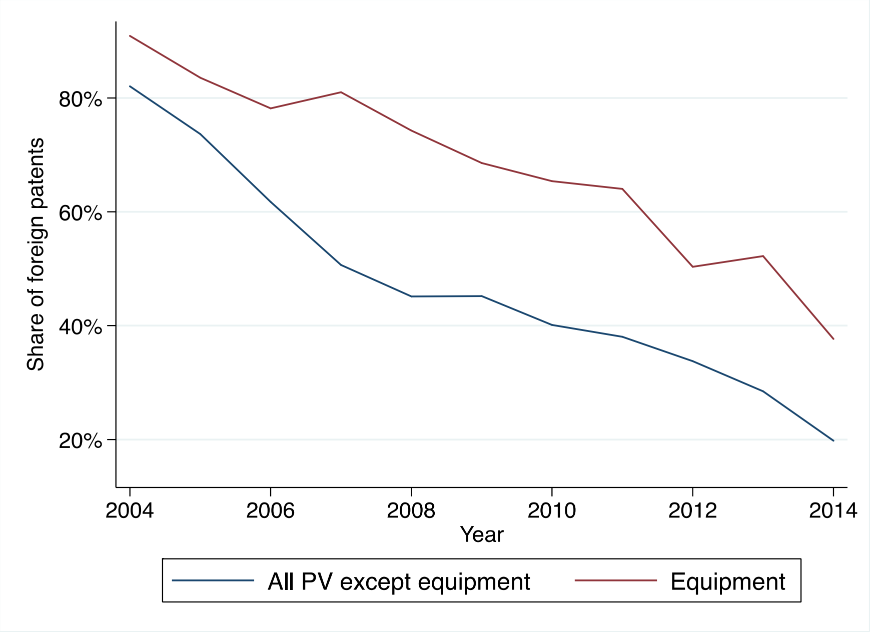
Table 3: Top Production Equipment companies in 2011

Company Name	HQ Country	Semiconductor Firm or Solely Solar Production Equipment Firm
Applied Materials	USA	Semiconductor
Centrotherm	Germany	Semiconductor/Electronics
MeyerBurger	Switzerland	Semiconductor/Electronics
GTAT	USA	Electronics
Schmid	Germany	Electronics
Komatsu-NTC	Japan	Semiconductor
Oerliko	Swizterland	Semiconductor
APPOLLO	USA	Electronics
RENA	Germany	Electronics
JGST	China	Solar

Source: Zhang & Gallagher (2016); Authors' research on company websites

Evidence of the diffusion of technology generated by the international trade of equipment goods comes from the progressive emergence of equipment goods suppliers that are solely Chinese. This is illustrated in Figure 13: at the end of our sample period, the share of patent applications filed by foreign applicants at SIPO in production equipment has decreased to 20%, showing that Chinese companies were able to progressively manufacture production equipment and relied less and less on imported machines. This is evidence of a progressive technological catch-up. This has important implications as it allows Chinese firms manufacturing PV products to buy cheaper production equipment, provided that they are able to customize their production line by integrating specific Chinese equipment.

Figure 13: Share of foreign patents applications filed at SIPO by segment, 2004-2014



Source: authors' calculations from the PATSTAT database

According to analysis on the ENF database, almost half of the world's production equipment firms listed by the end of 2016 in the database are headquartered in China, with the next significant headquarter locations of production equipment companies coming from the USA, Germany, and Japan (see table 4).

Table 4: Distribution of headquarters of Production Equipment Companies for Solar PV technologies in 2016

Economy	Number of Companies	% of Total Number of Companies
China	381	41%
United States	152	16%
Germany	125	13%
Japan	70	7%
Korea	53	6%
Taiwan (Province of China)	44	5%
Italy	18	2%
Switzerland	15	2%
R.O.W	81	8%
Grand Total	939	100%

Source: Authors' calculations from ENF database

The circulation of a skilled workforce has been another factor aiding the success of Chinese firms in upstream and midstream segments of the value chain. Recall that a major part of the technology concerns the operation of manufacturing processes, which mainly consists of know-how. In this context, the manufacturing experience of skilled employees is a key asset.

When entering the industry in the 2000s, Chinese PV companies benefited strongly from the arrival of highly skilled executives, who brought capital, professional networks, and technology acquired in foreign companies or universities to China. For instance, the founder and CEO of Suntech, China's largest PV company until 2013, had been studying at the University of New South Wales in Australia, and then worked for the Australian company Pacific Solar. Three of the largest Chinese companies – Shungfeng Suntech, Yingli and Trina – have been created by former Chinese researchers in Australia. 65% of the board members of the four largest Chinese PV firms in 2016 – Trina, GCL Poly, Jinko Solar, Canadian Solar – have studied or worked abroad. All big companies have recruitment programs to attract senior management from abroad.

The economic literature has shown for a long time that investment by a multinational firm in a productive asset such as factory in a foreign country also induces a transfer of knowledge, since the technology is operated directly in the recipient country. De la Tour (2011) show that this has not been a decisive factor in the emergence of the Chinese industry. Table 5 presents the top 6 cell / module manufacturers located in China. Only two of them feature investment links with foreign companies. Moreover, these FDI-based firms turn out to be late entrants, whose creation has followed in the footsteps of strictly Chinese pioneer firms. However, lately, Chinese companies have acquired foreign firms with a view to acquire the knowledge. In June 2012, Hanergy acquired Solibro, the CIGS operations belonging to Germany's Q-Cells. In January 2013, it announced the acquisition of MiaSolé, a start-up company specialized in thin-film based in Santa Clara, California, and in June 2013, of Arizona's Global Solar Energy (GSE), another thin-film company. This shows that Chinese firms are now moving into new technological areas and are using foreign acquisitions to get access to the knowledge.

Table 5: Top 6 solar module/cell companies in China 2015

Company	World Rank	Share of 2015 global revenue	Creation	FDI-JV links
Trina Solar	1	10%	1997	None
JA Solar	2	8%	2005	Australia (through JingAo)
Jinko Solar	3	7%	2006	None
Yingli	5	5%	1998	None
Canadian Solar	6	5%	2001	Canada
Shungfeng-Suntech	8	3%	2001	None

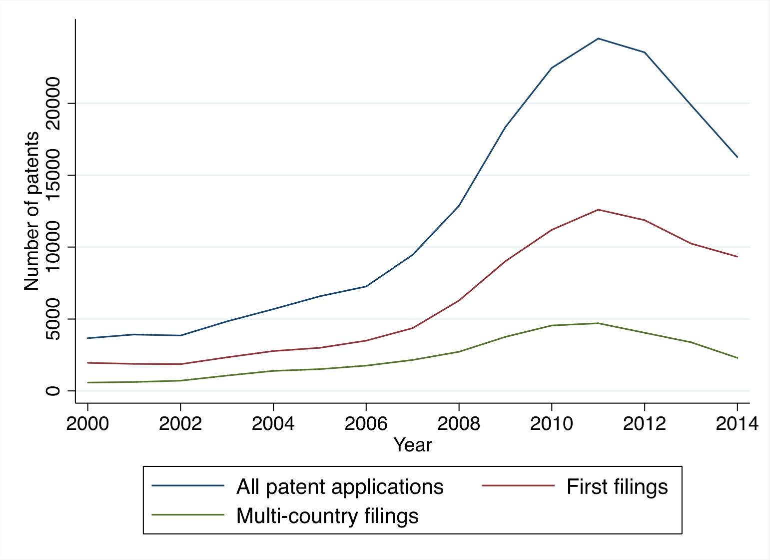
4. Innovation and patenting

We have seen that technology transfer to China between 2004 and 2012 has been the main factor shaping today's organization of the global PV value chain. In this section, we consider the role of innovation in the more recent period and the role of patenting in protecting this new knowledge.

4.1. Ups and downs in global PV patenting

The growth in the market demand for solar PV installations has been accompanied by a parallel growth in the number of patent applications worldwide, from less than 5000 annual patent applications in the early 2000s to close to 25,000 applications in 2011, corresponding respectively to less than 2000 and over 12,000 first filings (see Figure 14). However, this growth in patenting activity has reversed recently: between 2011 and 2014, the number of patent applications has fallen by 33% and the number of first filings by 26%. This decrease in patented innovation activity is not the consequence of an overall slowdown in the rate of patenting activity worldwide: in fact, as a share of global patenting activity, PV patents have fallen even more, by around 40% in just 3 years.

Figure 14: Growth and fall of PV patenting, 2000-2014



Source: authors' calculations from the PATSTAT database

The fall in patenting activity as measured by first filings has occurred in all segments of the supply chain, from production equipment all the way to modules. The decrease is most important in production equipment, silicon and cells (Table 6).

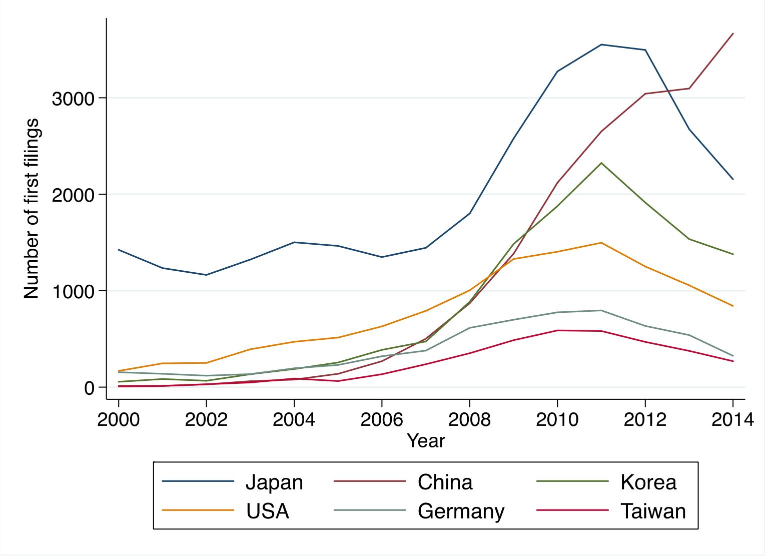
Table 6: Decrease of PV first filings 2011-2014 by segment

Segment	Variation 2011 -2014
All PV	-26%
Equipment	-46%
Silicon	-43%
Ingots / wafers	-25%
Cells	-42%
Modules	-21%

Source: authors' calculations from the PATSTAT database

Moreover, patented innovation has fallen in all major innovating countries with the notable exception of China, which now represents the highest number of first filings worldwide. This exception is striking from looking at Figure15 below: China is the only country that has not experienced a marked decline from 2011. This evolution is likely a consequence of the widespread dominance of Chinese firms in PV cells and modules in the market.

Figure 15: First filings in PV by major innovating countries, 2000-2014



Source: authors' calculations from the PATSTAT database

In order to understand better what is behind the drop in patenting activity revealed by Figure 14, in Table 7 we present descriptive statistics on the evolution of the number of patent filings and the number of applicants in PV for the main applicant countries in the world. The number of patent filings has gone down for applicants from all major countries except for Chinese applicants, reflecting the growth in first filings by Chinese inventors observed above. Moreover, it appears that the decrease in patenting activity is driven by a collapse in the number of applicants. For example, the number of unique US-based applicants having filed at least one patent in the PV sector has decreased by 71% between 2011 and 2014. This number has gone down by 78% for German applicants, by 80% for Japanese inventors and by 77% for Korean inventors. In contrast, the number of Chinese applicants has remained stable over the same period. Entry of new applicants has fallen even more: -77% for US applicants, -81% for German firms, -87% for Japanese applicants and -82% for Korean applicants. The number of Chinese newcomers has also fallen, but much less so (-11%). In the meantime, however, the average number of patent applications filed by each unique applicant has increased for applicants from all countries, but particularly so for applicants based in the US (+88%), Germany (+102%), Japan (+157%) and Korea (+114%). Chinese applicants file more patents on average (+32%), reflecting an increase in R&D expenditures, but this increase in patent filings per applicant is lower than in other countries. What is happening, therefore, is the following: many players have exited the market following the rapid collapse of crystalline silicon solar panels from China; entry is becoming even more difficult; but surviving firms are reacting by increasing their innovation efforts and filing *more* patents, suggesting that intellectual property protection might become more valuable in these times of sectoral reshaping.

Table 7: Changes in patent filings and applicants for the period 2011-2014 for the main applicant countries

Applicant country	Patent filings	Number of unique applicants	Number of first-time applicants	Number of filings per applicant
US	-46.56%	-71.58%	-77.84%	+88.05%
Germany	-56.29%	-78.41%	-81.92%	+102.42%
Japan	-49.97%	-80.57%	-87.97%	+157.55%
China	+32.25%	+0.06%	-11.10%	+32.17%
Korea	-52.68%	-77.96%	-82.88%	+114.68%

Source: authors' calculations from the PATSTAT database

Further evidence of this "gambling for resurrection" phenomenon in the industry is provided by distinguishing between different types of PV cells, depending on their dominance on the market. Dominant types of PV cells include microcrystalline and polycrystalline PV cells which account for close to 90% of the world's market, while alternative technologies include thin-films, dye sensitized solar cells, solar cells from Group II-VI and Group III-V materials and organic PV cells. We are able to identify those from patent classification codes. Table 8 shows the evolution of the number of patent filings and the number of applicants in PV in the major patent offices for these two types of cells. We find that the number of patent filings has decreased much less in alternative technologies than in dominant ones: for example, patent filings in crystalline PV cells by German applicants have decreased by 68% but filings in alternative technologies have only gone down by 33%. Overall, research has clearly switched from conventional solar panels made from crystalline silicon to thin-film modules in the recent period: in 2011, for every patent application protecting conventional cells, 1.5 patent application for alternative cells (thin-film, organic PV) was registered. Just three years later, in 2014, there are 3 alternative cells patent applications for each conventional cells patent application. A similar pattern is observed for the number of unique applicants. These results suggest that players are reacting to the industry shake-up by focusing their innovation efforts on the next generation of technologies.

Table 8: Changes in patent filings and applicants in dominant and alternative types of PV cells between 2011 and 2014

	Dominant cells types		Alternative cells types	
Applicant country	Patent filings	Number of unique applicants	Patent filings	Number of unique applicants
US	-54.82%	-79.15%	-46.10%	-79.66%
Germany	-68.67%	-80.63%	-33.00%	-61.71%
Japan	-70.06%	-90.00%	-44.27%	-72.75%
China	-10.22%	-32.14%	-10.94%	-11.36%
Korea	-58.88%	-92.32%	-27.48%	-82.24%

Source: authors' calculations from the PATSTAT database

The evolution of R&D intensity at major PV firms reveals a picture (see Table 9) which is consistent with patent data. Almost all major players have increased their R&D intensity between 2010 and 2015, sometimes substantially, but their patenting activity has grown even more. Because we cannot attribute the right past R&D expenditures to subsequently filed patents, it is difficult to provide reliable numbers on the evolution of the patenting intensity of companies, but the disproportionate increase in patenting activity compared to that of R&D intensity points to an increase in patenting intensity across the industry (among surviving firms). Across the whole period for which we were able to gather data, the average number of patents filed per million US$ of R&D expenditures is generally in line with usually reported numbers with between 1 to 10 million US$ per patent. However, it is highest for Chinese firms.

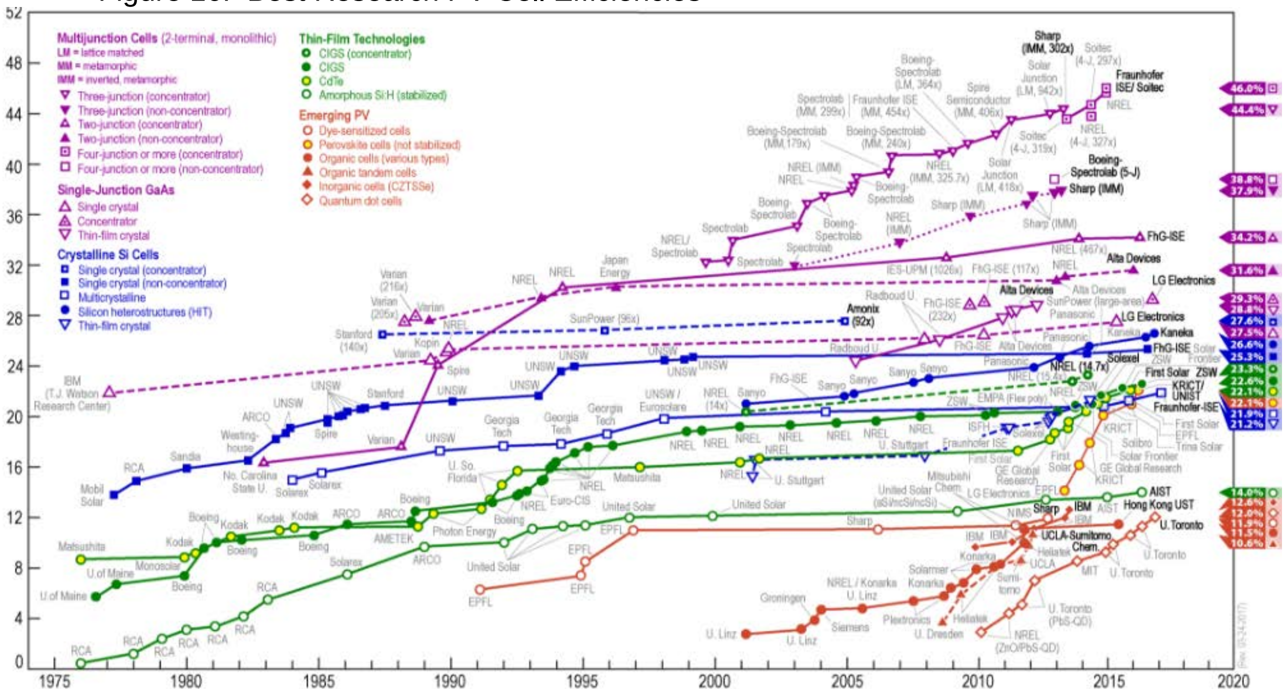
Table 9: R&D intensity and patent filings by top PV companies

Company	Country	R&D Intensity		Average first filings		Avg annual R&D exp. (mUSD)	Avg PV patent filings per mUSD in R&D exp.
		2010	2015	2005-2009	2010-2014		
Silicon							
GCL-Poly Energy	China		1,12%	5	3.4	20.5	0.20
Wacker	Germany	2.90%	3.30%	6	18.6	146.5	0.08
REC	Norway	2.10%	2.50%	3.4	11.6	11.65	0.64
OCI Company	Korea (Rep.)			1	1.75		
Cells							
First solar	US	3.70%	3.60%	5.6	52.2	112.8	0.26
Trina	China	1%	3.50%	6	41.8	26.05	0.92
JA Solar	China	2.50%	3.20%	3	9.4	16.5	0.38
Canadian Solar	China	0.45%	0.50%	1	2.75	12.5	0.15
Jinko Solar	China	0.38%	2.30%	0	19.75	15.1	0.65
SunPower	US	4.10%	6.30%	13.8	38.4	74	0.35
Hanwha Q CELLS	Korea (Rep.) & Germany		6.80%	12.75	14.8	28	0.49
Equipment							
Applied Materials	US	12.00%	15.40%	45.6	40.8	1297.5*	
Centrotherm Photovoltaics	Germany	6.80%	5.30%	4.4	11.8	20	0.41
Meyerburger	Switzerland	5%	17.20%	0	1.3	49.5*	
Inverters							
Sungrow	China		4.3%	2	13		
SMA Solar	Germany			9	26.2	78.5	0.22
SolarEdge	Israel		6.10%	6.3	5.6	22	0.27

Notes: (*) including non-PV R&D; Source: Authors' calculations from companies' annual reports and the PATSTAT database

These patent statistics show a sharp decrease in the level of patenting. Have we really experienced a technological innovation downturn since 2011? Other innovation indicators suggest the opposite. Product innovation measured in terms of improved conversion efficiencies has actually accelerated in the recent period. World records of power conversion efficiencies of PV cells of different PV cell families have been broken almost every year since 2010, after two decades of very slow progress. This is illustrated in Figure 16 below, by the National Renewable Energy laboratory (2017), which shows the firms who, at any given point in time since 1975, achieved the world's highest power conversion efficiencies of PV cells in any of the different types of cells (crystalline PV, thin-films, multi-junction and single-junction cells, and other emerging cells like organic or dye-sensitized cells). There has been fast progress in all alternative technologies to crystalline PV, in particular in multi-junction and single-junction cells (represented by purple lines), in thin-film PV cells (represented by green line with yellow dots) and in "emerging" PV technologies such as quantum-dot or peroskite PV cells (red lines). Figure 8 above, which presents the evolution the price of PV systems over time, yields the same message: The 80% price decrease between 2008 and 2015 reflects major technological improvements, even if they may have occurred outside research labs (in particular, through learning-by-doing in production facilities).

Figure 16: Best Research PV Cell Efficiencies



Source: NREL (2017)

4.2. *A focus on China*

As seen in Figure 15, the rise of Chinese companies on the final product market has been accompanied by a growth in patented activity in the PV sector. Table 10 shows the proportion of global first filings by segment for the main innovating countries in the most recent period (2011-2014). With over 28% of the world's first filings, China has now become the world's leader in global patented activity in PV. It ranks first in silicon production, ingots and wafers and modules. It is second to Japan in production equipment and cells. Within solar cells, it also ranks second worldwide in alternative types of technologies, but interestingly only ranks 4th worldwide (and very far away from the third main inventing country Korea) in crystalline PV cells. This is an interesting finding because within solar cells, China's competitive advantage lies *precisely* in this category. This suggests that China's success in commercializing crystalline PV cells at competitive prices was not driven by patentable innovation, but rather by unpatented or not patentable intangible assets such as uncodified knowledge of production processes.

Table 10: Main inventor countries by segment 2010-2014

Inventor Economy	All PV	Equipment	Silicon	Ingots / wafers	Cells	Modules
China	28.27%	23.45%	37.89%	40.76%	21.18%	27.33%
Germany	5.20%	6.64%	6.63%	4.71%	4.79%	5.30%
Japan	26.96%	33.59%	25.60%	22.21%	29.68%	23.80%
Korea	16.23%	9.67%	11.70%	16.05%	15.91%	19.38%
Taiwan (Province of China)	3.85%	3.31%	1.58%	2.12%	4.55%	4.51%
US	10.54%	14.49%	7.87%	6.27%	13.53%	10.27%

Source: authors' calculations from the PATSTAT database

Another way to look at China's relatively weak patenting activity in dominant types of solar cells is illustrated by Table 11, which shows the proportion of crystalline PV cells patents in total (crystalline + alternative) patents in column 2. Only 10% of China's patented innovations in solar cells relate to crystalline PV, and this ratio is much smaller than for other major innovators (the ratio is 37% in Japan and 55% in the US). In column 3 we carry out the same exercise for production equipment targeted specifically at crystalline PV vs production equipment targeted at alternative types of cells, which we identify through the use of co-classes (ie, to be considered as production equipment for crystalline PV a patent has to mention both a classification code related to production equipment and a code related to crystalline PV). We find, here, that China's efforts towards production equipment for crystalline PV cells are much higher at 60%, a ratio which is also much more in line with that found in other countries such as Japan (63%) and the US (67%). Thus, while China's innovators devote efforts to improving machines for producing crystalline PV cells, their patented innovation in crystalline PV cells themselves does not show up in patent statistics, suggesting that the knowledge acquired by Chinese producers in manufacturing crystalline PV cells is not patented or not patentable. This is consistent with the idea that Chinese manufacturers' competitiveness in crystalline PV cells relies more on uncodified knowledge related to production processes, along with transfer of the latest production equipment, than on IP-protected knowledge.

Table 11: Innovation in dominant VS alternative cells for main inventor countries 2010-2014

Inventor economy	% of dominant cells types patents in total PV cells patents	% of equipment patents for dominant cells types over total equipment patents for PV cells
China	10.05%	60.43%
Germany	43.17%	80.56%
Japan	37.90%	63.23%
Korea	26.46%	52.11%
Taiwan (Province of China)	50.11%	79.17%
US	55.84%	67.08%

Source: authors' calculations from the PATSTAT database

A final piece of evidence that Chinese firms' market dominance is not driven by frontier innovation that typically gets patented comes from looking back at Figure16 above. Chinese firms achieved the world's "best in class" technology in terms of conversion efficiency only 5 times out of the 289 observations in that Figure (see Table 12 below). In contrast, US firms achieved world's efficiency records 161 times, German firms 34 times and Japanese firms 32 times. Interestingly, Chinese firms achieved best-in-class performance twice in crystalline PV cells but 3 times in thin-films, a technology they do not commercialize yet.

Table 12: Best-in class product innovations by PV cell type and economy

Economy	Crystalline Silicon Cells	Thin-Film Technologies	Multi-junction Cells (2 terminal, monolithic)	Single Junction GaAs	Emerging PV	Total
USA	23	72	36	10	20	161
Germany	9	11	6	3	5	34
Japan	12	7	6		7	32
Australia	16					16
South Korea		1		2	5	8
Canada					7	7
Switzerland		1			6	7
China	2	3				5
France		2	2			4
Netherlands				3	1	4
Austria					3	3
India		3				3
Sweden		3				3
Hong Kong (China)					1	1
Spain			1			1
Total	62	103	51	18	55	289

Source: Authors' calculations based on NREL (2017), Figure 16.

A striking finding from the patent analysis is the relative absence of Chinese applicants in PV at major patent offices. Table 13 shows the proportion of patent applications filed by applicants from different countries at EPO, USPTO, JPO, KIPO and SIPO for the recent period. Chinese applicants represent between 1% and 2% of patent filings in PV at these offices. This comes in sharp contrast with other countries which file at least three times as many patents than Chinese applicants in the same offices. This finding is surprising given that Chinese companies dominate the market for solar cells and modules in all of these regions. Therefore, it appears that Chinese applicants do not protect their products against imitation through the use of patent applications.

Table 13: Share of patents with Chinese, German, Japanese, Korean, and US inventor at major patent offices, 2010-2014

	Applicant country of origin				
Patent office	China	Germany	Japan	Rep. of Korea	USA
SIPO	65.8%	3.7%	11.2%	4.2%	6.5%
EPO	2.0%	26.6%	18.0%	7.7%	16.2%
JPO	1.1%	2.8%	82.7%	3.0%	4.9%
KIPO	1.0%	3.7%	11.3%	72.2%	5.2%
USPTO	2.2%	5.6%	18.2%	9.6%	47.0%

Source: authors' calculations from the PATSTAT database

Of course, there is a well-known "home bias" in all patent offices worldwide, whereby patent applicants tend to file predominantly in their home market, and the figures in Table 13 partly reflect this home bias. Another way to look at the weak presence of Chinese patents in major offices is to calculate the proportion of patents initially filed at SIPO which later get extended in foreign offices, thus accounting for Chinese applicants' innovative performance. This is presented in

Table 14. We find that, out of 100 patents filed by Chinese applicants at the Chinese patent office, between 1 and 3 only are then extended to USPTO, JPO, EPO and KIPO. Looking at specific segments, the highest proportion is found is solar cells at USPTO, where nearly 6% of Chinese patents get extended. These are very low numbers when compared with Chinese companies' market share of around 80-90% in most of the segments of the PV supply chain. This contrasts with applicants from other countries, who typically "export" between 10 and 30% of their inventions in each major patent office. This result confirms that intangible assets possessed by Chinese companies – on which their commercial success relies – do not lie in intellectual property rights protection.

Table 14: Proportion of patents extended in major foreign offices 2010-2014, by country of inventor

	Inventor country of origin				
Patent office	China	Germany	Japan	Rep. of Korea	USA
SIPO	100%	27.6%	16.7%	10.6%	24.4%
EPO	1.3%	83.1%	11.3%	8.2%	25.6%
JPO	1.6%	19.7%	100%	7.3%	17.5%
KIPO	1.0%	16.5%	10.0%	100%	11.6%
USPTO	3.3%	40.3%	26.4%	23.5%	100%

Source: authors' calculations from the PATSTAT database

Several factors can explain this finding. A first explanation could be that given their competitive advantage, Chinese firms do not worry about being copied by local firms located in Europe or North America, because production costs here are much higher. However, Chinese firms may still want to protect themselves from competition from other Chinese firms. Another explanation could be that the combination of intense competition on the product market, overcapacities and declining public subsidies for solar energy means that Chinese firms may be financially constrained. Because extending patent protection abroad is very costly (much more so than filing patent applications domestically), Chinese companies may be reluctant to extend protection in foreign markets. In addition, Chinese firms typically receive public subsidies for filing patents at the Chinese office but not for second (foreign filings). This might partly explain the pattern we are observing. However, looking back in time, foreign extension of Chinese PV patents was even lower during the years 2000, before overcapacity and lower margins became an issue. This makes the validity of this potential explanation unlikely. Finally, Chinese technologies might not be patentable because Chinese companies have specialized on mature technologies like monocrystalline and polycrystalline PV that have been around for decades and where innovation is mostly incremental. However, there is a lot of patenting activity going on in these technologies as illustrated above.

This leads us to believe that innovation conducted by Chinese companies is not patented because their intangible assets are in the form of uncodified tacit knowledge over production processes and how to reduce production costs.

4.3. The role of patenting today

Is patenting in the PV sector becoming less attractive than before? It is clear from the recent evolution of the PV market that large patent portfolios built by Western companies has not offered them much protection against the intense competition induced by the rapid price decrease of Chinese crystalline PV cells. Indeed, looking at the global patent landscape in 2010 in crystalline PV technologies, Chinese companies were still a minor player: together, Chinese companies represented less than 4% of all the first filings worldwide between 2000 and 2010. Large patent portfolios of Japanese or US firms did not prevent them from rapidly losing market share. It is fair to say that patent exclusivity in crystalline PV does not seem to have contributed significantly to market power and profit margins in the recent period. This is acknowledged by the whole industry, including Chinese players, which has drastically reduced patenting activity in crystalline PV technologies although they cover more than 90% of the current global market

Are patents more valuable in second and third generation solar PV systems such as thin-film and organic PV? While many of the patents relating to the dominant technology of crystalline silicon have now expired, making the technology freely available, this is certainly not the case for these alternative technologies. The market share for alternative technologies is still small at around 7% globally and has furthermore *decreased* continuously since 2009, contrary to all expectations which typically projected this market share to be around 40% in 2020. However, the current market share of thin-film technology should not be the barometer of importance of filing patents, but rather future profits.

The empirical evidence is mixed. On a positive side, First Solar is one of the few solar companies to have maintained positive profits when many of the leading crystalline PV firms (including in China) were posting losses. Their success has been in successfully being able to manufacture thin-film (CIGS) cells below the low retail prices of crystalline PV, thereby offering more competitive price rates that still maintain profits. Their ability to compete is based on ensuring proprietary knowledge of their technologies.

However, patent protection does not guarantee commercial success for alternative technologies if the underlying technology cannot compete against market dynamics. An example of this is the recent collapse of the Chinese firm Hanergy Thin Film shares, which crashed by 47% on May 20, 2015. Furthermore, the acquisition of the patents of commercially distressed thin-film companies does not guarantee it will help the acquiring company improve their strategic position. The acquisition of large thin-film patent portfolios from Germany's Q-Cells and US' MiaSolé and GSE in 2012 and 2013 did not lead to the commercial success the firm had hoped for.

5. Conclusion

The spatial evolution of the solar PV value chain resembles what occurred in many other industries, such as semiconductors, electronics, and domestic appliances. The precise mechanisms are however specific.

PV panels and systems are commodities of which the almost unique quality variable is how much electricity can be produced per dollar invested. In this context, the dynamics of the industry have been profoundly driven by strategies to reduce production costs, rather than by product innovation. An indication is that the market is still dominated by the most mature technology – crystalline PV – while more advanced technologies bore great hopes fifteen years ago.

As a result, the PV products initially invented in the western world decades ago were no longer protected by patents and Chinese firms only needed to acquire the knowledge to manufacture efficiently the PV components along the solar PV supply chain. Our study highlights two channels of technology transfer. First, Chinese firms got access to production equipment and turnkey fabrication lines supplied by western firms. Although these production equipment were protected by patents, competition on the international markets helped to maintain reasonable prices. Second, Chinese firms also relied on knowledge transmission through the social networks of their founders and workers, many of whom studied abroad in regions that engaged with innovation in solar PV technologies. The PV industry is a perfect example of a complete form of technology transfer to an emerging economy, as is indicated by the fact that Chinese firms have now also become the world's leaders in production equipment.

Understanding how channels of knowledge transfer affect spatial changes in the supply chain, along with increased market competition, then has implications for future innovation efforts – particularly with regards to patenting activity. The solar PV market is now saturated with an incumbent technology whose depressed prices provide tight, and even negative, profit margins for companies. Firms can either dedicate R&D efforts to high level process innovations to reduce production costs in the dominant technology, or to new solar PV product innovations whose production prices are below the incumbent technology. These two lines of R&D activities are precisely the ones currently pursued by Chinese firms who dominate the global market.

Finally, our study indicates that the major changes underwent by the global PV industry during the last decade have been accompanied by a renewed interest in intellectual property protection, which is illustrated by the fact that companies which survived the collapse in PV prices worldwide have seemingly increased their patenting propensity recently. While IP protection of intangible assets was not a key determinant in the success of Chinese companies, nor did it protect incumbent firms in developed economies from the competition of Chinese firms, it might well become a key ingredient for commercial success in the coming decades, if alternative technologies to crystalline PV cells finally make their way to the market. In this respect, a few highly innovative firms and research institutes with large patent portfolios and highly efficient cells (such as Fraunhofer ISE, Sharp, IPFL, and Boeing Spectrolab) have these products 'on the shelf'.

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