Solar PV Trade and Manufacturing

A Deep Dive

February 2021

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Section 1. Executive Summary

172GW

Crystalline silicon PV module manufacturing capacity build since 2017

83%

Polysilicon supplied by top 10 firms in 2019

$0.20/Watt

Monocrystalline silicon module price in 3Q 2020

The following is an in-depth examination of current solar photovoltaic (PV) manufacturing and trade trends produced under an ongoing partnership between BloombergNEF and the Energy Security & Climate Change Program at the Center for Strategic and International Studies in Washington. This report focuses exclusively on the PV industry and offers a deeper-dive look at current global competitive dynamics. Similar reports covering the wind and battery storage sectors have been published separately and are available for download at both CSIS.org and BNEF.com.

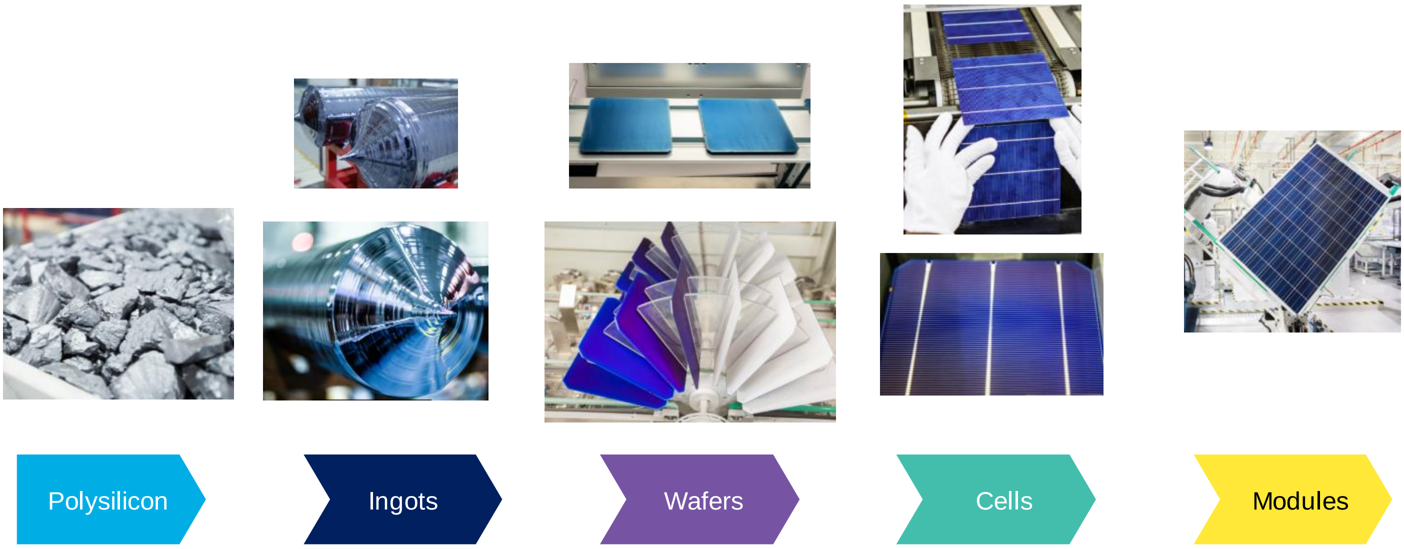
1. The PV manufacturing value chain consists of five main components: polysilicon, ingots, wafers, cells and modules.
2. The quality of Chinese products across all value chain segments is improving. The trade dispute between the U.S. and China that began in 2012 prompted Chinese companies to up their game and Chinese companies are now leading innovators in the space.
3. The greatest level of market consolidation exists farthest up the PV production chain. The top 10 polysilicon and wafer firms supplied 83% and 95% of the market in 2019, respectively.
4. Technical hurdles are highest for plants that make polysilicon and wafers. These plants are also costly to build and take longest to construct. Cell and module factories can be built faster and can respond quicker to technological trends and policy developments like import tariffs.
5. Major polysilicon makers in South Korea have recently ceased domestic production because they can no longer compete against new, more efficient factories in China. Since 2017, 91% of new polysilicon processing capacity (on a nameplate basis) has been built in China. In the U.S., the newest factory was built in 2016 by Wacker-Chemie in Tennessee.
6. Since 2010, over 220GW of new wafer manufacturing capacity has been brought online. Almost all of this was built in China where there is over 227GW of commissioned nameplate capacity, compared with just 18GW in all other countries combined.
7. The market for solar cells is much less consolidated. In 2019, the top 10 cell producers supplied 59% of the market. Leading cell makers are vertically-integrated companies that own wafer and/or module manufacturing as well. This allows them to exert better cost control and manage output certainty.
8. Module assemblers rely heavily on supply of external components such as PV-quality glass and aluminum frames. A local module assembly industry in a country can benefit from these adjacent industries being located nearby.
9. Given low technical and financial barriers, companies have historically proven relatively agile at responding to tariffs or other policy developments. After the U.S. imposed duties on Chinese-made solar cells, for instance, large integrated manufacturers built both cell and module assembly plants across Southeast Asia. The tariffs had limited success in boosting domestic manufacturing in the U.S.

10. The U.S. surge in demand for PV equipment over the past decade has not been accompanied by a similar rise in domestic PV manufacturing across the value chain. Instead, the U.S. has relied on imports, first from China then from Southeast Asia.
11. The U.S. has relied heavily on other countries to fulfil its demand for solar cells and modules. Countries of origin for imported cells and modules fluctuate with different U.S. government trade actions.
12. Most U.S. solar installations today use modules manufactured at plants located in Vietnam, Malaysia and Thailand that are owned by Chinese firms.
13. Whether a silicon-based module is assembled on U.S. soil or abroad, about half its total value is accounted for by non-silicon raw materials mainly produced in China. As a result, despite U.S.-imposed tariffs on Chinese-made PV cells and modules, China continues to accrue the largest share of value from modules installed in the U.S. – regardless of where the equipment gets assembled.

Section 2. Solar PV manufacturing overview

The PV manufacturing value chain can be broken down into five main components: polysilicon, ingots, wafers, cells and modules (Figure 1). The production of each of these components requires very different processes and competencies. A variety of specialized materials and equipment are used in each of the five steps of the value chain.

Figure 1: The solar PV manufacturing value chain



Source: BloombergNEF, Longi

Manufacturing plants in different segments of the value chain can have substantially different output volumes. As a result, there are relatively few plants globally producing polysilicon compared to those assembling modules. Currently, much of the industry is concentrated in China though other countries are also producers. Table 1 provides a summary of key characteristics of the solar PV sector.

Table 1: Summary of PV supply chain characteristics

	Number of factories	Largest manufacturer	Market concentration (by country)	Market concentration (by company)	Adjacent industries	U.S. reliance on imports	Barrier to entry	Value
Overall	1,215	China	High	High	Power, silicon, glass	High	Med	High
Polysilicon	77	Germany	High	High	Power, silicon metal	N/A	High	High
Wafers	158	China	High	High	Crucibles, wire saws	Low	High	High
Cells	363	China	High	Med	Silver, aluminum	High	Med	High
Modules	617	China	High	Med	Glass, aluminum	High	Med	Med

Source: BloombergNEF. Note: Does not include standalone ingot factories, most ingot production is made within wafer plants.

The manufacturing process at a glance

Polysilicon is the key feedstock for the production of solar cells. Its raw material, silicon dioxide (SiO_2), is high purity quartz sand and one of the most common minerals on Earth. The purification process that transforms raw silicon into hyper pure polysilicon, or “solar-grade” silicon that is suitable for PV, occurs in two stages.

The first involves taking the sand and heating with a clean type of charcoal or coke. This results in 98% pure silicon, also known as “metallurgical grade silicon”. The next step is to heat the metallurgical grade silicon with acid to convert it to a gas called silane. The gas is then put into a hot reactor vessel, with some cooler 'seeds' of silicon crystal, and condenses to form pure rods of silicon, which are broken into chunks.

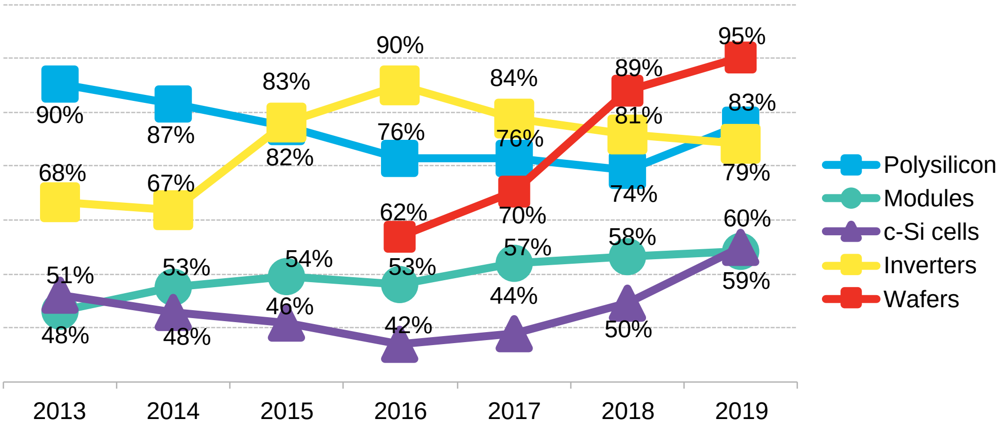
After the polysilicon arrives at the ingot factory as a sack of chunks, it is shaped into either multicrystalline or monocrystalline ingots by melting it and allowing it to cool slowly into solids. To create higher-value monocrystalline (mono) ingots, the crystal must grow very slowly into a single perfect block. Multicrystalline is made much faster by allowing interlocking crystals to form multiple nodes. Ingots are then sliced into wafers and doped with either phosphorus (p-type) or boron (n-type), which change their electrical properties by making either free electrons or electron holes that respond when excited by light.

Mono is a more efficient, yet costly product. However, as outlined later in this report, the costs for mono have fallen at a faster pace. Most ingot factories also contain wafer-manufacturing capabilities. This report has assumed wafer manufacturing data to include ingot capacity as well. The doped wafers are electrically connected and sealed into cells, then finally strung and finally assembled into the modules that go onto roofs or into open spaces.

Market overview

Generally speaking, the further up the PV production chain, the more consolidated the market is (Figure 2). The top ten polysilicon and wafer firms supplied 83% and 95% of the market in 2019, respectively. Polysilicon and wafers have higher technical hurdles and factories are more expensive and time-consuming to build. Cell and module factories can be built relatively quickly and can respond faster to market trends and policy moves such as the imposition of import tariffs.

Figure 2: Share of market supplied by the top ten firms across the PV value chain



Source: BloombergNEF

Large solar manufacturing companies often have some degree of vertical integration. The module assembly giants of 2020 – Longi Green Energy Technology, Trina Solar, Jinko Solar and Canadian Solar – all have some wafer and cell capacity too. Most polysilicon companies are large chemical firms not otherwise involved in the downstream solar industry.

Section 3. Manufacturing

In this section, we review production trends in each segment of the value chain in greater depth. For each segment, we give an overview of total available manufacturing capacity and production. Because overcapacity has been commonplace in the PV industry historically, we have sought to differentiate between capacity and production of goods whenever relevant.

3.1. Polysilicon

Market concentration among top polysilicon makers increased in 2019 as many small Chinese manufacturers halted production. Larger Chinese polysilicon firms have now concluded most of the capacity expansions they announced in 2017, and this has fundamentally altered the global market landscape.

OCI and Hanwha Chemical, major polysilicon makers in South Korea, both recently ceased domestic production after determining they could no longer compete against newer, more efficient factories in China, which also have access to cheap electricity. The trend towards market consolidation is expected to continue as big Chinese firms expand capacity and profitability and less cost-efficient players suffer.

Polysilicon prices respond to the market

Solar wafers and cells today require less polysilicon on a gram per Watt basis thanks to manufacturer improvements. This partially offsets growth in installation of solar modules.

From 2005-2009, polysilicon prices surged due to undersupply, but they have fallen since as more production has come online (Figure 3). Prices that exceeded $450/kg pre-2009 made the industry highly profitable for the few firms with operating factories, mainly Japanese, U.S. and German producers. Prices dropped to an all-time low of $6.27/kg in 2Q 2020, though they rose in 3Q 2020 as two Chinese factories closed due to accidents.

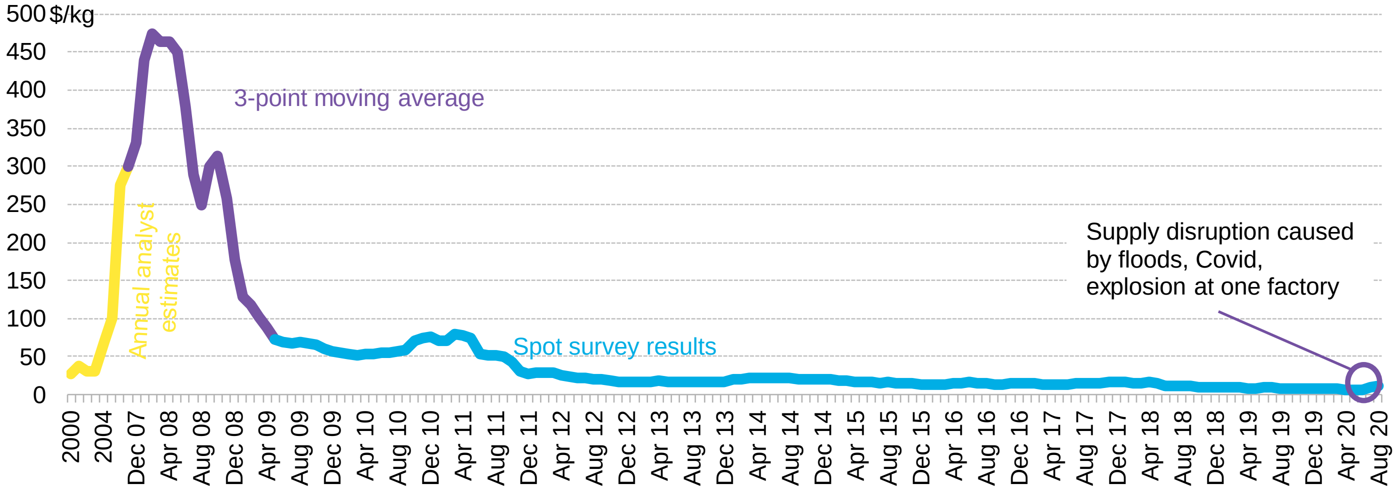
Falling prices have cut into profits across the industry, even for the largest producers. A majority of medium-sized players and non-Chinese manufacturers have suffered from negative operating margins and need a price range of $10-11/kg to keep positive cash flows.

Some price volatility and risks remain as the global polysilicon supply is increasingly dependent on a handful of factories in China. Production halts in July 2020 across just a few factories sent prices soaring 58% and 90% for monocrystalline and multicrystalline wafers, respectively (Figure 3).

Monocrystalline cells require higher-quality polysilicon

Demand for higher-purity polysilicon feedstock has taken off as the PV industry has moved from multicrystalline towards monocrystalline wafers and cells. The price premium for higher quality polysilicon encouraged large Chinese makers to upgrade their factories and improve their product. High capital expenditures, long timelines, technical hurdles and uncertainty around profitability have it hard for smaller firms to keep pace.

Figure 3: Historical polysilicon prices



Source: BloombergNEF, Various. Note: Annual data 2000-07 from various industry sources. Data November 2007 to May 2009 based on a 3-point moving average of actual spot deals. Consistent monthly data collection using the BloombergNEF Spot Price Index (web | terminal) began in May 2009. Starting in March 9, 2020, the data is from PV Infolink.

Polysilicon price drivers

The cost of making polysilicon is largely determined by electricity prices and the cost of silicon metal (Figure 4, Figure 5). Factories have high energy needs for the chemical process used to refine silicon metal into solar-grade silicon, or polysilicon.

Figure 4: Polysilicon cash costs across large producers, 2018

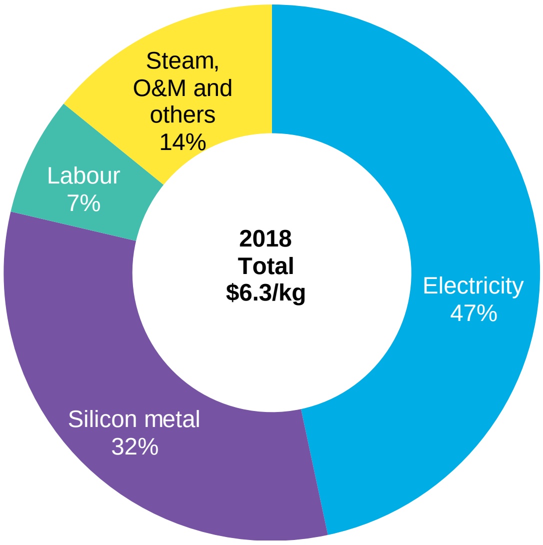
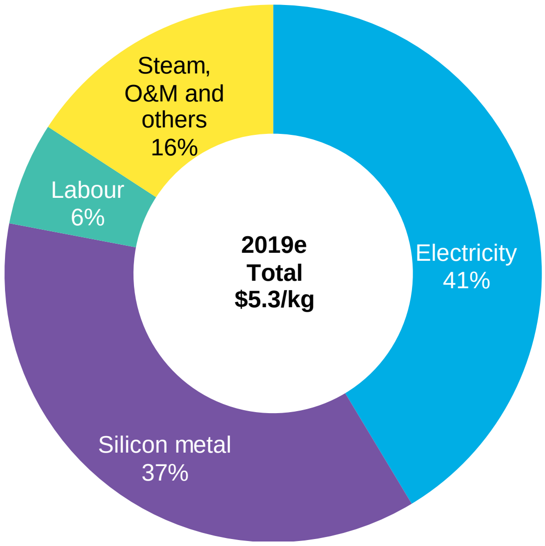


Figure 5: Polysilicon cash costs across large producers, 2019



Source: BloombergNEF, company filings, industry sources

Most big Chinese manufacturers are able to produce at lower cost than the weighted average spot price for polysilicon. The seven most cost-competitive plants across Xinjiang, Sichuan and

Inner Mongolia supplied 65% of the market in 2020 at costs significantly below the annual marginal cost of $6.6/kg.

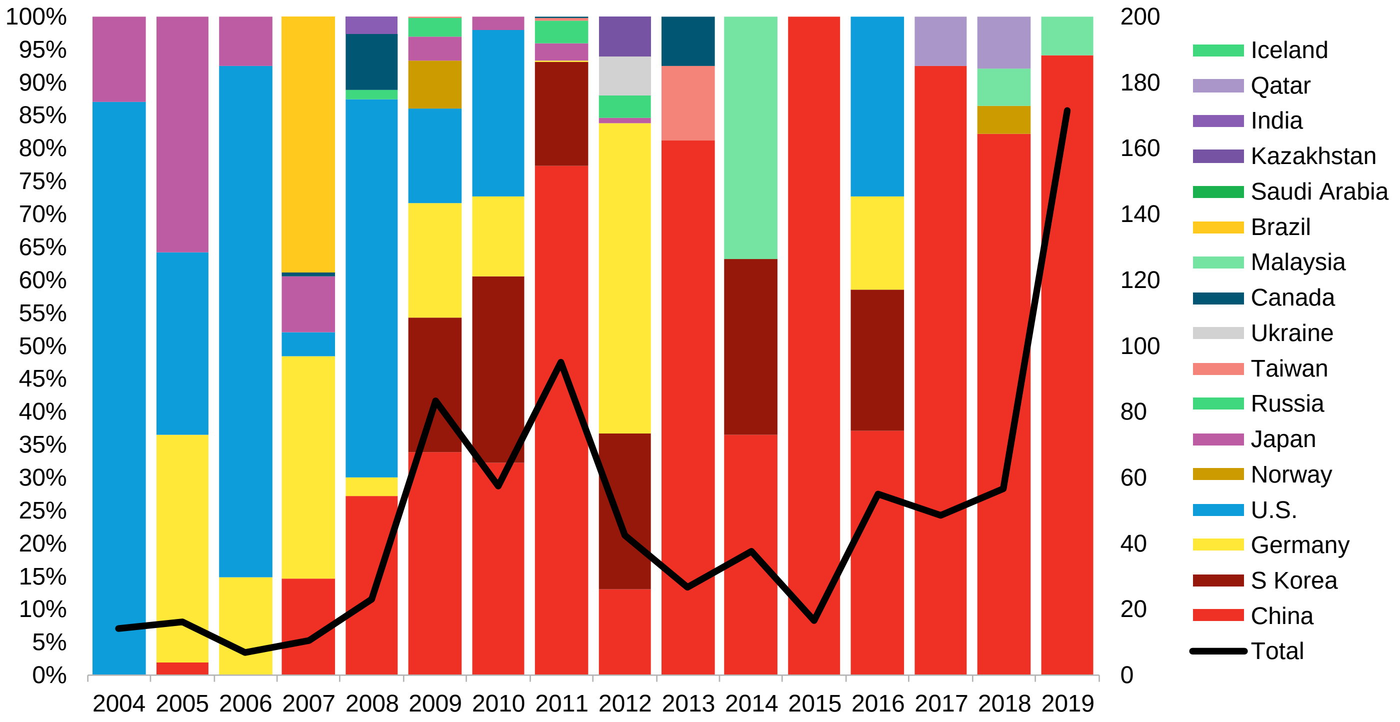
Global polysilicon manufacturing capacity

Chinese polysilicon firms added 74,000 tons of new nameplate capacity in 2011. Up to around 2012 however, Chinese products did not satisfy quality requirements from many wafer makers and could not compete against U.S. and German equipment. The story changed after China retaliated against U.S. import tariffs on Chinese cells and modules in 2012, by levying duties on U.S. polysilicon. Chinese polysilicon makers used the trade dispute to scale up and gain the experience to produce higher quality polysilicon.

Since 2017, 91% of new global polysilicon nameplate production capacity has been built in China (Figure 6). The current cost of building a new factory in China runs at about $15 million per thousand tons, or $39 million per gigawatt. Factory capex has come down over time, but high technical hurdles remain.

Tongwei, Daqo, Xinte, GCL and East Hope alone added over 80% of new capacity in China since 2017 (261,000 tons). In the U.S., the newest factory was built back in 2016 by Wacker-Chemie in Tennessee with a capacity of 20,000 tons. OCI, headquartered in South Korea, has faced stiff competition from China for its domestic-made polysilicon. The firm built its newest plant in Malaysia in 2014 and has recently closed all of its South Korean manufacturing.

Figure 6: Annual polysilicon factory additions per country of factory location and capacity in tons (right)



Source: BloombergNEF

Annual polysilicon production

Chinese polysilicon output

Chinese ingot and wafer makers at one time relied on international polysilicon companies in Germany and the U.S. for high-quality polysilicon. However, this foreign dependence has shrunk over time and China imported only 20% of the polysilicon it used in PV production in 1H 2020. Meanwhile, German and South Korean polysilicon producers rely heavily on exporting to China.

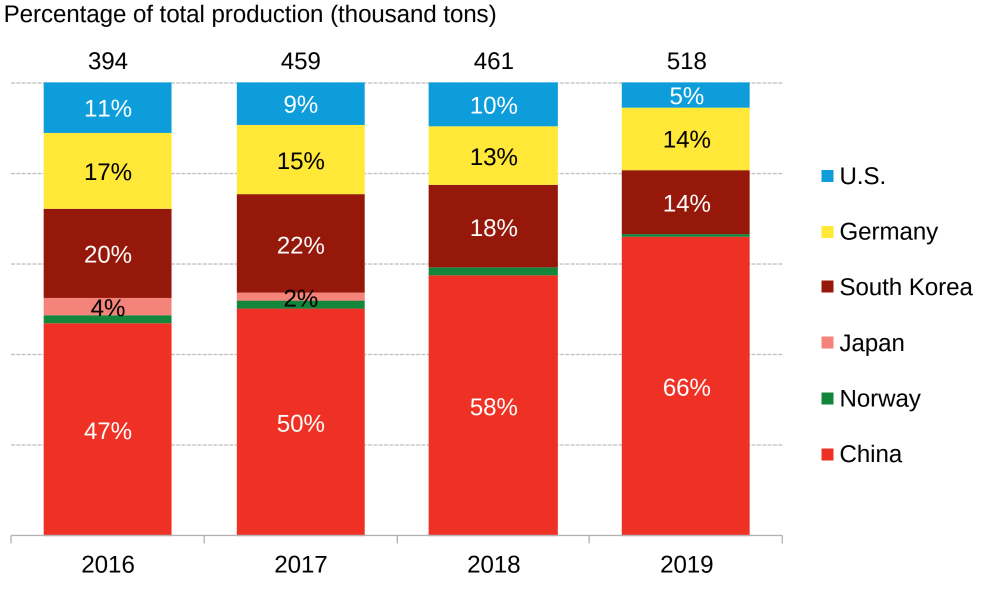
Seven of the world's top 10 polysilicon producers in 2019 were Chinese (Figure 7). After adding 60,000 tons of new capacity in 2019 under a partnership with Longi Green Energy Technology, Tongwei became the largest Chinese polysilicon maker in 2019 with 64,464 tons. This represented a 234% increase in output compared with 2018 and can be attributed to having the lowest production costs. Tongwei's ambitions go even further; the firm is building two new factories totalling 75,000 tons along with Longi Green Energy Technology.

International players – Germany, South Korea, the U.S. and Norway

International players, especially Wacker-Chemie in Germany, still do a better job than Chinese companies at avoiding undesired contamination during both the breaking up of rods into smaller pieces and the packaging process. As the market moves toward mono wafers, polysilicon of higher purity is required. Chinese firms have raised their quality standards since 2017, but are still not at the same level of Wacker's product.

Wacker was the biggest producer of polysilicon in 2019 and increased its output by 20% to 72,000 tons. As well as supplying the solar industry, the firm also sells to the electronics semiconductor industry. The company owns three factories, two in Germany and one in Tennessee. The U.S. plant, affected by Chinese import tariffs on U.S. polysilicon, made 12,000 tons with a total capacity of 20,000 tons in 2019.

Figure 7: Annual polysilicon production by country of company headquarters



Source: BloombergNEF

South Korean firm OCI was the second-largest producer of polysilicon in 2019 thanks to a capacity expansion of its Malaysian plant. However, like other Korean manufacturers such as Hankook Silicon (bankrupt in 2018) and Hanwha Chemical, OCI had to shutter its 52,000-ton factory in South Korea in early 2020. OCI and Hanwha's plant closures in 2020 will leave South Korea with no active polysilicon capacity due to high electricity prices and Chinese import tariffs on South Korean polysilicon.

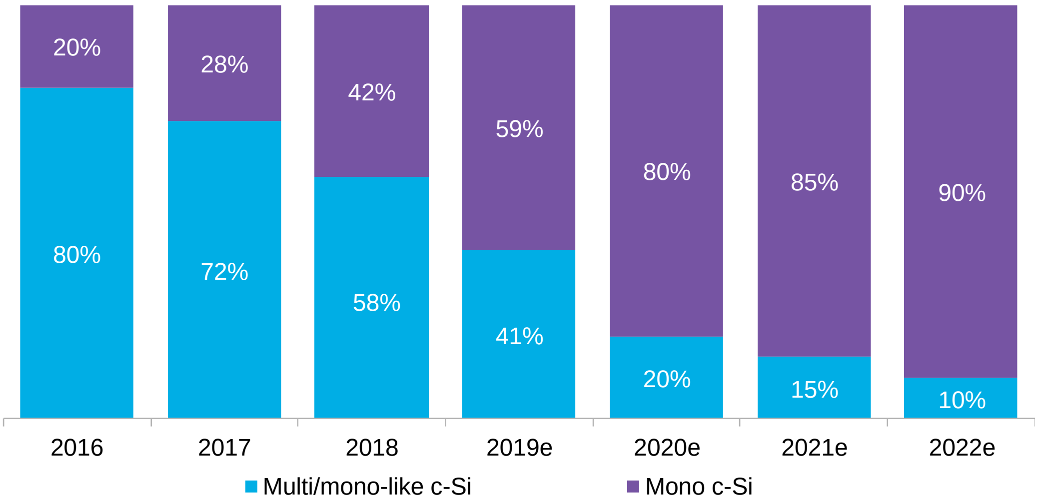
Hemlock Semiconductor's plant in Michigan produced 25,000 tons of polysilicon in 2019 vs. a total nameplate capacity of 35,000 tons. Cheap electricity in China, tariffs on U.S. polysilicon imports and improved quality across Chinese product have make it increasingly hard for Hemlock to find buyers in China, where almost all PV wafer makers are based. However, the U.S. firm still has some long-term supply contracts outstanding and owns ingot production in Taiwan. Product from that plant is shipped to some Chinese wafer makers.

3.2. Wafers

The share of monocrystalline wafers used in PV cells has surged since 2017 at the expense of multicrystalline. The market share for mono was expected to exceed multi in 2019, with almost 60% of the total. From 2020 on, the overwhelming majority of silicon wafer production is expected to be monocrystalline (Figure 8).

The surge in mono products can be explained by a combination of both supply and demand forces. On the supply side, new Chinese polysilicon factories built after 2017 have finally met the necessary product quality required for monocrystalline silicon wafers. On the demand side, cell manufacturers have switched to monocrystalline because it yields higher cell efficiencies.

Figure 8: Market split between mono and multi silicon wafer products



Source: BloombergNEF

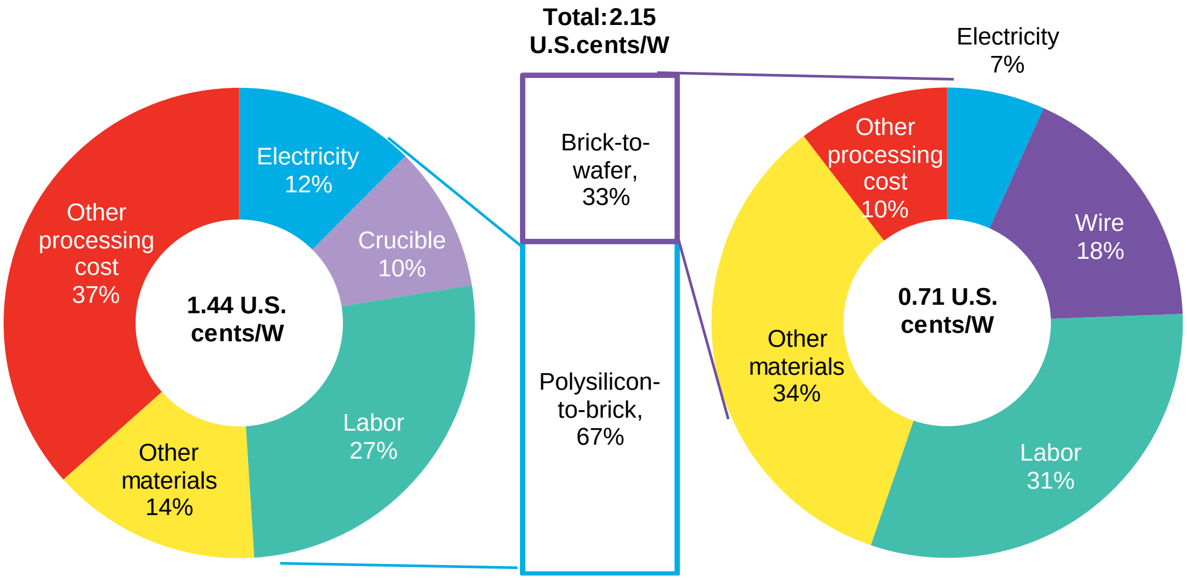
High barriers to entry caused market consolidation

Vertical integration, high factory capex and technical hurdles have made the wafer market the most consolidated segment of the PV value chain. While some wafer makers also make cells, most cell makers have limited or no wafer capacity, preferring to outsource this step of the value chain.

Best-in-class cost structure

Best-in-class cash costs for processing silicon into mono and multi wafers were 2.15 cents Watt in 2019 (Figure 9). The corresponding cost for producing multi wafers was 1.73 cents per Watt. Polysilicon ingots are cut into bricks before being further sliced into wafers. Major costs are labor, electricity and crucibles. The lowest cost mono and multi producers typically enjoy lower crucible costs thanks to in-house crucible production. Monocrystalline silicon is more expensive to make due to the use of premium polysilicon, as well as higher processing and labor costs in the polysilicon-to-brick conversion.

Figure 9: Best-in-class cash costs of making polysilicon into mono wafers by the end of 2019



Source: BloombergNEF

Wafer manufacturing capacity

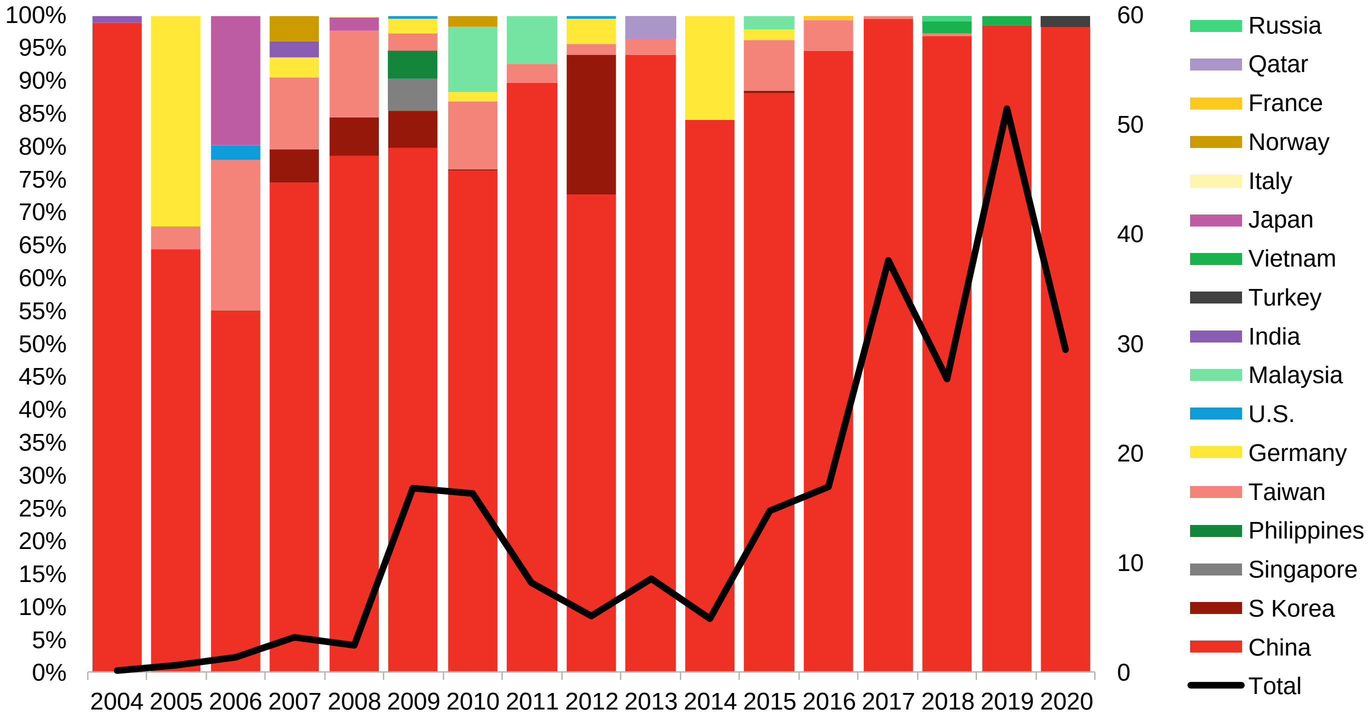
Since 2010, over 220GW of new wafer manufacturing capacity has been brought online. Almost three quarters of this was built after 2016. With minor exceptions, all of these new factories are located in China. China has over 227GW/year of commissioned wafer nameplate capacity as of 2020, compared with just 18GW/year across the rest of the world.

Nearly all the PV industry's demand for polysilicon comes from China. For the country, having control over wafer manufacturing has been critical on its path to global dominance of the PV supply chain. Wafer factories require high upfront capital expenditure and bear many technical hurdles, which makes it difficult for new factories to be built outside of China.

Wafers are an essential piece of the final cell and module composition. Given the current state of global polysilicon oversupply, wafer makers enjoy strong market and purchasing power. International polysilicon makers have struggled since China managed to supply most of its domestic wafer needs with locally manufactured polysilicon (Figure 10).

At the same time, wafers are a large part of the cost breakdown for solar cells and modules. Many large cell and module companies such as Trina Solar, Jinko Solar or Canadian Solar own wafer factories as well. Meanshile, Longi Green Energy Technology is a wafer maker that has entered cell and module production. Cell and module producers compete fiercely to supply high-efficiency solar panels at competitive costs. Therefore, securing reliable supply of mono wafers is crucial for large incumbents.

Figure 10: Annual wafer factory additions per country of factory location and yearly GW



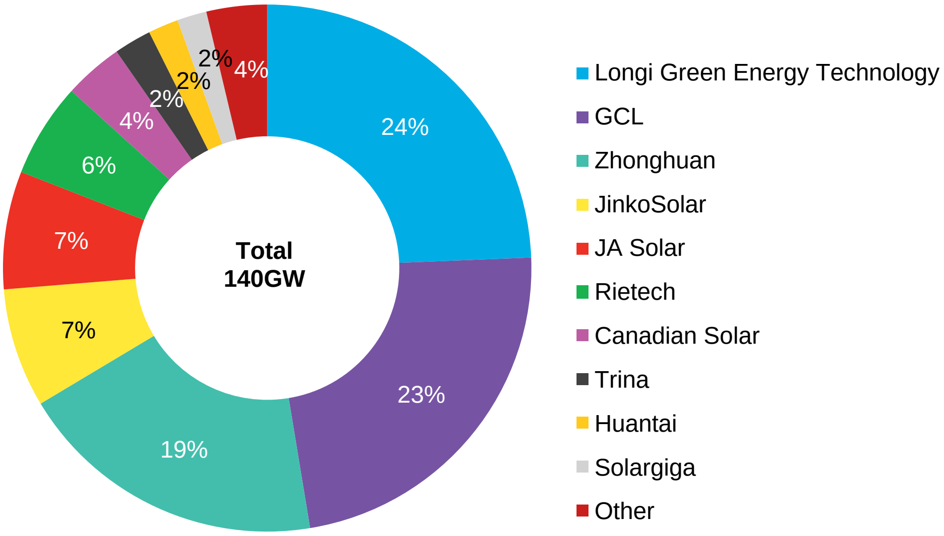
Source: BloombergNEF

Annual wafer production

In 2019, the top ten wafer makers supplied 95% of the market, up from 62% in 2016 (Figure 11). With the exception of Canadian Solar, which is headquartered in Canada but has factories in China, all of the companies were based in China. A total 140GW worth of wafers were made in 2019. The three biggest players alone (Longi, GCL and Zhonghuan) supplied 66% of the market.

In 2018, almost the entire wafer market flipped to using diamond wire saws to cut the wafers. The change meant thinner wafers and less losses of valuable silicon ingot. It also gave monocrystalline cells a decisive advantage over multicrystalline. Mono wafer specialist Longi Green Energy Technology, which had expanded into cell and module production to prove the viability of mono, became the biggest wafer producer in 2019 and increased its output by 68% from 20GW in 2018 to 34GW in 2019. This growth followed the latest expansions of its Chinese factories in Ningxia, Shaanxi and Yunnan, which has brought Longi's total nameplate capacity to 55GW in 2020. The integrated solar company has already announced plans for an additional 40GW of capacity and is currently building another 12GW.

Figure 11: Top ten solar wafer manufacturers by annual production, 2019



Source: BloombergNEF. Note: All 10 firms are headquartered in China, with the exception of Canadian Solar though the company has extensive manufacturing plants in China.

3.3. Cells

Compared with polysilicon and wafers, the solar cells segment of the value chain is far less consolidated. In 2019, the top ten cell producers supplied 59% of the market. Leading cell makers are often vertically integrated companies that own wafer and/or module manufacturing as well, but may buy outsourced wafers if the spot price is lower than their cost of production.

Cell manufacturing is more versatile compared to wafers and polysilicon and has lower technical hurdles. A multicrystalline cell factory can be upgraded to monocrystalline passivated emitter rear contact (PERC) production, for example, while a multi wafer factory would need significant investment to make mono wafers.

In addition, compared with wafers and polysilicon, it is easier to temporarily halt production lines across cell factories and quickly ramp them back up again. Over the last decade, there has been overcapacity global cell manufacturing, particularly as older capacity has been slow to retire.

Different cell types, efficiencies and costs

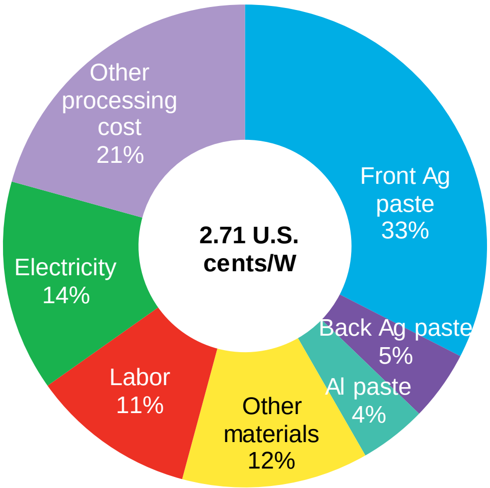
Mono PERC cells have become the market standard over the last two years at the expense of multi Al-BSF cells. Wide market adoption of different cell products is a factor of both efficiency and cost, where higher cell efficiencies command higher prices.

Historically, multicrystalline dominated the market because its lower efficiency was offset by lower costs. However, the additional cost of making mono PERC cells has decreased over time, to the point where better efficiencies of mono cells outweigh their higher expenses. The introduction of diamond wire saws in 2018, and the move to PERC designs, brought the production cost of mono below the cost of multi for the top players.

Cell cost breakdown

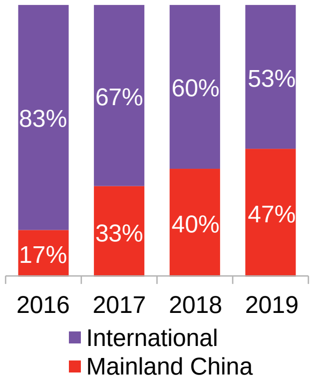
Over half of the cost of making monocrystalline silicon wafers into cells comes from the purchase of materials such as silver (Ag) and aluminum (Al) pastes (Figure 12). Front silver paste alone is the single largest cost component and accounted for 33% of total cost. It is used to form the electrical contacts on the front side of the cell.

Figure 12: Best-in-class cash costs of making silicon wafers into mono PERC cells as of year-end 2019



Source: BloombergNEF, company filings, industry sources.

Figure 13: Front Ag paste supply by company origin



Source: BloombergNEF

The largest silver paste suppliers have their factories in China. In addition to lower labor costs, there is an advantage of being located close to cell manufacturers. However, the majority of silver paste is still produced by non-Chinese companies. DuPont (U.S.), Heraeus (Germany), Samsung SDI (South Korea) and Gigasolar (Taiwan) supplied over 50% of the market in 2019 (Figure 13).

Global crystalline silicon solar cell manufacturing

Era of tariffs

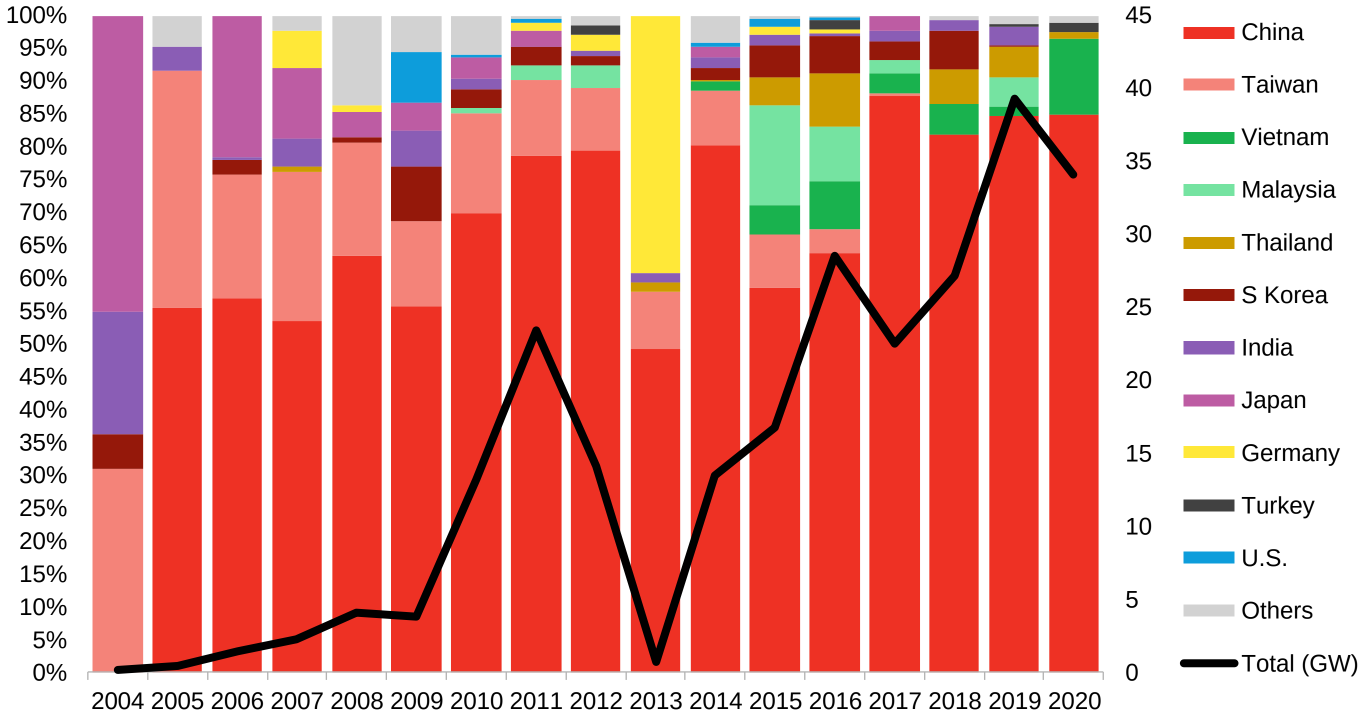
In 2011, there was about 49GW/year of cumulative solar cell manufacturing capacity worldwide, of which 71% was located in China. A year later, U.S. imposed antidumping (AD) and countervailing duty (CVD) tariffs on Chinese cells. Manufacturers then turned to Taiwanese cell makers to avoid the duties. However, the U.S. government responded in early 2015 by imposing tariffs on Taiwanese cells too.

U.S. trade restrictions on China and Taiwan triggered a rapid expansion of cell production across Southeast Asian countries in 2015 and 2016. Hanwha made the most aggressive move and built a 1.6GW plant in Malaysia in 2015, followed by other early movers such as JA Solar and JinkoSolar. Since 2015, cell makers have added almost 24GW of nameplate capacity across Southeast Asia.

Tariffs on China and Taiwan also benefited Hanwha's South Korean manufacturing, which grew from 600MW in 2015 to 3.7GW just three years later. However, in 2018, the U.S. imposed its Section 201 and 301 tariffs on crystalline silicon cells from outside China, which included Southeast Asia and South Korea. The first 2.5GW batch of cell imports is however tariff-free.

The various sets of tariffs did not spur U.S. domestic cell manufacturing as hoped. Even with recent tariffs in place, U.S.-made cells have not competed on cost with those made in Southeast Asia. By 2012, the U.S. had 0.5GW of nameplate PV cell-making capacity. In 2017, a few years after tariffs were imposed on China and Taiwan, capacity grew to 0.88GW. Since 2018, and despite the latest set of tariffs, U.S. cell manufacturing has been reduced to just Maxeon's (SunPower) 0.25GW cell plant in Oregon.

Figure 14: Crystalline silicon cell factory additions per country of factory location and yearly GW



Source: BloombergNEF

At present, most new cell capacity is being built in China (Figure 14), with some in Vietnam and the Philippines as well. New cell factories can cost between $57-85 million per gigawatt/year to erect. This varies by the size of the wafers that will be used as well as the type of solar cell produced.

Annual cell production

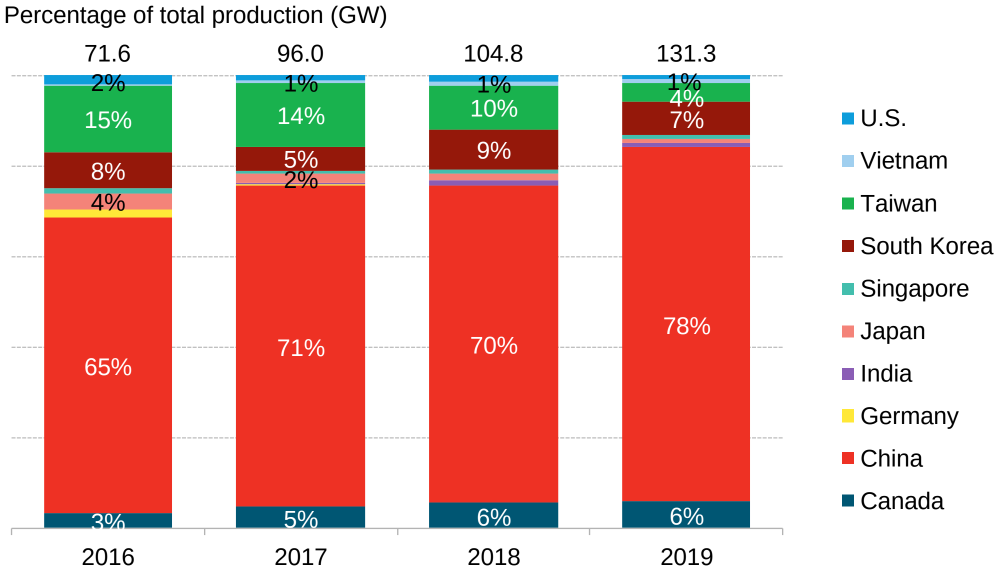
Taiwanese makers get squeezed out of the market

Companies headquartered in China were responsible for 78% of total cell output in 2019. The share is even higher when accounting by factory location rather than location of corporate headquarters (Figure 15). Canadian Solar and Hanwha Q Cells, which are based in Canada and South Korea, respectively, both own large manufacturing facilities in China, although some Chinese-headquartered companies own capacity in Southeast Asia to avoid U.S. import tariffs.

Taiwanese companies continued to lose market share in 2019 to Chinese competitors, which have rapidly moved into the production of mono PERC cells. Taiwanese cell producers such as URE (also known as Neo Solar Power) and Motech used to be main sources for Southeast Asian module makers. However, they lost this advantage as soon as Chinese cell producers opened factories in Southeast Asia.

Taiwanese cell makers also lost market share in the Indian market as a result of 2018 safeguard duties against PV cell and module imports, set in an attempt to boost local PV manufacturing in India.

Figure 15: Annual cell production by country of headquarters (not factory location)



Source: BloombergNEF

Large cell makers own other parts of the value chain as well

Seven of 2019’s top 10 cell manufacturers owned wafer manufacturing capacity as well. Vertical integration and industry partnerships across the PV supply chain are common among big players to have some control over production costs.

Tongwei, which was the largest Chinese polysilicon maker in 2019, topped the list of cell makers in the same year with 13.4GW of output, 105% more than in the previous year. The firm just closed a supply contract with Longi’s wafer factories for about 13.5GW, which gives it supply certainty. In exchange, Tongwei will supply a fixed amount of polysilicon to Longi’s wafer plants.

Other top producers such as JA Solar, Longi, Canadian Solar and Hanwha also achieved record cell outputs in 2019 as they expanded factories and moved new manufacturing to Southeast Asia.

3.4. Modules

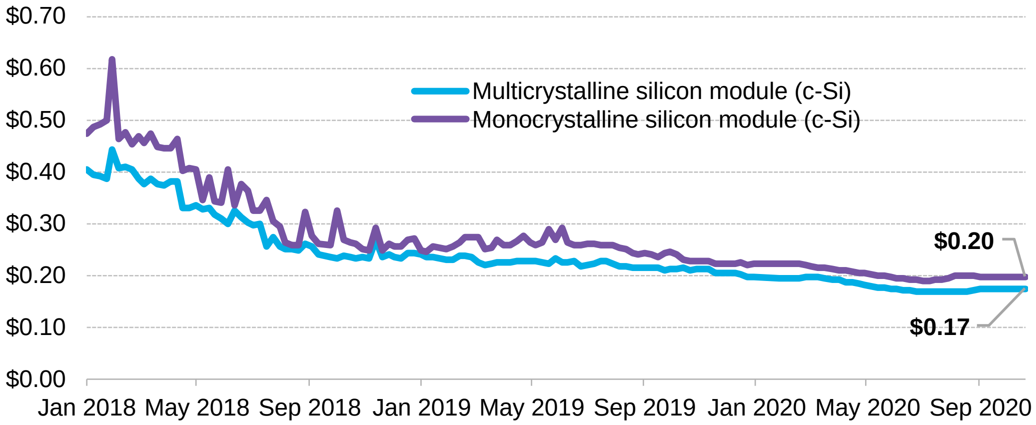
Module makers are heavily reliant on the supply of external components such as PV glass and aluminum frames. Recent glass supply shortages have increased production costs for module makers and caused disruptions across module production lines.

Despite U.S. tariffs on Chinese-made cells and modules, China continues to expand its global dominance. Big, Chinese integrated solar firms participate in multiple segments of the PV value chain, which allows them to have better cost control and supply certainty. In addition, most of the key components for panel assembly are now being produced in China.

Transition from mono to multicrystalline modules

Prices of mono modules have come down significantly since 2018 and are now nearing the costs of their multi counterparts (Figure 16). On a total project-level, using mono-crystalline modules is cheaper because they offer more watts per area installed.

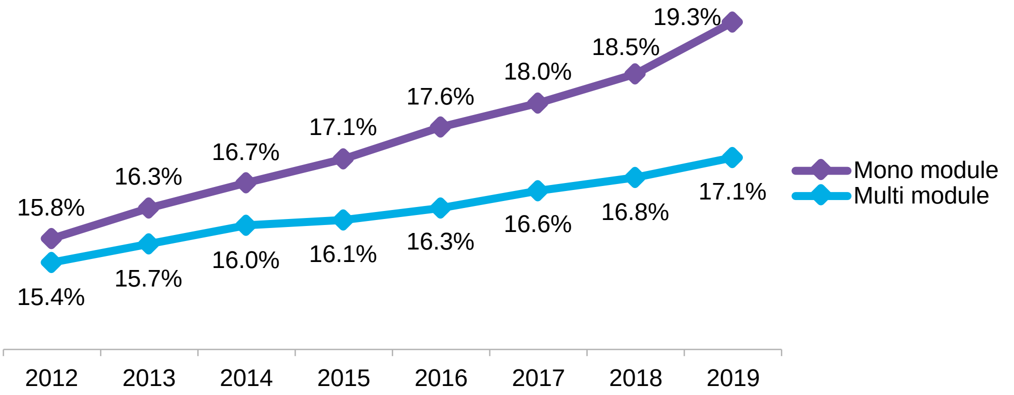
Figure 16: Average module spot prices ($/Watt)



Source: BloombergNEF

At the same time, average efficiencies of mono modules have increased faster than for multi (Figure 17), increasing the price premium mono modules command in the market. More efficient modules can sell for a higher price because a lot of the costs of engineering and installation are per-area or per-Watt, so if a module has more Watts, the other project costs per unit come down.

Figure 17: Average efficiency of commercial modules



Source: BloombergNEF

Module cost breakdown

Heavy reliance on external components

Solar module assembly costs are heavily determined by the price of external materials, also known as “bill of materials” (Figure 18). The main inputs, apart from polysilicon, are glass, the aluminum frame, backsheets (the layers at the bottom of panels), junction boxes and ethylene vinyl acetate (EVA).

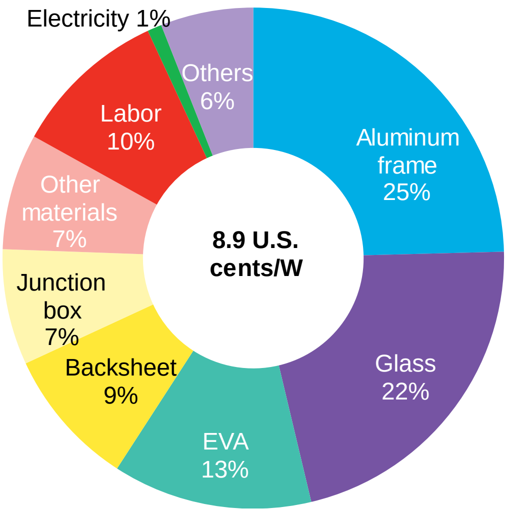
Compared with more upstream manufacturing components, module assembly quality and costs are influenced by the supply of this equipment. As a result, securing reliable supply of high-quality product is essential for module manufacturers. Large players, such as Longi, secure stable supplies by signing volume contracts that span two to three years. These agreements offer some discount but are still exposed to spot price fluctuations of raw materials like glass and aluminum. Longi has closed contracts for 47GW worth of PV glass and 44GW of aluminum frames. The company plans to spend over $2.6 billion on these agreements between 2019 and 2025. Other module makers, such as Canadian Solar and Jinko Solar, have gone further and own subsidiaries that produce frames, junction boxes and EVA. In April 2020, Longi also announced the creation of a joint venture for the production of 10GW worth of frames.

The price of external materials is determined by production costs and suppliers' gross margins. Both variables are exposed to spot prices of commodities and supply-demand market dynamics. In 2020, glass supply was pinched by a sharp rise in demand for bifacial modules, which use 25-56% more glass than traditional monofacial modules. Bifacial demand has spiked since 2018 when such modules accounted for just 3% of the installed market. By 2019, that had grown to 18% and was expected to reach 35% in 2020, and 60% in 2021.

Glass manufacturers have not invested in factories to keep up with the changes in product required by module makers, who are switching to bifacial dual-glass modules that require thinner glass, and are making larger product. Glass prices have risen by 71% since July 2020 as glass manufacturers struggle to meet demand. (The Chinese government has also tried to control overcapacity in glass production through quotas, but this is really a minor contributor to the glass shortage).

As a response to shortages, PV glass giants Xinyi Solar and Flat Glass are expected to add a total of 2.1 million tons of capacity in 2020 and an additional 1.4 million tons in 2021. These two Chinese producers alone will supply over 50% of the market in 2020.

Figure 18: Best-in-class cash cost for cell-to-module for mono c-Si modules made by large firms as of year-end 2019



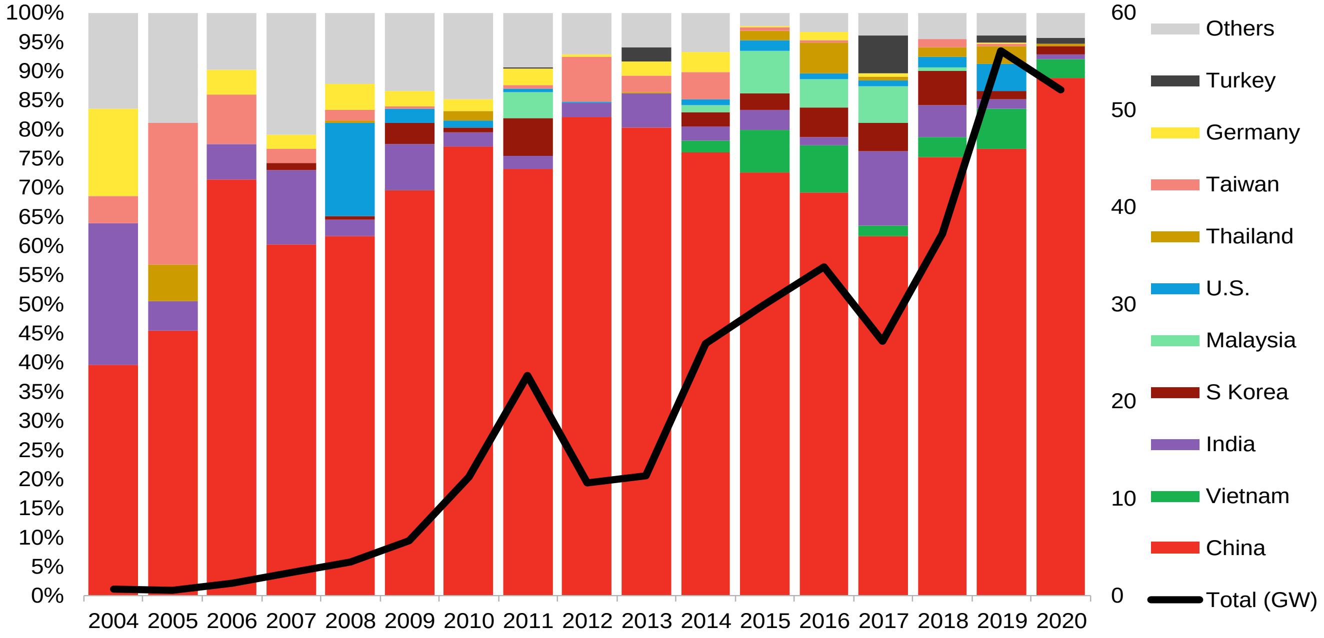
Source: BloombergNEF. Note: Most costly components in "other materials" are ribbons and adhesives. Packaging cost is categorized into "others".

Global c-Si module manufacturing capacity

Module factories have low technical hurdles

Since 2017, almost 172GW/year of c-Si module manufacturing capacity has been built globally, 134GW of it in China (Figure 19). Building a new module factory has low technical hurdles compared with wafer and polysilicon.

Figure 19: Crystalline-silicon module factory additions per country of factory location and yearly GW



Source: BloombergNEF

Large module makers have been regularly upgrading their production lines to adjust for new cell structures and other technological needs. Factories that lack the most modern equipment can become obsolete quickly in the current competitive market environment.

Factory locations track policy developments

Given low technical and financial barriers, it is also easier for module companies to open shop in other countries in response to tariffs or other policy developments. Once duties on Chinese solar cells were imposed by the U.S., large integrated manufacturers built both cell and module assembly plants across Southeast Asia. Since 2015, Longi has added over 7.4GW/year of module factories in Malaysia and Vietnam, followed by Hanwha (6.3GW/year) and Canadian Solar (2.7GW/year).

India's local content rules for its national solar auctions require cells and modules to be produced domestically. This condition spurred local manufacturing in the country. Over 11GW/year of crystalline silicon module capacity has been added since 2009 in India, of which 6.8GW/year were built after 2016. Indian module makers have also benefitted from U.S. tariffs on Chinese product, as well as their own government's duties on imports from China and Malaysia in 2018.

In the U.S., about 3.6GW/year of module assembly capacity has come online since 2017. Hanwha built a 1.7GW/year module assembly factory in Georgia in 2019, where it uses its own cells imported under the 2.5GW tariff-free cap. JinkoSolar and LG built 0.5GW and 0.4GW of annual module capacity in 2019, respectively. The two firms import their own cells for assembly in the U.S. under the 2.5GW tariff-free cap, from their facilities in Malaysia and South Korea. In 2018, over 1.3GW/year of new module factories were announced in the U.S. by firms including Sunpreme, Solaria or Mission Solar. However, no significant construction milestones have been achieved to date.

More module assembly capacity is expected online over the next couple of years, with the vast majority of it planned for China.

Annual module production

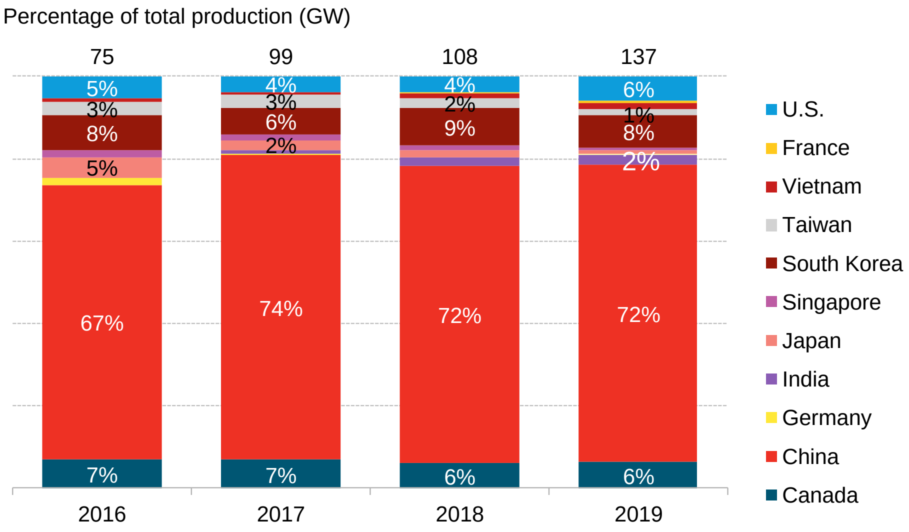
Compared with the 313GW/year of commissioned crystalline silicon module assembly capacity, around 137GW worth of modules (44%) were actually made in 2019. Many of the factories built several years ago have halted production or are waiting to be upgraded because their product is no longer competitive. Other have stopped production altogether.

About 118GW of solar modules were installed in projects across the world in 2019. The majority of the remaining 19GW of modules produced were “safe-harbored” in the U.S. (purchased on paper) for tax credit purposes.

China’s global dominance in module production has not diminished over time (Figure 20). Besides ample supply of components along the PV value chain such as cells and wafers, China is also home to the largest manufacturers of key materials such as PV glass and aluminum frames. Overall, integrated Chinese solar manufacturers have been able to expand their production lines across the entire PV value chain due to the proliferation of other adjacent industries in China. For another country to keep up with Chinese PV output, a network of industries would need to be significantly expanded or built from scratch. Even still, it is unclear whether these new factories could be cost-competitive against China.

In 2019, India- and Vietnam-based module makers benefited from U.S. import tariffs on China and were able to grow their U.S. sales. First Solar and SunPower, the largest U.S. manufacturers, also profited from the tariffs and sold 5.7GW and 2.55GW worth of modules in 2019, respectively.

Figure 20: Annual module production by country of headquarters (not factory location)



Source: BloombergNEF

Section 4. U.S. PV cell and module trade trends

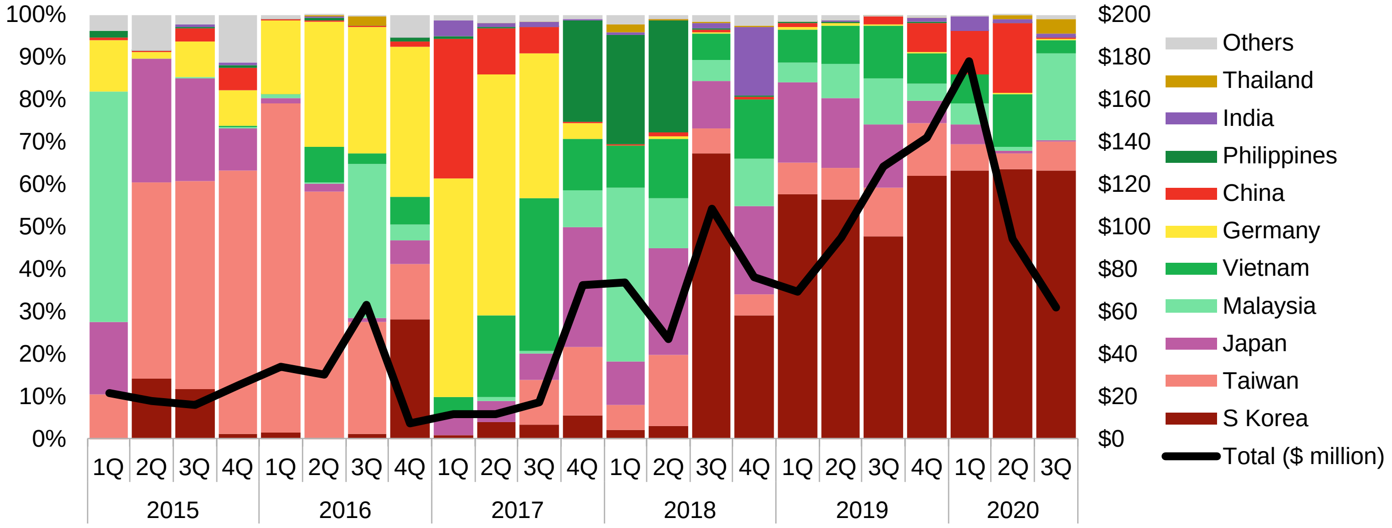
Given its limited PV manufacturing capabilities, the U.S. has heavily relied on other countries to fulfil its demand for solar cells and modules. The countries of origin of U.S. imported cells and modules have varied over the years in the wake of various U.S. government trade actions.

PV cell imports

After imposing anti-dumping and countervailing duties against Chinese-made cells in 2012, U.S. module makers began to predominantly import cells from Taiwan (Figure 21). Cell imports plummeted in 4Q 2016 after tariffs were imposed on Taiwan in 2015. Module makers continued to import Taiwanese cells despite the tariffs through 4Q 2016, because tax credits for solar projects in the U.S. were expected to step down after 2016. To circumvent the tariffs, Chinese and Taiwanese cell makers started building factories across Southeast Asia around 2015, which started exporting to the U.S. in 2017.

Starting in 3Q 2018, South Korea became the single biggest exporter of solar cells to the U.S. Hanwha's 1.7GW/year and LG's 0.5GW/year module factories in the U.S. were two of the main destinations. Despite the set of new tariffs that were lifted in 2018, U.S. module factories have continued to import South Korean and Southeast Asian cells under the 2.5GW tariff-free cap. A total of 1.7GW was imported in 2020 through September.

Figure 21: U.S. PV quarterly cell imports by country and value ($ million)



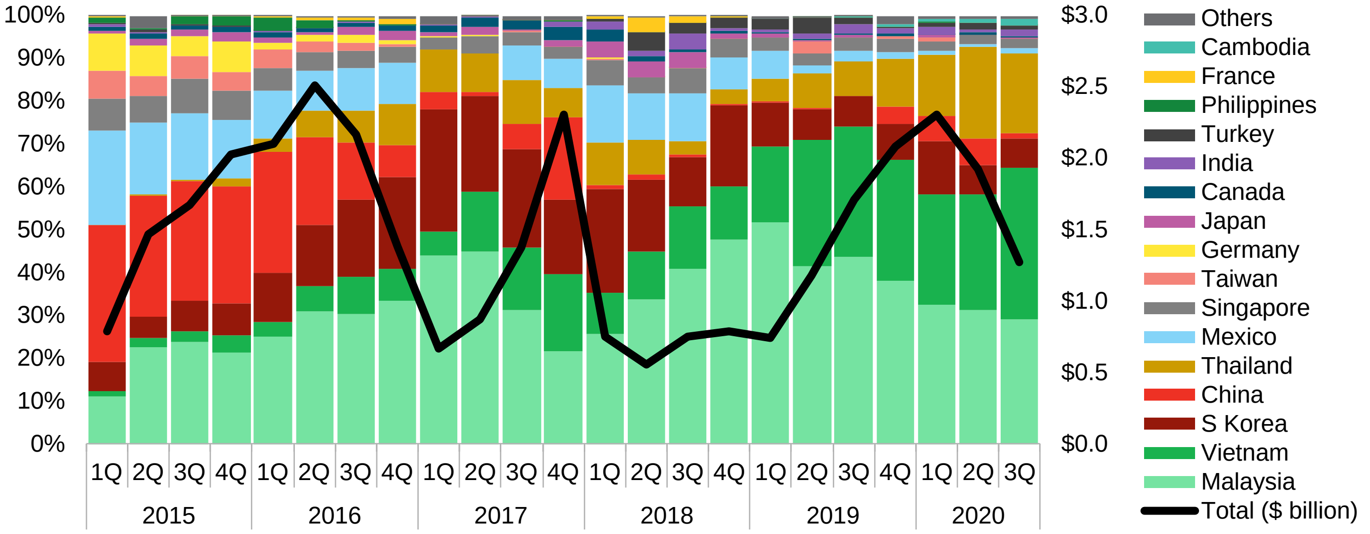
Source: BloombergNEF

PV module imports

Most U.S. solar installations today use imported modules from Vietnam, Malaysia and Thailand. Most module-assembly plants that ship from Southeast Asia to the U.S. are Chinese-owned. The U.S. imported about 20GW of modules between January-September 2020.

Module assembly in Southeast Asian countries and South Korea remains still considerably cheaper than in the U.S. Despite the 2012 AD and CVD duties imposed on Chinese cells, plenty of solar modules continued to arrive from China until 2016. As outlined earlier, Chinese module makers found a loophole under which they imported Taiwanese-made cells to China and assembled them into modules to sell the final product tariff-free into the U.S.

Figure 22: U.S. PV quarterly module imports by country and value ($ billion)



Source: BloombergNEF

Value break-out of projects built in the U.S.

The U.S. imported 21GW of PV modules and cells in 2019. That far exceeded the 11.5GW of projects actually built that year as installers sought to “safe harbor” (stockpile) equipment ahead of a looming step-down in the value of the U.S. Investment Tax Credit (ITC) subsidy. The U.S. imported a further 20GW of PV modules through the first three quarters of 2020, well above the 16GW of solar BloombergNEF that ultimately got built. This continuing stockpiling of PV equipment suggests that most, if not nearly all, projects commissioned in the U.S. in 2020 and 2021 will be outfitted with equipment assembled abroad.

In the wake of tariffs the U.S. imposed on equipment made in China, the majority of goods the U.S. imports arrive from Southeast Asia post-assembly. However, 70% of the actual value of that equipment accrues to China where key, pre-assembly steps in the making of the equipment take place, including production of solar-grade silicon, ingots, wafers and cells. For this reason, Southeast Asian nations account for just 27% of the value of a typical PV module exported to the U.S., despite those nations being most likely to be the last port of call before final, assembled equipment arrives in the U.S. (Figure 24). One other important fact: most of the plants assembling modules in Southeast Asia are actually owned by Chinese firms.

For the minority of modules installed in U.S. projects after having been assembled on U.S. soil, 26% of the value is accrued locally, mainly in the form of the labor and electricity used to put together the PV panels (Figure 23). Even for this equipment, however, the majority of the value creation (60%) still accrues to China. China-based firms produce 80% of the world’s refined polysilicon, as well as virtually all wafers and non-silicon materials that go into the final cells that U.S. module-makers import. In the rare cases where cells are also manufactured in the U.S., the share of value creation only marginally increases, to 29% and does so at the expense of countries other than China.

BloombergNEF assumes just 2.5GW of the approximately 16GW installed in the U.S. in 2020 was assembled on U.S. soil. Module makers in the U.S. mainly imported cells from South Korea and Southeast Asia up to 2.5GW but no higher because that is the quota the U.S. government has set for tariff-free imports from those nations. Were the current U.S. tariffs on imported PV cells to be lifted, most modules installed in the U.S. would come directly from China or Southeast Asia, given the significantly lower all-in production costs those nations offer.

Figure 23: Value break-out of a typical crystalline silicon PV module assembled on U.S. soil (based on cash costs)

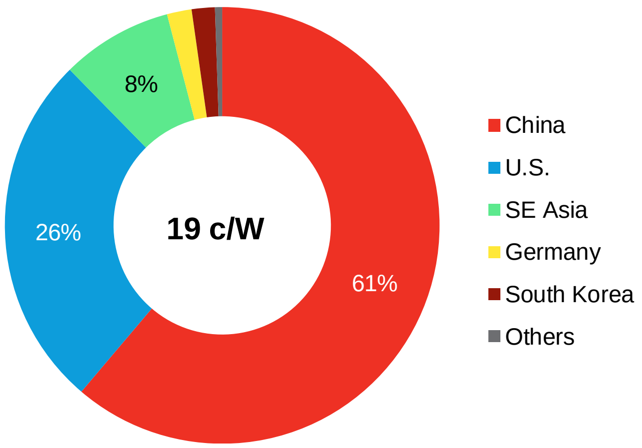
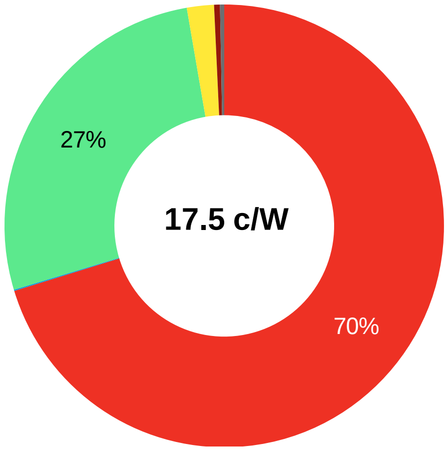


Figure 24: Value break-out of a typical crystalline silicon PV module imported from Southeast Asia (based on cash costs)



Source: BloombergNEF Note: Value creation distributed by country for modules assembled in the U.S. based on cash costs. Cash costs exclude tariffs, depreciation and transport fees, as well as profit margins. Cash costs components include: polysilicon, silicon-to-wafer production, non-silicon raw materials, wafer-to-cell production, non-cell raw materials and cell-to-module assembly.

Whether a silicon-based module is assembled on U.S. soil or abroad, about half its total value is accounted for by non-silicon raw materials such as silver paste, glass and back sheets. The vast majority of suppliers of these materials are concentrated in China. As a result, despite U.S.-imposed tariffs on Chinese-made PV cells and modules, China continues to accrue the largest share of value from modules installed in the U.S. – regardless of where the equipment gets assembled.

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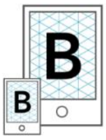

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