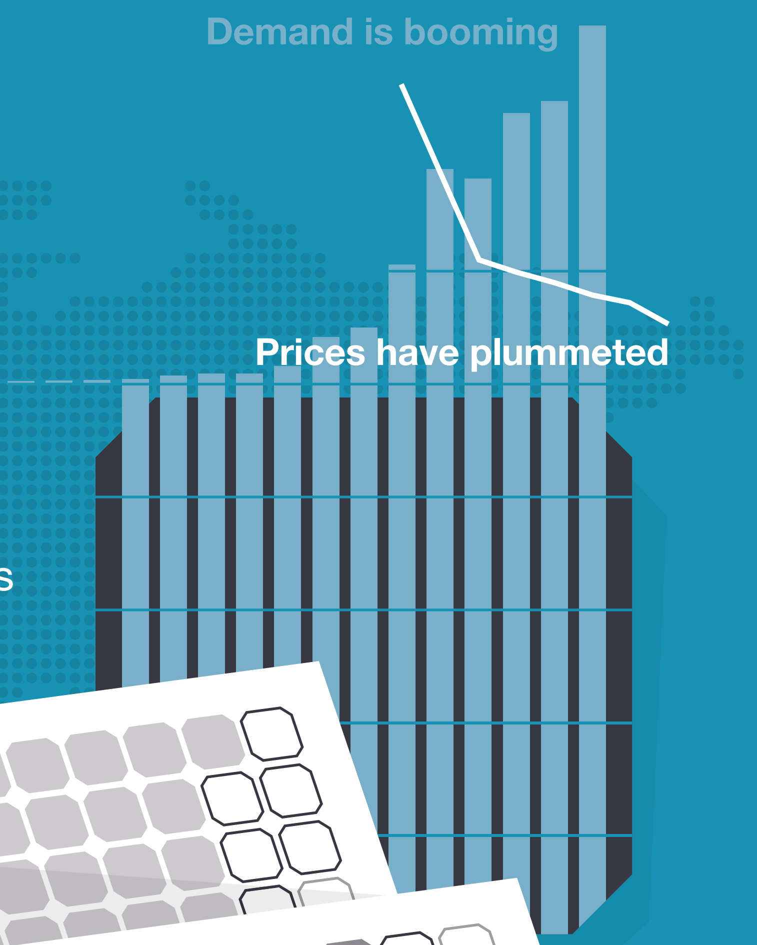
# Innovation is transforming the photovoltaic industry




Western companies used to dominate but now Chinese firms lead production of PV modules.


China
Japan
USA
Germany
Others

**Leading firms are looking to intangibles for competitive edge,** intensifying their investments in R&D and patenting.

Source: World Intellectual Property Report 2017

# Chapter 3
# Photovoltaics: technological catch-up and competition in the global value chain

New technologies related to renewable energy are a pillar of sustainable economic growth and development. Recent decades have seen increasing global interest and demand for successful innovations capable of transforming solar, wind or geothermal energy – among other sources – into electricity.[1]

This chapter explores how the global value chain for solar photovoltaic (PV) technologies has evolved to meet the demand for sustainable electricity generation. It focuses on the importance of intangible assets as a crucial means of adding value in the different segments of this particular global value chain, where technological innovation and diffusion have played a key role.

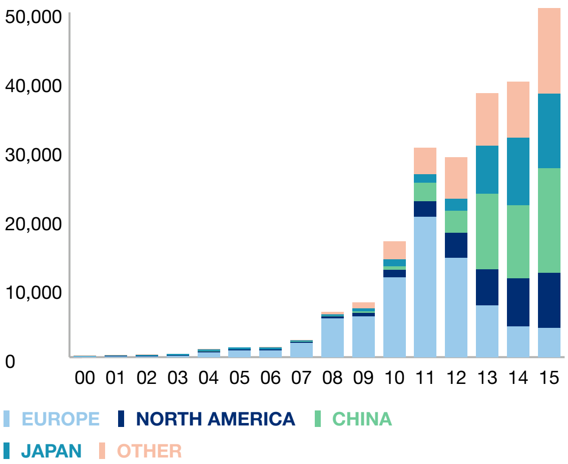
As with many technologies, an accidental discovery led to the initial development of solar PV technology for electricity generation. In the late 1930s and early 1940s at Bell Laboratories in New Jersey, United States, Russell Ohl discovered that shining light on a monocrystalline material registered electric potential on a voltmeter. He patented a device that employed this principle in 1941.[2] Ohl was not the first scientist to discover a material that conducted electricity – known as the semiconductive effect – when exposed to sunlight. The earliest documented incident was almost a century earlier in France, when Edmund Becquerel noted that an electric current was produced when two metals immersed in a liquid were exposed to sunlight. Though several scientists had managed 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.[3]

Nowadays, two different solar PV cell technologies are being commercialized – wafer-based crystalline and thin-film PV cells – but the former accounts for over 90 percent of the PV market. Present systems based on either PV cell technology can provide electricity similar to a conventional power plant, known as utility-scale generation. Such systems can act as a power plant generating electricity exclusively for the grid. Alternatively, large industrial plants – or other loads such as data storage centers – can generate electricity from PV systems on a large scale solely for their own consumption, thereby potentially offsetting some or all of their electricity consumption from the grid. Smaller-scale PV systems can also be used for residential or commercial uses. These too may be either connected to the grid or used solely for own consumption, particularly in remote, off-grid areas. Any PV system that is used purely for own consumption needs to rely on batteries or be hybridized with other fuel sources to ensure a consistent supply of electricity throughout the day.

## Figure 3.1

### Demand for PV is growing exponentially

Annual PV capacity additions (MW), 2000-2015




Source: IEA (2016).

Demand for PV systems has grown exponentially since 2000 (figure 3.1). In 2016, 34 percent more new capacity was installed worldwide than in the previous year, and growth hit 126 percent in China. Until 2011, growth occurred mainly in Europe. Demand has become more evenly distributed since then, and China is now the largest market. Figure 3.1 shows additions to annual PV capacity by origin of demand from 2000 to 2015. The growth trend is exponential, with an increase from little more than zero in 2000 to 50.6 GW in 2015. Capacity growth in Europe has slowed markedly since 2011, but it remains strong in China, Japan and North America.

Government support policies have been the main drivers of development in the solar PV market (figure 3.2). Historically, regulators have mostly used feed-in tariffs (FITs), which impose guaranteed prices for electricity generated from solar energy sources on grid operators. This mechanism allows solar PV power generated at higher cost to benefit from a higher price than power generated from conventional sources, accelerating investments in PV technology that spread upward through the value chain.

However, such mechanisms limit the price information passed from the supply side to regulators, which in turn to some extent limits the incentives to invest in cost-reducing PV technologies along the value chain. As the price is set by the regulator, supply margins depend on the quality of its information about the costs of generating electricity through PV technology. Experience suggests that regulators have regularly overestimated these costs, as installed capacity has almost systematically exceeded the quantities that were initially planned to be commissioned.

As an alternative, regulators now tend to rely more on auctioning and competitive mechanisms, such as FITs through tender or power purchase agreements (PPAs). These policies rely on clearer price signals from suppliers, giving current suppliers and project developers stronger incentives to reduce their costs. Arguably, PPAs can spread cost-reducing innovations more rapidly along the whole value chain, as solar PV developers submit bids to develop new power generation projects and the government agrees on the purchase for the most cost-competitive bids. However, FITs without tender still accounted for almost 60 percent of the PV market in 2015.

This chapter is organized in three main sections. In section 3.1, the evolution of the global value chain is analyzed. Section 3.2 examines how intangible assets – particularly product and process innovations – have shaped the global supply chain. Section 3.3 explores the role of IP protection, notably patents, in the new business environment that has emerged from major recent changes in the industry. A final section summarizes the main findings.

## 3.1 – The evolution of the PV global value chain

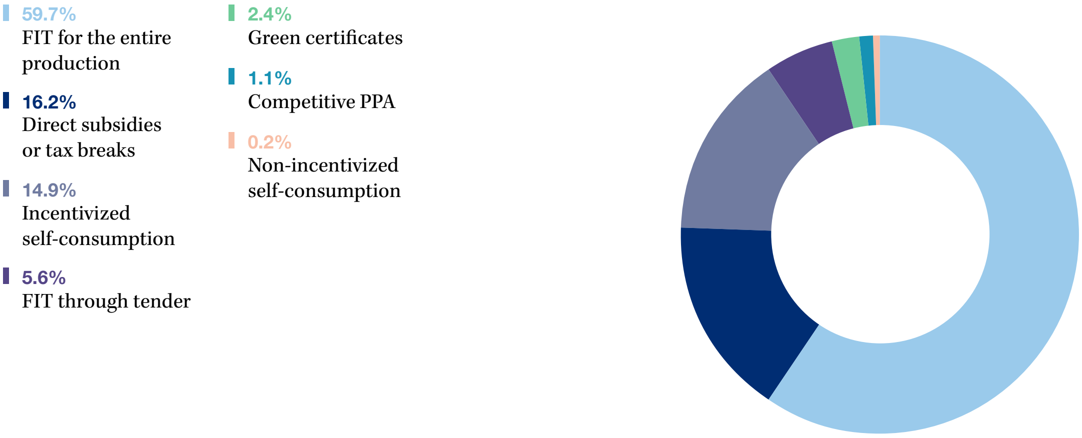
### A linear value chain structure

This section describes the structure of the value chain for wafer-based crystalline PV cells, which constitutes the vast majority of the PV market. Following the taxonomy described in chapter 1, the typical value chain structure for wafer-based crystalline PV technologies is snake shaped, as schematized in figure 3.3. The upstream and midstream segments concern all the processes involved in the production of PV systems. These segments rely heavily on production equipment, which has played a crucial role in technology dissemination in the PV industry.[4] The downstream segments concern the services involved in generating electricity from PV systems.

## Figure 3.2

### Governments are the main driver of PV market development

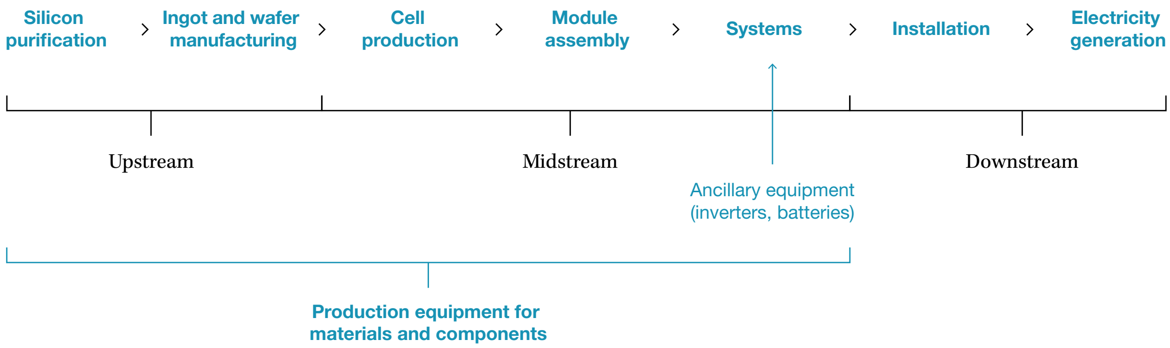
Distribution of solar PV market incentives and enablers, 2015




Source: IEA (2016).

## Figure 3.3

### The global value chain for crystalline PV is shaped like a snake




Source: Carvalho, Dechezleprêtre and Glachant (2017).

The production of crystalline PV systems involves five main segments. The first stage is the purification of silicon from silica ($SiO_2$) found in quartz sand. The ultra-high purity required for the PV industry – greater than 99.999 percent pure – is obtained through a heavy and highly energy-consuming chemical process, resulting in a material called polysilicon. The semiconductor industry also makes use of polysilicon, but the PV industry accounts for 90 percent of polysilicon production.[5] The second stage is the manufacturing of ingots and wafers, which consists of growing cylinders or bricks of pure silicon (ingots) and slicing them into thin layers (wafers). Stage three is the production of crystalline PV cells by assembling two differently doped wafers to form a p-n junction responsible for the photovoltaic effect. Many treatments or process modifications can be applied at this stage to increase the PV efficiency. Stage four is the assembly of modules, where PV cells are soldered together and encapsulated in glass sheets, forming a module which will be cooked in a laminating machine. The fifth stage is integration into PV systems: modules are combined with complementary equipment – such as batteries or inverters – to deliver electricity to devices or to the grid.

Regardless of whether crystalline or thin-film solar PV technologies are used, there are two main downstream segments. The first is installation of PV systems in the end-user market, which includes all market services related to the development of PV projects, financing, logistics, certifications and labor.

The second is the generation of electricity from PV systems, including all services related to operating and monitoring installed PV capacity.

### Despite the crisis, the PV industry is booming, with increased market competition

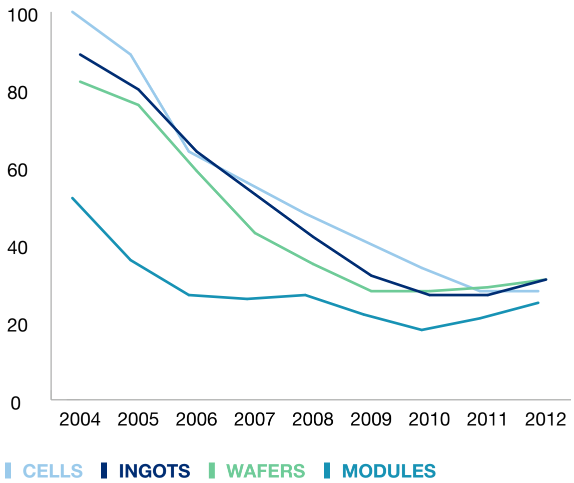
Despite the financial crisis of 2008, demand for PV systems, and consequently production, increased between 2005 and 2011. Demand is still booming, and more production capacity is being created everywhere. As an illustration, between 2005 and 2012 global ingot manufacturing capacity grew by 9,590 percent, and capacity to manufacture wafers grew by 3,991 percent. The traditional main players in the sector – Germany, Japan and the United States – as well as new ones like China and India all multiplied their production capacities in the upstream and midstream segments of the crystalline PV value chain between 2005 and 2011.[6]

This boom also involved market entry of new players, which in turn induced more competition. In 2004, the different production segments were heavily concentrated, with the five largest players supplying most global production. As depicted in figure 3.4, in 2004 the top five producers accounted for between 80 and 100 percent of production in most segments. The only exception was the module segment, and even there the top five accounted for over 50 percent of module production. But by 2012 their share of production in the other four segments had dropped markedly to around 30 percent.

# Figure 3.4

## Competition in the PV market has increased markedly

Top five companies' market share for upstream and midstream segments of the crystalline PV value chain, 2004-2012




Source: ENF (2013a, 2013b).

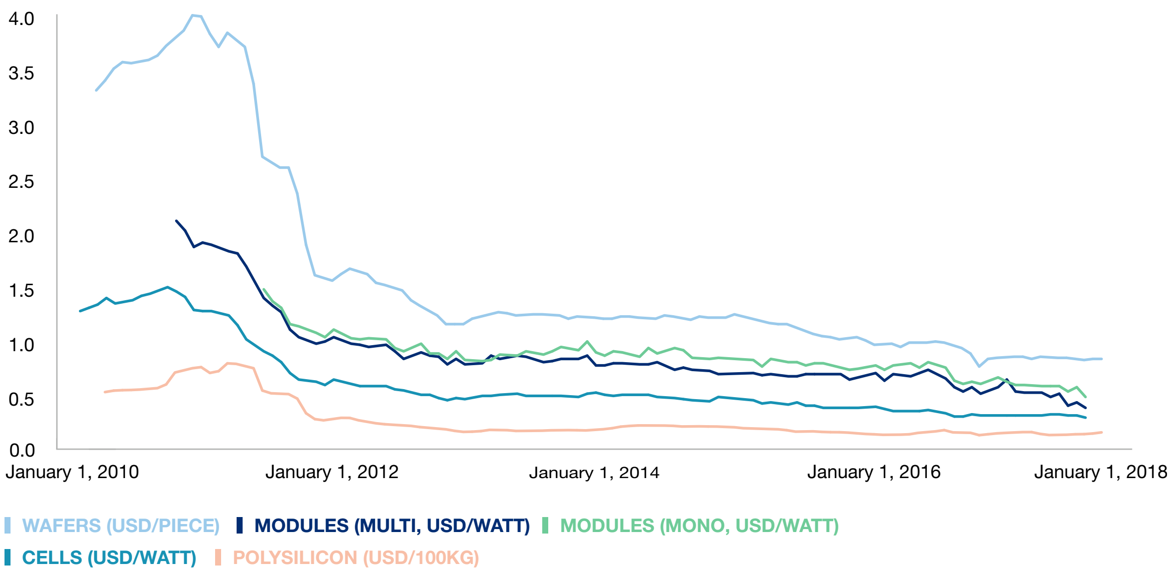
These developments resulted in a dramatic decrease in solar PV prices from 2008. Solar PV module prices are estimated to have decreased by more than 80 percent between 2008 and 2015, with price reductions of 26 percent for each doubling of capacity.[7] Prices have fallen for all solar PV components, which to a great extent are now considered as commodities, competing on price only, rather than differentiated goods, where both price and quality are important for success in the market. Prices fell sharply until early 2012, and have continued to decline since then, but more gently (figure 3.5).

The decrease in solar PV prices is making PV systems cost-competitive with conventional energy sources, particularly in markets with high conventional electricity prices, high levels of solar radiation and low interest rates. These conditions have increased incentives to install solar generation for self-consumption, and so demand in that market has also increased. It is not surprising that the increase in PV demand from regions other than Europe has coincided with the steep price fall observed since 2011. Moreover, the abovementioned government support policies based on tenders are likely to have reinforced the downward price trend. For example, in 2016 Abu Dhabi and Mexico achieved some of the lowest bids for solar PV pricing contracts.

# Figure 3.5

## PV component prices have fallen dramatically

Spot price of multi-crystalline PV individual components, 2010-2017




Sources: WIPO based on BNEF (2017).

### China: the new big player in the PV value chain

The global distribution of the PV value chain has changed dramatically in the last decade, with a massive relocation of upstream and midstream activities to China.[8] While traditional producing economies did manage to increase their production output and capacities between 2005 and 2011, growth was much larger and faster in China.

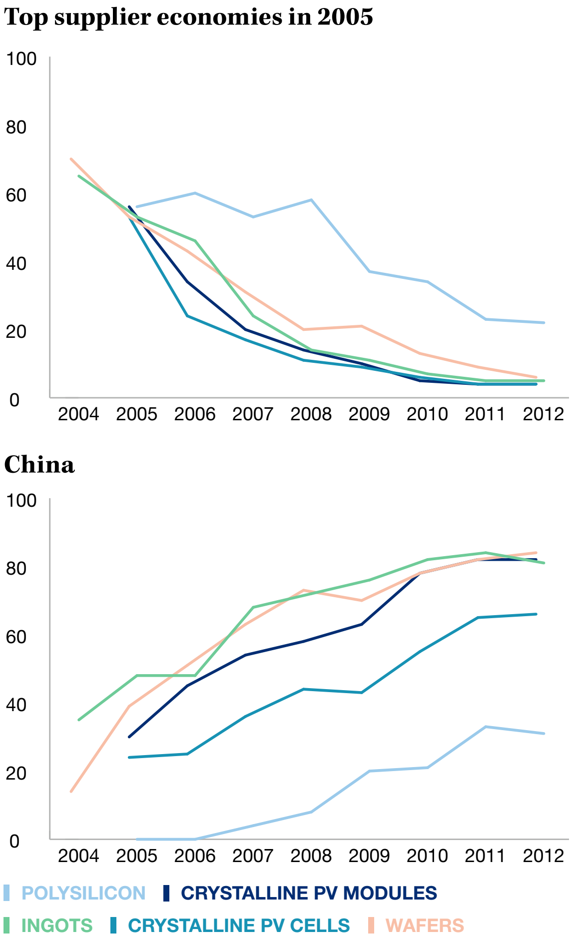
Until 2004, demand and production was largely concentrated in Europe, where governments gave generous support to accelerate the deployment of PV capacities. This created powerful economic signals in countries with a strong semiconductor industry – such as Germany, Switzerland, Japan and the United States – which initially became leaders in providing production equipment for wafer-based crystalline PV technologies. Production and demand then slowly started to catch up in Asian economies, most notably in China. This led to overcapacities, drastic price decreases and the exit of many upstream and midstream Western firms.

By 2015, China had become the main PV market and the lead economy in all upstream and midstream production segments. Figure 3.6 contrasts the evolution of Chinese market shares with those of the leading economy in the production of each segment in 2005. The trend is clear: by 2012 the Chinese economy was the main supplier of the global PV market in all these segments. It concentrated more than 60 percent of production in all segments of the chain except polysilicon production. Chinese companies did enter the polysilicon market and became the main supplier there too, accounting for one-third of production by 2011; but compared to the other production segments, they entered much later and have concentrated appreciably less of the global market.

## Figure 3.6

### China is now the top supplying economy in all upstream and midstream PV market segments

Percentage of global manufacturing capacity, 2004-2012




Sources: ENF (2013b) and BNEF (2013).

Note: Top supplier economies in 2005 were the United States for polysilicon and crystalline PV modules, Europe for ingots and wafers, and Japan for crystalline PV cells.

### Trade restrictions: policy actions and economic reactions

The steep price fall mentioned above caused competitive pressures against U.S. and European solar PV companies, which had enjoyed significant profits prior to 2008. This resulted in an increase in bankruptcies and acquisitions in 2011 and 2012.[9]

As a result, solar PV manufacturing associations in both the United States and Europe petitioned their respective governments to impose tariffs against Chinese solar PV products.[10]

They argued that Chinese solar PV firms benefited from subsidized loans from their government, allowing them not only to set up production facilities, but also to sustain production even when market prices fell below the cost of production.[11] This led both the U.S. and EU governments to impose anti-dumping duties on different Chinese crystalline PV products in 2012 and 2013. These duties are currently still in place due to extensions in both the United States and the EU.[12]

Furthermore, other countries that have set up market support mechanisms for solar PV have invoked local content requirements, meaning a certain percentage of technologies used in local PV markets must be sourced from local manufacturing facilities. Such requirements were introduced in India, South Africa and Ontario, Canada, although Ontario eventually had to revoke its measures following a ruling by the World Trade Organization.[13]

Chinese firms have partially bypassed these trade barriers by setting up manufacturing plants in Brazil, Germany, India, Malaysia, the Netherlands, Thailand and Viet Nam.[14] These plants serve the domestic markets in these countries, but are also used as export bases to other markets that currently have duties against them. Thus, political economy factors – such as how trade restrictions affect market access – can play an important role in the geographical distribution of the global value chain.

### Surviving through vertical integration

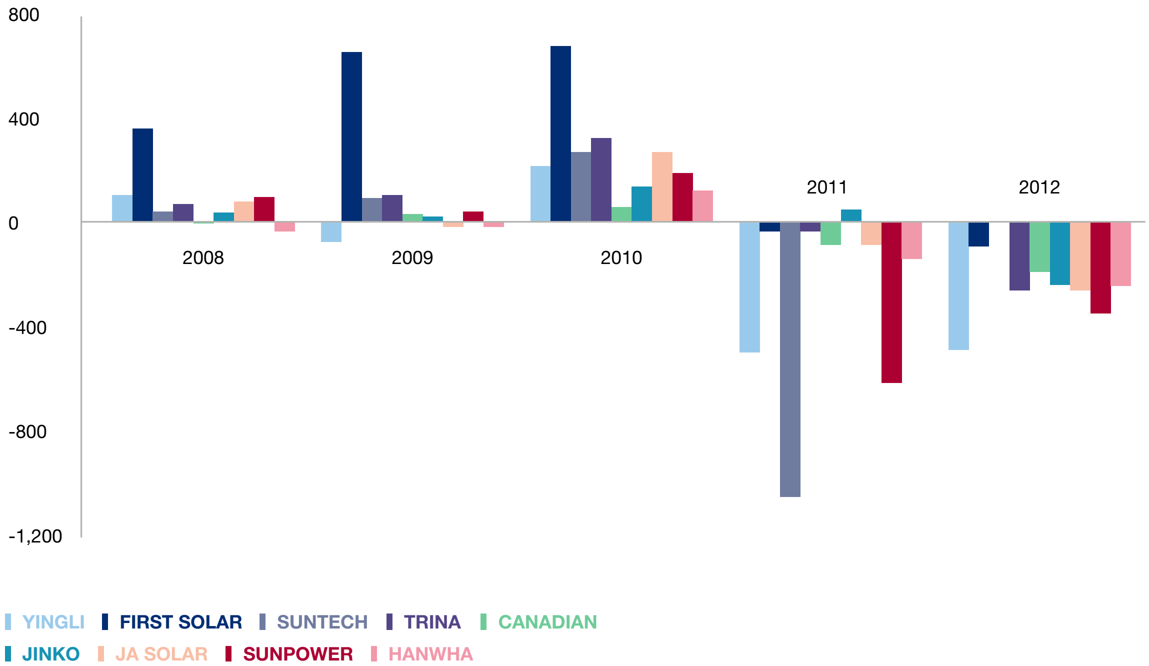
The distribution of gains in the PV value chain has changed drastically in the last decade. Before 2011, generous subsidies in Europe maintained prices well above production costs in all segments of the value chain. Following the price downturn in 2011, upstream and midstream players suffered a fall in profit margins that made it difficult for companies to survive (see box 3.1 and figure 3.7).

Although the economic environment has improved since then, several companies operating in different segments continue to face serious difficulties. In general, midstream firms' margins fall short of the average in the semiconductor industry. Low market prices for upstream and midstream segments of the value chain mean that a greater proportion of the value in the chain now lies downstream, in the market development segment. In consequence, many upstream and midstream solar PV companies have consolidated with downstream companies (see table 3.1).[15]

## Figure 3.7

## PV manufacturers have become much less profitable

Net profits of leading PV firms (USDm), 2008-2012




Source: Carvalho et al. (2017).

# Box 3.1

## Creative destruction in the PV value chain?

All major midstream players started losing money in 2011 or 2012 (see figure 3.7). In 2012, Q-Cells, a German-based cell manufacturer that led the market in most of the 2000s, went bankrupt and was then bought by Hanwha of the Republic of Korea. Chinese PV giant Suntech also defaulted in 2013, leading to a complete restructuring of its activity. Since then, the situation has become less severe, but it remains difficult. Companies like REC Silicon and Centrotherm Photovoltaics, which operate in different segments, continue to face serious difficulties. In general, midstream firms' margins fall short of the average in the semiconductor industry.

Vertical integration has been the solution for many companies in the PV value chain. As can be seen in table 3.1, several upstream and midstream players, such as GCL, First Solar, Canadian Solar, SunPower and Jinko Solar, have also vertically integrated downstream activities.

Many argue that process innovation is the only possible survival strategy for upstream and midstream companies.[16]

First Solar provides an interesting case in point. Specializing in thin-film cells, which account for a minor share of the market – just 7 percent in 2015 – has enabled it to become the most profitable midstream company. What drives its commercial success is being able to manufacture innovative PV components below the market price and production costs of competitors. Its thin-film PV cell has power conversion efficiencies nearing crystalline PV levels, but with production costs substantially below the retail market price for crystalline PV. First Solar can maintain its comparative advantage because other companies do not know how to reproduce its product – a PV cell made from cadmium telluride materials – and because it uses specialized production equipment protected by intellectual property rights.

But how replicable is this example? First Solar was able to attract finance, scale up production and commercialize its technology when solar PV technology prices were high.[17] It is hard to see such a window of opportunity in current market conditions.

# Table 3.1

## EBITDA margins of main PV companies, 2015-2016

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

Source: Carvalho et al. (2017).

Notes: (a) 2015; (b) 2016.

Solar PV manufacturers are increasingly moving downstream by getting involved in market development. This trend was initially observed during the financial crisis of 2008, when orders for solar PV technologies were cancelled due to the inability of solar PV project developers to obtain financing support.[18] Prior to the crisis, most developers financed their solar PV projects through bank loans. Banks were willing to finance solar PV projects – along with other renewable energy projects – because governments' FIT policies provided guaranteed prices for at least 20 years. However, the financial crisis hit the liquidity of banks and their capacity to provide loans to project developers.

As a result, project developing companies had to cancel their projects, which in turn meant cancelled orders for PV products upstream in the value chain. Solar PV manufacturers that had enjoyed high profits up to this time faced cancellation of their orders and could not resell them to other project developers. Those companies with strong balance sheets started moving downstream to project development in order to generate demand for their own upstream products.

## 3.2 – How do intangibles add value in the PV global value chain?

As described in the previous section, the past decade has seen a striking relocation of most upstream and midstream activities to China. As a direct consequence, a significant share of the economic activities related to the PV value chain – including total value added – has also been transferred to that country.

But the story in regard to the creation and returns to PV intangible assets is less straightforward.[19] First, knowledge assets in the PV value chain were not necessarily tied to either the main production location (China) or demand locations (Europe). Second, as suggested in the previous section, knowledge assets relate not only to product innovations, but also to cost-reducing process innovations. Third, it is important to understand how China acquired the knowledge assets needed to reshape the current global PV value chain.

This section explores how knowledge assets have shaped the current structure of the PV value chain. The role of reputational assets in downstream segments is explored in the next section.

## Box 3.2

### The photovoltaic revolution

There are now four different families of solar PV cell technologies: (i) wafer-based crystalline, (ii) thin-film, (iii) high-efficiency (often referred to as Group III-V) and (iv) organic PV cells. Only the first two are currently commercialized, while the latter two show great promise. Wafer-based crystalline PV cells account for over 90 percent of the PV market.[20]

Newer PV technologies have to overcome two challenges to reach the market. First, the technology has to generate electricity reliably and stably in non-laboratory settings, and second, production costs have to be lower than competing market prices for existing PV technologies. As of today, certain types of thin-film and high-efficiency PV cells have achieved higher power conversion efficiencies than commercialized technologies, but they struggle to meet the prices of the marketed technologies, partly because they are produced on a smaller scale.[21]

This makes process innovation along the value chain crucial for the PV industry (see figure 3.3). Two major production processes are used for polysilicon production: the Siemens process and the fluidized bed reactor (FBR) process.[22]

Since the production of polysilicon is electricity-intensive, a large part of decreasing costs lies in improving the energy efficiency of these processes, with the FBR process being more efficient than the Siemens one. Companies in the United States, Canada and Norway are trying alternative and proprietary metallurgical processes to reduce the energy and production costs of polysilicon. Another way in which companies attempt to reduce electricity costs is relocating plants to regions where electricity is cheap. Cost-reducing innovations in the production of ingots and wafers have also been achieved through innovations in the production equipment installed in those factories. For ingots, this is done by growing larger crystals and improving the seed crystals needed to reduce process time and increase yield.[23] Other production equipment improvements include cutting ingots into thinner wafers, reducing loss of unused ingot material (known as kerf), increasing recycling rates and reducing consumables.[24] Other process innovations include reducing the amount of metallization pastes/inks containing silver and aluminum, which are the most process-critical and expensive non-silicon materials used in current crystalline silicon cell technologies.[25]

### Where are PV knowledge assets created?

Since 1975, the National Renewable Energy Laboratory (NREL) has been tracking the stakeholders – companies and academic institutions – achieving the world's highest power conversion efficiencies of PV cells in any of the different PV cell technologies (see box 3.2). Over that period, world records have been broken frequently within each PV cell family. Moreover, record power conversion efficiencies across all PV cell technologies have been achieved almost every year since 2010, after two decades of very slow progress. There has also been fast progress in all alternative technologies to crystalline PV, such as multi-junction, single-junction, thin-film and emerging PV cell technologies.[26]

Who is behind these current and alternative PV product innovations? As shown in table 3.2, the United States achieved 56 percent of the 289 observed world efficiency records, followed by Germany (12 percent), Japan (11 percent) and Australia (6 percent). These four countries account for most of the documented PV product innovations. The United States dominates the best-in-class landscape across all PV cell types, with particular strength in the alternative thin-film and multi-junction PV cell innovations. Australia is second in terms of breaking records for the current crystalline PV cells, but has not achieved any record for alternative PV technologies. Conversely, other countries such as the Republic of Korea, Canada and Switzerland have set records only in alternative PV technologies.

## Table 3.2

### Best-in-class product innovations by PV cell type and economy, 1976-2017

| Economy | Crystalline silicon cells | Thin-film technologies | Multi-junction cells (two-terminal, monolithic) | Single-junction GaAs | Emerging PV | Total |
|---|---|---|---|---|---|---|
| United States | 23 | 72 | 36 | 10 | 20 | 161 |
| Germany | 9 | 11 | 6 | 3 | 5 | 34 |
| Japan | 12 | 7 | 6 | | 7 | 32 |
| Australia | 16 | | | | | 16 |
| Rep. of 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: Carvalho et al. (2017).

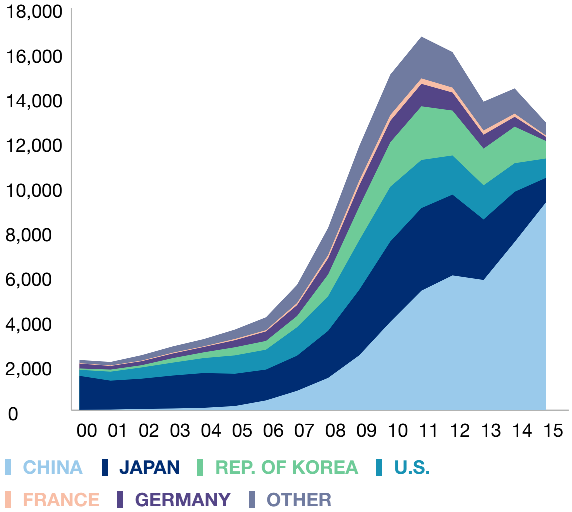
It seems that frontier innovation has not driven the market dominance of Chinese firms. The greatest product innovations – in terms of improved conversion efficiencies of different PV cell families – still appear to occur in other countries. In contrast to these economies, China has achieved global best-in-class technology only five times, including three records in thin films, a technology that is not yet commercialized.

A similar but more detailed picture can be seen when patent applications for PV-related technologies are analyzed (see figure 3.8). Growing market demand for solar PV installations has been accompanied by parallel growth in the number of patent applications worldwide. First patent filings increased from less than 2,500 in the early 2000s to over 16,000 in 2011. Until 2008, most of these technologies originated in Japan and the United States. Since then, China has seen rapid growth in PV patenting, becoming the top PV filing economy by 2010 and accounting for the majority of filings by 2014.

## Figure 3.8

### China – the new PV innovation champion?

First filings of PV-related patents by origin, 2000-2015



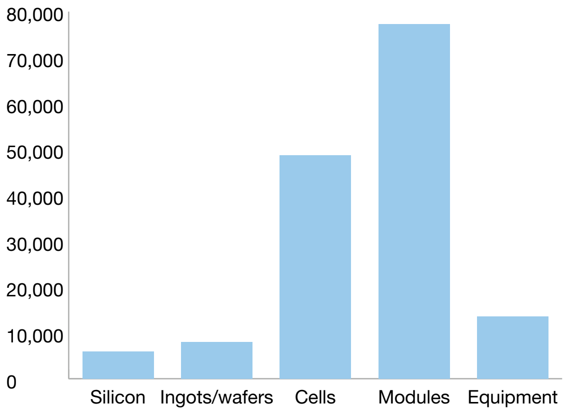

Source: WIPO based on PATSTAT; see technical notes.

With over 46 percent of the world's first filings in the period 2011-2015, China has now become the global leader in PV-related patent filings (figure 3.10). It ranks first in first filings for technologies related to each PV segment, and has the majority of these in the case of silicon, ingots/wafers and modules. But when the specialization of Chinese firms between current (crystalline) and alternative cell-related technologies is considered, a different picture emerges. As observed for the world's efficiency records, China seems to have specialized more in alternative cell technologies than crystalline ones. Indeed, China holds the largest share of alternative cell patent filings, while still behind Japan, the United States and the Republic of Korea in filings for crystalline technologies. These figures contrast with China's current competitive advantage as regards crystalline PV cell production.

## Figure 3.9

### PV modules and cells dominate patent filings for PV innovations

First filings of PV-related patents by segment, 2000-2015



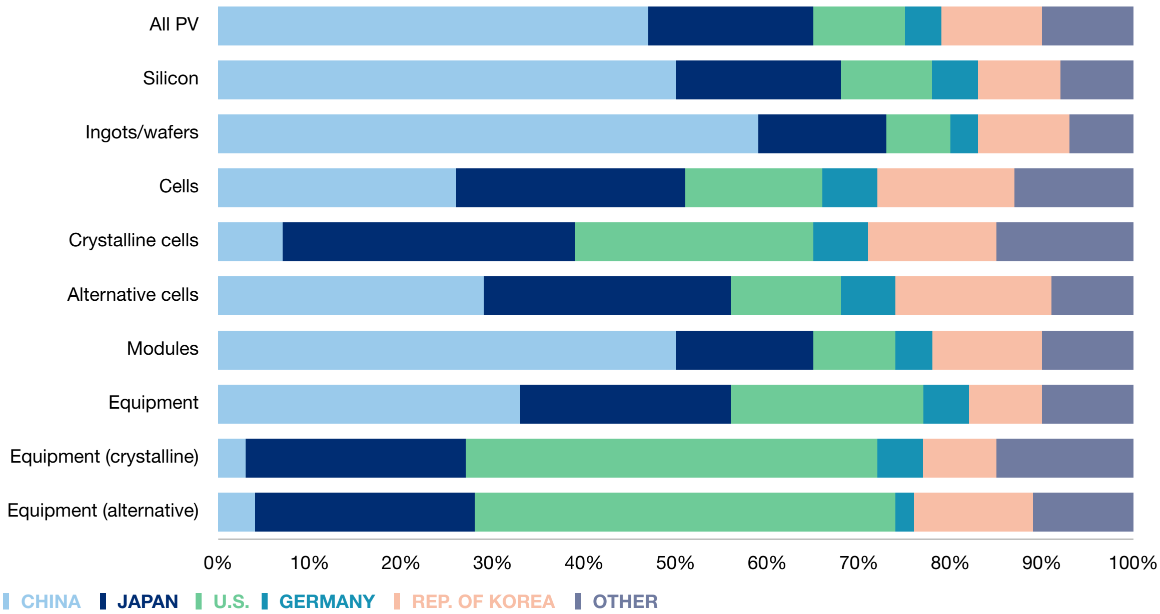

Source: WIPO based on PATSTAT; see technical notes.

Most patenting activity happens in the two midstream segments. More than half of all PV-related patents filed in the period 2000-2015 concerned module technologies, and almost a third related to cell ones (see figure 3.9). Technologies related to silicon, ingots and wafers accounted for less than 10 percent of patents.

# Figure 3.10

## China has become a major PV technology stakeholder

Percentage distribution of PV-related patents by origin and value chain segment, 2011-2015




Source: WIPO based on PATSTAT; see technical notes.

This is not to say that innovation is less frequent in the upstream and production equipment segments. Indeed, field studies have found that companies patent minor inventions intensively – particularly in China – but critical inventions are usually kept secret. Many of these critical innovations focus more on process, which is often not carried out in specific R&D departments but directly on production lines, and protected by secrecy rather than patenting. This is the case not only for new-entrant Chinese companies, but also for major Western and Japanese silicon producers, which have developed advanced know-how on purifying silicon at reasonable cost that they keep secret.[27]

### Cost-reducing process innovations

Neither power conversion records nor patents can ensure the successful introduction of PV product innovations. As noted in box 3.2, for a new PV technology to achieve success, it needs to be both reliable and competitively priced, and while certain alternative PV cell technologies have achieved impressive results in the laboratory, they are not yet being offered on a competitive scale.

Moreover, the products already in the market along the PV value chain – from purified silicon to solar panels – are highly standardized. Market competitiveness of these 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 and survival within each market segment requires access to state-of-the-art production technology, which in turn requires international markets for production equipment that are competitive.

This means that process innovations are instrumental for introducing new PV products into the market and maintaining existing ones. New technologies can only be introduced into price-competitive markets if they achieve large-scale production and are supported by complementary process innovations to reduce costs. In fact, several companies in the upstream and midstream segments of the crystalline PV cell value chain have only survived through high-level process innovations that allowed them to reduce their production costs faster than their competitors operating in the same segment.[28]

## Table 3.3

### Top production equipment companies, 2011

| Company | Headquarters country | Sector of origin |
|---|---|---|
| Applied Materials | United States | Semiconductors |
| Centrotherm | Germany | Semiconductors/electronics |
| MeyerBurger | Switzerland | Semiconductors/electronics |
| GTAT | United States | Electronics |
| Schmid | Germany | Electronics |
| Komatsu-NTC | Japan | Semiconductors |
| Oerliko | Switzerland | Semiconductors |
| APPOLLO | United States | Electronics |
| RENA | Germany | Electronics |
| JGST | China | Solar |

Source: Carvalho et al. (2017) and Zhang and Gallagher (2016).

Who generates PV production equipment innovations? Production equipment for crystalline PV initially came from companies specialized in producing equipment for the semiconductor and electronics industry. These companies applied their technological capabilities in the semiconductor industry to produce equipment suited for manufacturing ingots, wafers, cells and modules. Semiconductor companies based in the United States, Germany and Japan consistently featured as the top companies in terms of market share and quality of equipment for solar PV production equipment (see table 3.3).

Patent mapping complements this picture. Until 2012, the United States and Japan largely dominated the landscape of patent filings relating to production equipment. Since then, such filings have declined sharply; they fell by around 60 percent between 2012 and 2015 (see figure 3.11). The drop was higher for the United States and Japan, allowing China to claim the largest share in this segment in 2012. China accumulated one-third of the patents filed during the period 2011-2015. Nevertheless, the United States still accounted for almost half of all patent filings relating to production equipment for crystalline or alternative cells in that period (see figure 3.10). Japan and the Republic of Korea also rank higher than China, which holds a very low proportion of such patents.

### How did China catch up technologically?

What has been the role of intangible assets in shaping the current global PV value chain? Addressing this question primarily entails understanding how Chinese upstream and midstream firms acquired the necessary knowledge assets to enter at different stages of the value chain. There were two main channels for technology transfer to China: production equipment and skilled human capital.

## Table 3.4

### Distribution of headquarters of solar PV technology equipment producers, 2016

| Economy | Number of companies | Share of total number of companies (%) |
|---|---|---|
| China | 381 | 41 |
| United States | 152 | 16 |
| Germany | 125 | 13 |
| Japan | 70 | 7 |
| Rep. of Korea | 53 | 6 |
| Taiwan (Province of China) | 44 | 5 |
| Italy | 18 | 2 |
| Switzerland | 15 | 2 |
| Rest of world | 81 | 8 |
| Total | 939 | 100 |

Source: Carvalho et al. (2017).

## Table 3.5

### Top six solar module/cell companies in China, 2015

| Company | World rank | Share of total 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 |

Source: Carvalho et al. (2017).

Chinese companies mostly acquired PV technologies by purchasing production equipment from international suppliers.[29] Pioneering Chinese firms entered the market by purchasing production equipment from Western providers.[30] But technological knowledge diffusion to China went beyond the transfer of such equipment. Indeed, evidence of technological catch-up is apparent from the progressive emergence of equipment goods suppliers that are solely Chinese. By 2016, almost half the world's production equipment firms were headquartered in China, with the next most significant headquarter locations being the United States, Germany and Japan (see table 3.4).

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.[31] 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 and universities to China.

For instance, the founder and CEO of Suntech, China's largest PV company until 2013, studied 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 – were created by Chinese nationals who had formerly been researchers in Australia, and nearly two-thirds of the board members of the four largest Chinese PV firms in 2016 – Trina, GCL Poly, Jinko Solar and Canadian Solar – had studied or worked abroad. All big companies have recruitment programs to attract senior management from abroad.

Conversely, there is little evidence to support the hypothesis that investment by multinational firms was a decisive factor in the emergence of the Chinese industry.[32] Table 3.5 presents the top six cell or module manufacturers located in China. Only two of them have 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.

## 3.3 – What is the role of IP in the PV industry?

This section looks in more detail at the role of IP in protecting knowledge and reputational assets. It will first consider how IP has been used to protect knowledge assets and its role in future technological appropriation by China, then examine recent trends in the use of IP to protect reputational assets and ornamental features of PV products.

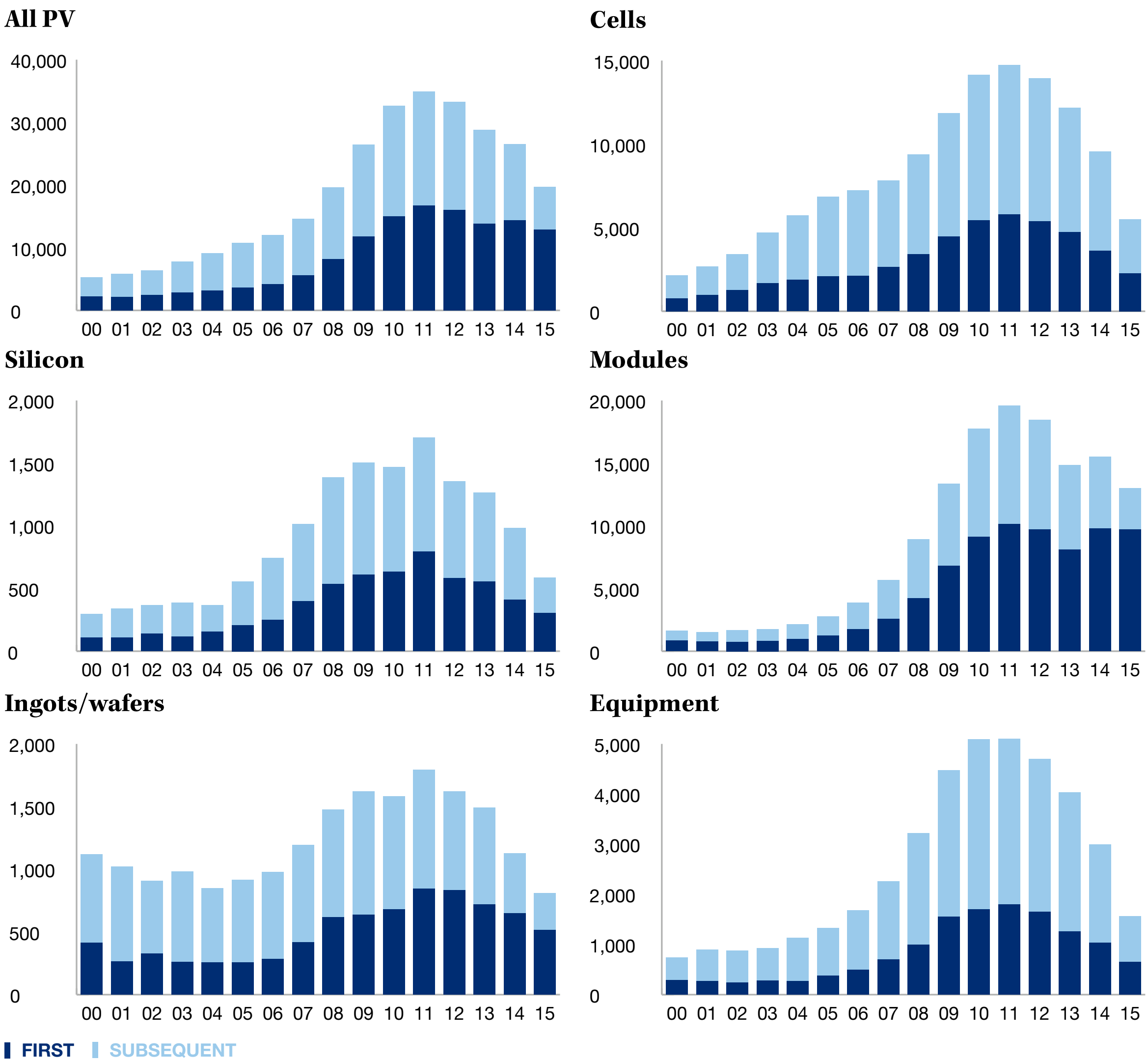
### How the PV value chain protects its knowledge assets

Throughout the first decade of the 21st century, there was a growing tendency to use patents to protect knowledge assets for all the technologies in the PV value chain (figure 3.11). The largest increases were observed for cells and modules, which peaked in 2011 at around 15,000 and 20,000 patent applications, respectively.

## Figure 3.11

### PV-related patent filings have been falling since 2011

PV-related patent applications worldwide by value chain segment, 2000-2015




Source: WIPO based on PATSTAT; see technical notes.

The growth in PV patenting activity has reversed recently. Between 2011 and 2015, the number of PV-related patent applications fell by 44 percent. PV patent filings have also fallen as a share of global patenting activity, decreasing 30 percent in just four years. The fall has occurred across all segments of the value chain, from silicon to module technologies, but is particularly pronounced for silicon, cells and equipment (figure 3.11).

There has also been dramatic change as regards the country of origin of patent applications. PV-related patent filings have fallen in all major innovating countries with the notable exception of China (see figure 3.8).

At first sight, the downward trend in global PV patenting since 2011 suggests that the outlook for technological innovation in the sector is gloomy. Is patenting becoming less attractive in the PV industry?

## Table 3.6

### R&D intensity and patent filings by top PV companies

| Company | Country | R&D intensity* (%) | | Average first patent filings per year | | Average annual R&D expenditure (USDm)* | Average PV patent filings per USDm R&D expenditure* |
|---|---|---|---|---|---|---|---|
| | | 2010 | 2015 | 2005-2009 | 2010-2014 | | |
| Silicon | | | | | | | |
| GCL-Poly Energy | CN | | 1.12 | 5 | 3.4 | 20.5 | 0.20 |
| Wacker | DE | 2.90 | 3.30 | 6 | 18.6 | 146.5 | 0.08 |
| REC | NO | 2.10 | 2.50 | 3.4 | 11.6 | 11.65 | 0.64 |
| OCI Company | KR | | | 1 | 1.75 | | |
| Cells | | | | | | | |
| First Solar | US | 3.70 | 3.60 | 5.6 | 52.2 | 112.8 | 0.26 |
| Trina | CN | 1 | 3.50 | 6 | 41.8 | 26.05 | 0.92 |
| JA Solar | CN | 2.50 | 3.20 | 3 | 9.4 | 16.5 | 0.38 |
| Canadian Solar | CN | 0.45 | 0.50 | 1 | 2.75 | 12.5 | 0.15 |
| Jinko Solar | CN | 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 | KR-DE | | 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 | DE | 6.80 | 5.30 | 4.4 | 11.8 | 20 | 0.41 |
| Meyerburger | CH | 5 | 17.20 | 0 | 1.3 | 49.5* | |
| Inverters | | | | | | | |
| Sungrow | CN | | 4.3 | 2 | 13 | | |
| SMA Solar | DE | | | 9 | 26.2 | 78.5 | 0.22 |
| SolarEdge | Israel | | 6.10 | 6.3 | 5.6 | 22 | 0.27 |

*Note: includes non-PV R&D.

Source: Carvalho et al. (2017).

In fact, it appears that the decrease is driven by two different forces. First, the number of applicants has collapsed.[33] Between 2011 and 2014, the number of applicants from the United States, Germany, Japan and the Republic of Korea declined, and entry of new applicants fell even more sharply. This also implies that, on average, the number of patent applications filed per applicant has increased, particularly in the main PV-producing countries. These trends are even more marked for alternative types of PV cells, where the decline in patent filings has been much lower.

The evolution of R&D intensity at major PV firms is consistent with these patent figures (see table 3.6). Almost all major players increased their R&D intensity between 2010 and 2015 – sometimes substantially – but their patenting activity grew even more. While the relation between R&D expenditure and patents is not straightforward, the disproportionate increase in patenting activity compared with R&D intensity suggests an increase in patenting intensity among surviving firms across the industry.

In other words, what seems to be happening is the following. Many players have exited the market and entry is becoming even more difficult. However, surviving firms are reacting by increasing their innovation efforts and filing more patents. In addition, these players are reacting to the industry shake-up by focusing their innovation efforts on the next generation of technologies. This suggests that IP-protected knowledge assets may become more valuable in this time of sectoral recomposition.

The second driving force is a reduction of the internationalization of PV patents. Patent applications can be divided into first applications for patent protection of an invention (known as first filings) and extensions of protection to another country for existing patent applications (known as subsequent filings). Both first and subsequent filings grew rapidly in the PV industry in the 2000s, but since 2011 both have fallen, with subsequent filings falling even faster than first filings. In the mid-2000s, each PV invention was filed on average in three different patent offices; by 2015, that average was only one-and-a-half.

This reduction suggests that more and more PV patent applicants opt out of seeking international protection. Virtually all PV patent applications from the main origins are filed domestically first. But the internationalization of PV technologies differs substantially across origins and destinations (table 3.7). U.S. applicants are the most foreign oriented across the main origins. Although they file less than 40 percent of their applications in any of the other main patent offices, the proportion is even lower for applicants from Europe, Japan and the Republic of Korea. Chinese applicants are the least likely to file for foreign protection, which reinforces the overall statistical trend away from internationalization as they are the only ones increasing their PV-related patent applications.

## Table 3.7

### Percentage share of patent families filed at major patent offices by origin, 1995-2015

| Origin | WIPO | USPTO | EPO | JPO | KIPO | SIPO |
|---|---|---|---|---|---|---|
| United States | 51.8 | 96.2 | 38.3 | 33.3 | 22.5 | 37.8 |
| Europe | 48.8 | 51.8 | 58.4 | 32.1 | 20.7 | 33.3 |
| Japan | 28.6 | 45.8 | 21.5 | 99.2 | 17.7 | 26.2 |
| Rep. of Korea | 15.2 | 31.7 | 10.1 | 13.9 | 99.5 | 17.1 |
| China | 2.0 | 1.7 | 0.7 | 0.6 | 0.3 | 99.7 |
| Other | 12.3 | 47.4 | 10.7 | 11.3 | 5.4 | 30.1 |
| Total | 20.0 | 32.8 | 16.9 | 31.0 | 21.3 | 55.5 |

Source: Carvalho et al. (2017).

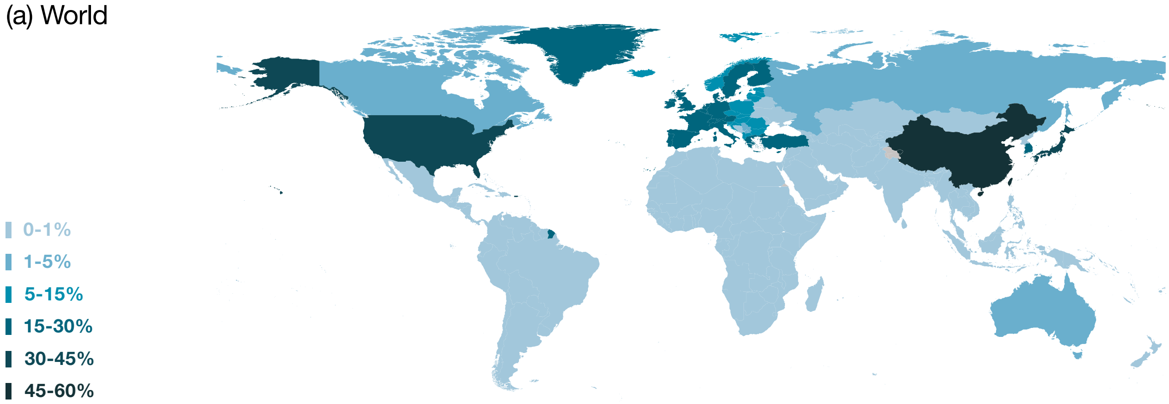
Worldwide extension of patent protection for PV-related innovations is very limited. Indeed, a handful of economies – notably China, the United States, Japan, the Republic of Korea and European countries – are among the few locations where some patent protection is sought. Figure 3.12a shows that PV technologies are virtually unprotected in all remaining economies, including Australia, the Russian Federation, Latin America, Africa and the Middle East. The huge number of recent Chinese PV patent applications – most protected only domestically – may affect these results (see figure 3.12b). But the general distribution remains qualitatively the same when these are excluded, as shown for the distribution of PV patent families from the United States in figure 3.12c.

## Figure 3.12

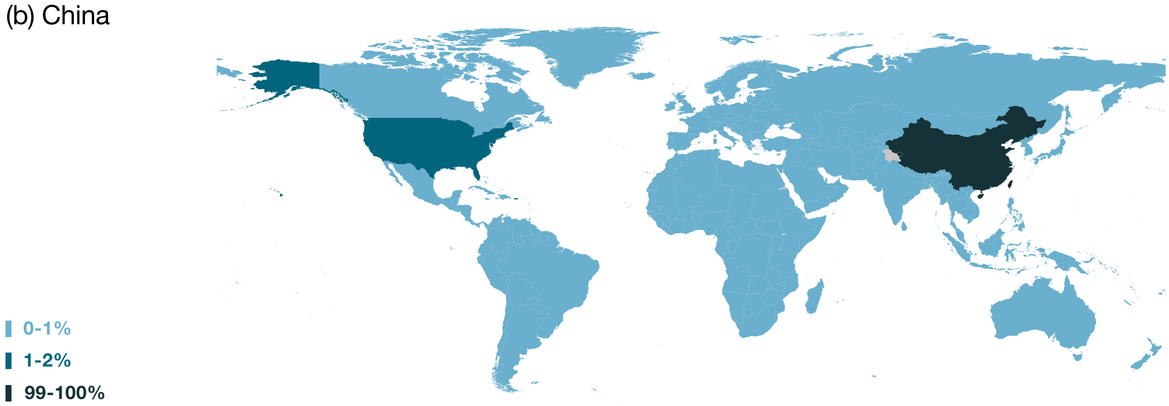
### Patent-protected PV technologies are concentrated in a few economies

Share of world, Chinese and U.S. PV patent families by protected country, 1995-2015

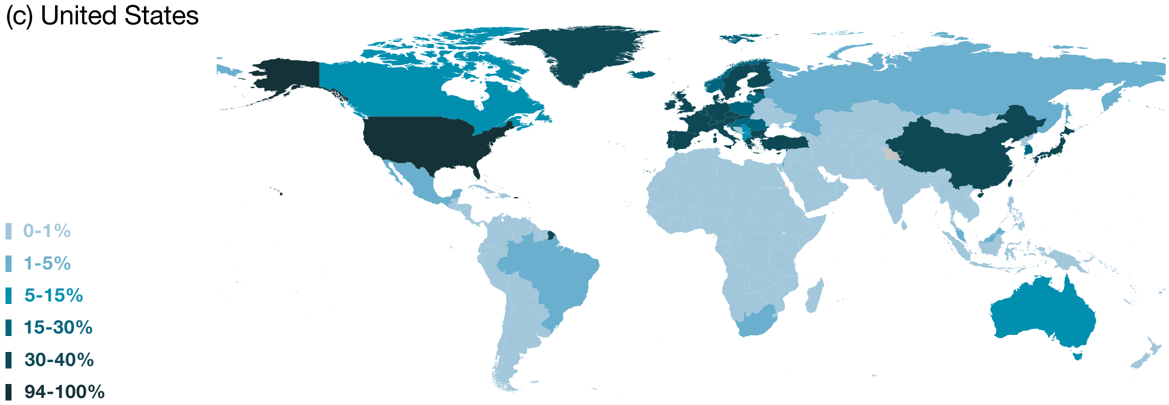
(a) World




(b) China




(c) United States




Source: WIPO based on PATSTAT; see technical notes.

### Can China sustain its position in PV production without IP protection?

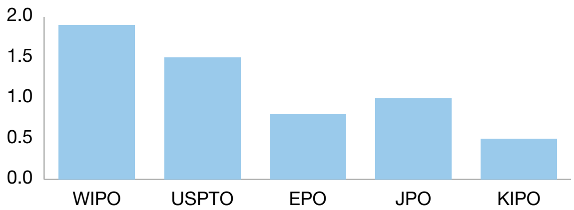
A striking finding from the patent analysis is the relative absence of Chinese applications at major patent offices. This is a phenomenon that is not unusual in terms of Chinese patenting activity generally; most foreign extensions of Chinese patents are confined to ICT-related technologies. The proportion of Chinese PV-related patent applications filed at all main foreign IP offices has never exceeded 2 percent. Shares for PV technologies are slightly higher than those for Chinese applications filed in these offices overall, but still remarkably low.

## Figure 3.13

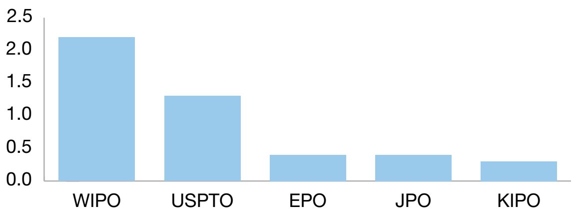
## Chinese applicants tend not to seek patent protection for PV technologies in other markets

Percentage share of Chinese patent families filed at major patent offices by PV value chain segment, 1995-2015

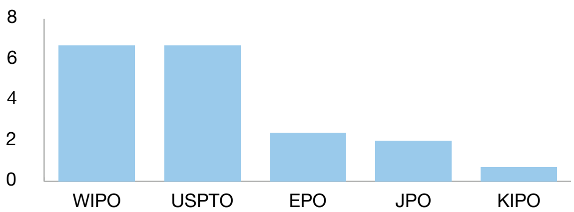
**Silicon**



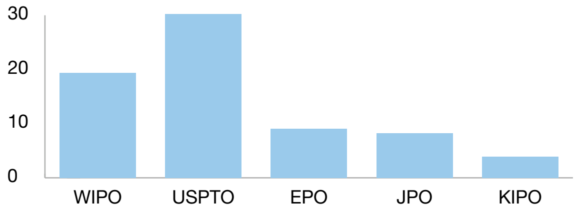

**Ingots/wafers**



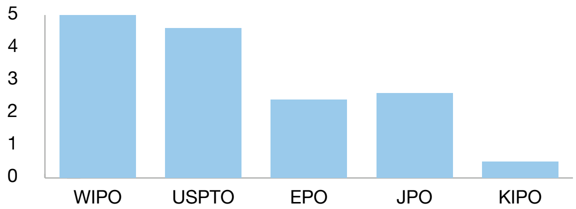

**Cells**



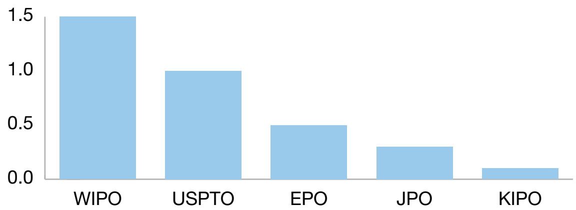

**Crystalline PV cells**



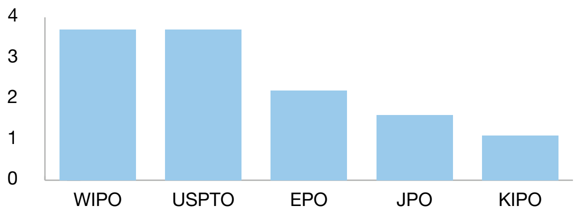

**Alternative PV cells**



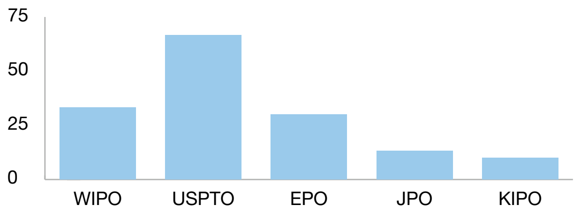

**Modules**



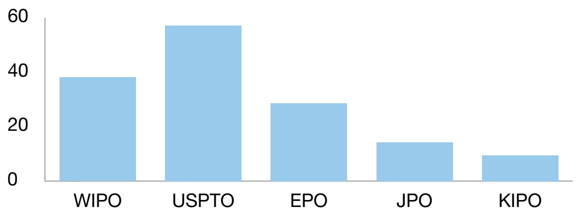

**Equipment**




**Equipment for crystalline PV cells**




**Equipment for alternative PV cells**




Source: WIPO based on PATSTAT; see technical notes.

As shown in figure 3.13, there is some variation in the internationalization of Chinese patent protection across PV segments. Patents are more likely to be filed internationally in relation to PV cells than for any other PV segment. In particular, international filings related to PV cells peak at roughly 7 percent in both the United States and through the Patent Cooperation Treaty (PCT) System. The generally very low internationalization rates for Chinese PV patenting contrast with Chinese companies' market share of around 80 to 90 percent in most segments of the PV value chain.

There are, however, some differences across the type of PV technology. The internationalization rate is significantly higher for Chinese patent filings related to crystalline cell technologies and production equipment for both crystalline and alternative cells (figure 3.13). China has a relatively small number of patents in these three technologies, but they are remarkably likely to have foreign extensions, especially in the United States.

It remains to be seen what the long-term impact of the absence of international protection for most Chinese-owned PV technologies will be. Will protecting them in China only be enough to maintain Chinese producers' commercial success, or does it give other industry players an opportunity to come back? Only time will tell.

This is particularly the case if alternative technologies to crystalline PV cells finally make their way to 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 – may be better positioned to exploit PV products currently on the shelf.

### A brand new PV world?

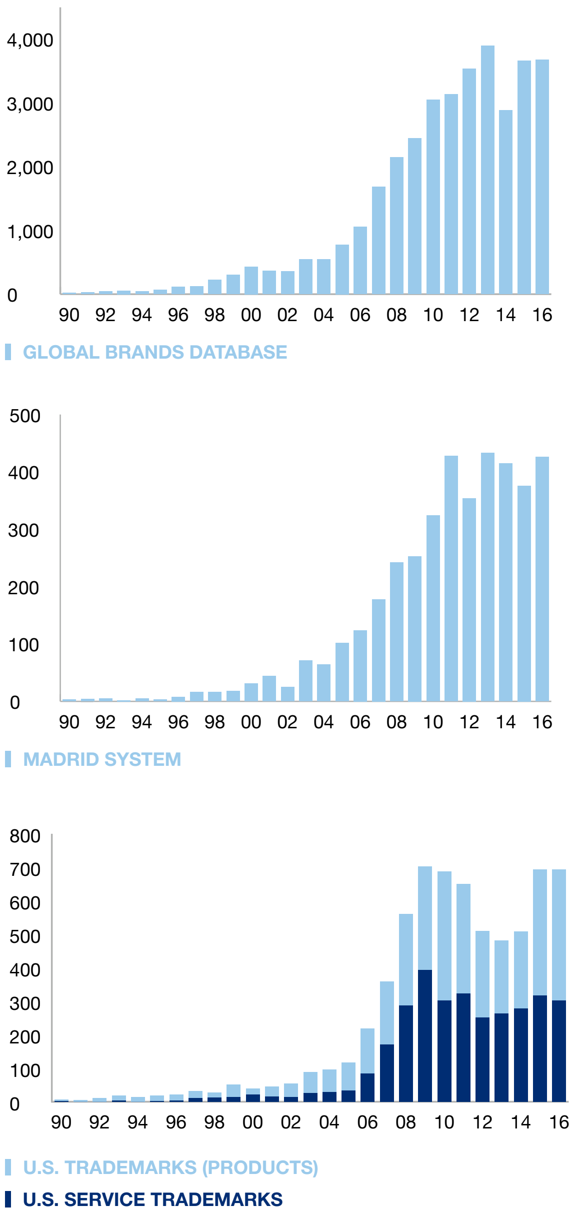
There is increasing evidence of a growing role for reputational assets in downstream segments. This is very relevant for at least two reasons. First, these are the more profitable segments, where value added must to a great extent be produced locally. Second, these segments have a broader geographic distribution than upstream or midstream ones, remaining located largely in industrialized economies such as Europe and the United States.

A sign of consolidation in the PV industry is the increasing importance of branding-related activities. As demand for PV technologies and their capacity have grown exponentially in the past 10 years, so too has the use of trademark protection for PV products and services. Figure 3.14 illustrates this trend. All the main sources of trademark data – the USPTO, WIPO's Global Brands Database and the Madrid System – support this finding, with figures for 2016 four to six times higher than those for 2005.

## Figure 3.14

### Brand protection is increasingly important in the PV market

PV-related trademark applications, 1990-2016




Source: WIPO based on the USPTO, the Global Brands Database and the Madrid System.

What lies behind this trend? One direct cause is simply the rapid growth of the market. A complementary explanation relates to the tight margins and vertical integration discussed above. Most solar PV projects are financed through debt financing from banks, meaning that interest rates account for a significant part of the project cost. Interest rates are determined not just by market risk, but also by technological risk, making it particularly important for solar PV project developers to source technologies from recognized players. The bank has to have confidence in both the project developer's reputation and the technological inputs that will be employed. PV projects will be considered "bankable" if they have demonstrated well-functioning technologies in the market, providing stable electricity generation and reliable project yields.

One way in which upstream and midstream companies have managed to maintain their profit margins is by moving downstream to project development, to demonstrate how well their technologies function in the market. In this process, vertically integrated companies have invested in building upstream and midstream reputation – the so-called Tier 1 and 2 brands.

The increasing importance of private end-users of PV technologies may also change the role of other knowledge and reputational assets along the PV value chain. A disproportionate increase in PV-related service marks hints at this downstream pull for branding activities in the PV industry. Another increasingly important aspect of intangibles concerns the aesthetics of PV modules that are installed in private consumers' residences. Following this trend, other forms of IP – notably industrial designs – are likely to become more important in the PV industry (see figure 3.15).

## 3.4 – Conclusion

The spatial evolution of the solar PV value chain resembles that which occurred in many other industries such as semiconductors, electronics and domestic appliances.

PV panels and systems are now mostly commodities rather than differentiated goods: their most relevant quality 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 alternative PV technologies bore great hopes in the early 2000s, when market demand and prices for solar PV technologies were high due to policy support mechanisms in Europe.

As a result, PV products initially invented in the Western world decades ago were no longer protected by patents, and Chinese firms needed only to acquire the knowledge to manufacture their components efficiently along the value chain. This highlights two channels of technology transfer. First, Chinese firms got access to production equipment and turnkey fabrication lines supplied by U.S., European and Japanese firms. The production equipment was protected by patents to some extent, but there was enough competition in international markets to maintain reasonable prices. Second, Chinese firms also relied on knowledge transmission through human capital, in the form of their founders and workers who studied abroad in regions that engaged with innovation in solar PV technologies. The PV industry is a case study of a complete form of technology transfer to an emerging economy, as indicated by the fact that Chinese firms have now also become the leaders in PV production equipment.

Understanding how channels of knowledge transfer affect the spatial distribution of the value chain has implications for future innovation. The solar PV market is now saturated with an incumbent technology whose depressed prices provide tight profit margins for companies. Firms can dedicate their R&D efforts either to high-level process innovations that will reduce production costs in the dominant technology, or to new solar PV product innovations whose production prices are below those for the incumbent technology.

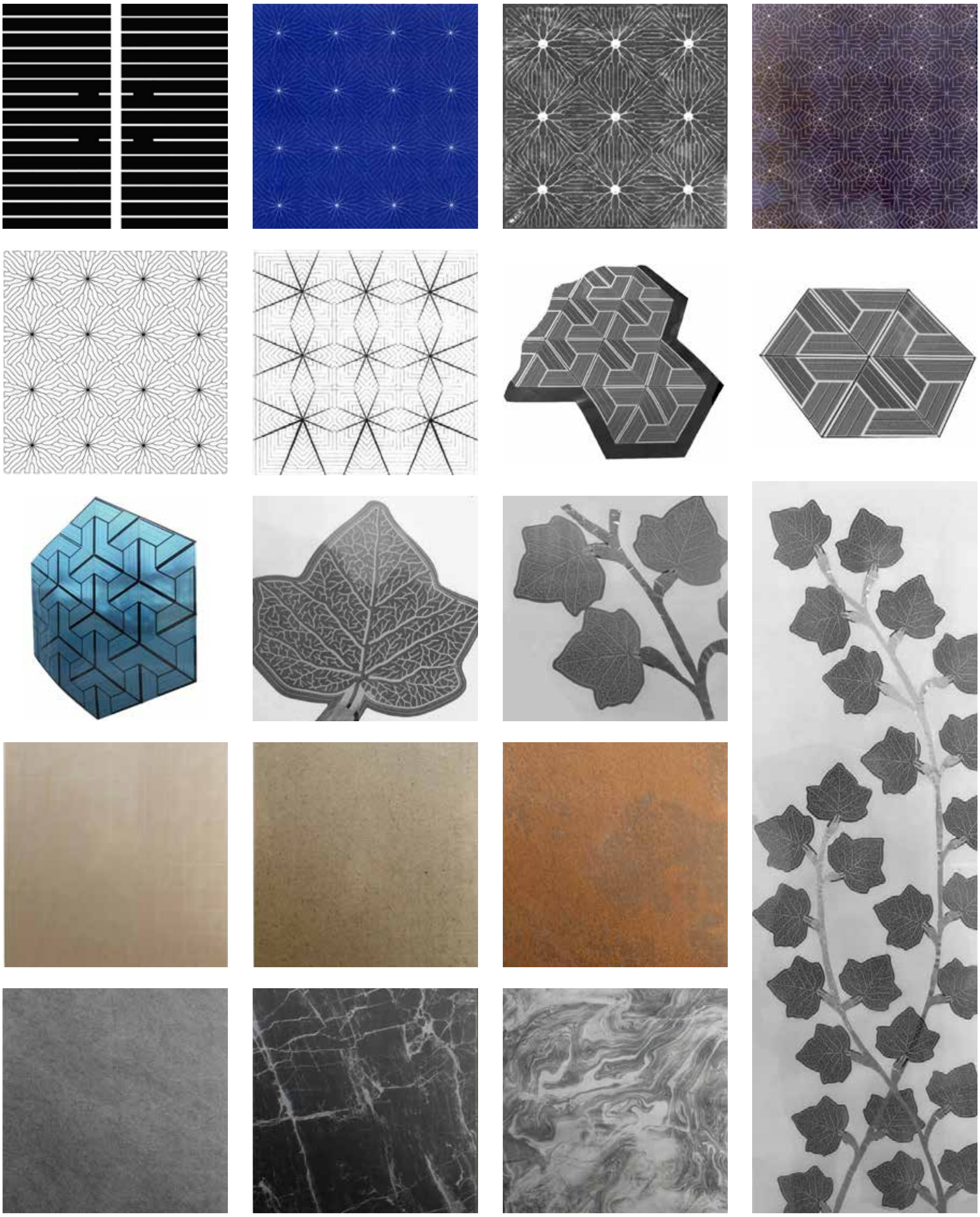
The major changes undergone by the global PV industry during the last decade have been accompanied by a renewed interest in intellectual property protection, as is illustrated by the fact that companies that survived the collapse in PV prices worldwide seem to have increased their patenting propensity recently.

As this chapter has documented, IP protection of intangible assets was not a key determinant in the success of Chinese companies, but it may well nevertheless become a key ingredient for commercial success in the coming decades.

## Figure 3.15

### Solar panel designs are becoming more creative

Selected solar panel industrial designs filed via the Hague International Design System



Source: Hague System, WIPO.

# Notes

1. This chapter draws on Carvalho et al. (2017).
2. US patent 2402662, filed on May 27, 1941.
3. See Fraas (2014) and Perlin (1999).
4. See Carvalho (2015b), de la Tour, Glachant and Ménière (2011), Fu and Zhang (2011) and Wu and Mathews (2012).
5. Schmela et al. (2016).
6. BNEF (2014).
7. BNEF (2017).
8. See BNEF (2014) and ENF (2012, 2013a, 2013b).
9. Wesoff (2015).
10. Ghosh (2016).
11. Goodrich et al. (2011).
12. Schmela et al. (2016).
13. Johnson (2013).
14. Schmela et al. (2016).
15. See IEA (2016).
16. IEA (2016) and SEMI PV (2017).
17. See Carvalho (2015a).
18. See BNEF (2013).
19. See the general discussion in chapter 1, section 1.4.
20. See IEA (2016), SEMI PV (2017) and Schmela et al. (2016).
21. Ekins-Daukes (2013) and NREL (2017).
22. SEMI PV (2017).
23. IEA (2016).
24. IEA (2016) and SEMI PV (2017).
25. SEMI PV (2017).
26. NREL (2017).
27. de la Tour et al. (2011).
28. IEA (2016) and SEMI PV (2017).
29. de la Tour et al. (2011), Fu and Zhang (2011) and Wu and Mathews (2012).
30. de la Tour et al. (2011) and Wu and Mathews (2012).
31. Luo et al. (2017).
32. de la Tour et al. (2011).
33. See Carvalho et al. (2017).

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