U.S. DEPARTMENT OF ENERGY

Solar Photovoltaics

Supply Chain Deep Dive Assessment

U.S. Department of Energy Response to Executive Order 14017, "America's Supply Chains"

February 24, 2022

About the Supply Chain Review for the Energy Sector Industrial Base

This is one of a series of reports and deep dive assessments produced in response to Executive Order 14017 "America's Supply Chains," which directs the Secretary of Energy to submit a report on supply chains for the energy sector industrial base. The Executive Order is helping the federal government to build more secure and diverse U.S. supply chains, including energy supply chains.

To combat the climate crisis and avoid the most severe impacts of climate change, the U.S. is committed to achieving a 50 to 52 percent reduction from 2005 levels in economy-wide net greenhouse gas pollution by 2030, creating a carbon pollution-free power sector by 2035, and achieving net zero emissions economy-wide by no later than 2050. The U.S. Department of Energy (DOE) recognizes that a secure, resilient supply chain will be critical in harnessing emissions outcomes and capturing the economic opportunity inherent in the energy sector transition. Potential vulnerabilities and risks to the energy sector industrial base must be addressed throughout every stage of this transition.

The DOE energy supply chain strategy report summarizes the key elements of the energy supply chain as well as the strategies the U.S. government is starting to employ to address them. Additionally, it describes recommendations for Congressional action. DOE has identified technologies and crosscutting topics for analysis in the one-year time frame set by the Executive Order. Along with a policy strategy report, DOE is releasing 11 deep dive assessment documents, including this one, covering the following technology sectors:

- carbon capture materials,
- electric grid including transformers and high voltage direct current (HVDC),
- energy storage,
- fuel cells and electrolyzers,
- hydropower including pumped storage hydropower (PSH),
- neodymium magnets,
- nuclear energy,
- platinum group metals and other catalysts,
- semiconductors,
- solar photovoltaics (PV), and
- wind

DOE is also releasing two deep dive assessments on the following crosscutting topics:

- commercialization and competitiveness, and
- cybersecurity and digital components.

In addition to the solar energy-related policy strategies laid out in DOE's companion energy supply chain policy strategy report, this deep dive assessment includes its own section focused on policy strategies and recommendations.

More information can be found at www.energy.gov/policy/supplychains.

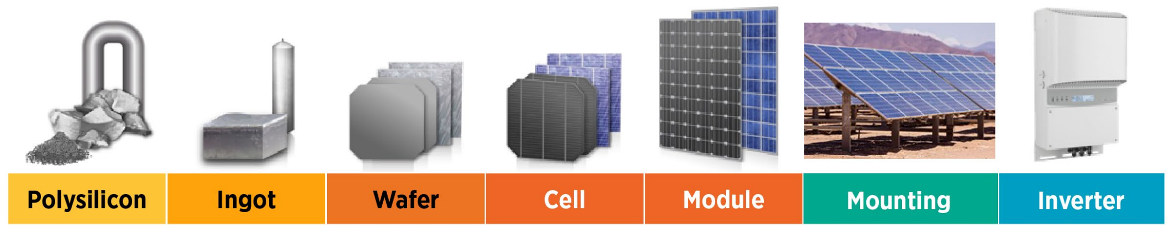
Executive Summary

The Important Role of Solar Power

Over the past decade, solar power has gone from an emerging, niche technology to a mature energy industry. By 2035, solar power could supply 40% or more of U.S. electricity demand, dramatically accelerating the decarbonization of buildings, transportation, and industry; and, if current technology trends continue, it could do so without increasing the price of electricity.*

The rapid expansion of solar energy has the potential to yield broad benefits in the form of economic activity and workforce development. The solar industry already employs roughly 230,000 people in the United States, at an average wage that is higher than the national average for most comparable positions. By decarbonizing the electricity sector by 2035, the U.S. solar industry could employ 500,000–1,500,000 people by 2030.

The Solar Photovoltaics Supply Chain



The components that are assembled to install a photovoltaic power system are produced by a global supply chain. Photovoltaic (PV) modules (also called panels) are made of cells that use a variety of technologies. There are two leading types of solar modules used in the United States, with crystalline silicon (c-Si) modules representing 84% of the market and cadmium telluride (CdTe) modules representing 16% of the market. Modules of either type require mounting structures to provide mechanical support (racking), which may be configured to follow the sun (tracking). The output of any PV module is direct current (dc), which is almost always converted to alternating current (ac) by an inverter.

The supply chain for c-Si modules starts with the refining of high-purity polycrystalline silicon (polysilicon). The primary input material for polysilicon is metallurgical-grade silicon (MGS). MGS (also called silicon metal) is a commodity material produced from high-grade quartz. About 12% of the world's MGS is refined to make high-purity polysilicon for the solar supply chain. Polysilicon is melted to grow monocrystalline silicon ingots, which are sliced into thin silicon wafers. Silicon wafers are processed to make the solar cells that are interconnected and sandwiched between glass and plastic sheets to make c-Si modules.

About 97% of the world's production of silicon wafers occurs in China. Those wafers are shipped from China and made into solar cells. About 75% of the silicon solar cells incorporated into modules installed in the United States are made by Chinese subsidiaries located in just three Southeast Asian countries: Vietnam, Malaysia, and Thailand. As of this writing, the United States has no active c-Si ingot, wafer, or cell production.

**Solar Futures Study*, U.S. Department of Energy, September 2021.

The United States does have production capacity for thin-film CdTe modules, which do not rely on obtaining materials from Chinese companies. The U.S. PV installations using CdTe modules (16% of the total) were all supplied by a single U.S. company that produced roughly one-third of those modules in the United States.

The concentration of the c-Si supply chain in companies with close ties to China, a country with documented human rights violations and an unpredictable trade relationship with the United States, poses a significant risk of disruption to the c-Si supply chain. Given the rate at which the U.S. economy will need to decarbonize, it is unlikely that any alternate PV technology, including CdTe, could displace c-Si before 2035.

Strategies, Actions, and Recommendations

Significant financial support and incentives from the U.S. government as well as strategic actions focused on workforce, manufacturing, human rights, and trade will facilitate a global solar industry aligned with U.S. interests and the reestablishment of robust U.S. domestic solar manufacturing leadership –thus leading to tremendous benefits for the climate as well as for U.S. workers, employers, and the economy. Three strategies, actions, and recommendations are critical to U.S. success in building a robust solar supply chain:

Enact legislation to provide tax incentives to support domestic manufacturing, including incentives for building new facilities and for the ongoing operation of those facilities.

Tax incentives are needed to provide a clear demand signal and help U.S. manufacturers build and maintain a competitive edge in clean energy technologies such as solar photovoltaics. To reestablish domestic solar manufacturing in the United States, companies that produce and sell solar components will require financial support to offset the 30 to 40% higher cost of domestic solar production. Expansion of ingot and wafer production should receive the highest incentive because nearly all the world's capacity currently exists inside China, and expansion in these sectors would have the compounding effect of creating demand for existing U.S. polysilicon producers to run at full capacity. These tax credits should be enacted for at least a decade to provide the long-term signal for companies to establish new production facilities. Renewal for some time thereafter, perhaps at a reduced level, could be required to maintain domestic competitiveness.

Enact legislation to encourage domestic solar adoption and deployment

Extend and revise credits for clean energy deployment, such as the Production Tax Credit (PTC) and Investment Tax Credit (ITC) to provide stronger incentives for clean energy projects that support domestic manufacturing and increase family-sustaining jobs. To provide demand certainty in support of domestic manufacturing investments, these tax credits should be in place for at least 10 years and should not phase out until significant progress has been made toward domestic competitiveness and decarbonization goals.

Enhance coordination of trade policy across the U.S. government to create fair conditions for the U.S. solar industry and its workers

U.S. solar manufacturers have too often faced unfair – and illegal - competition from firms that benefit from foreign, non-market practices such as dumping. The United States has responded with trade remedies designed to protect domestic manufacturing. Transparent, effective coordination and implementation of these policies is critical to supporting domestic manufacturing as well as clean energy deployment. The U.S. government will continue to conduct expert analysis and engage with relevant stakeholders to refine implementation of trade policies to optimize their effectiveness in leveling the playing field across the supply chain, while removing barriers to solar deployment.

Supplement these strategies and recommendations with supportive policy actions.

See Section 3.4 for detailed strategies starting to be implemented by the U.S. government and recommendations for Congressional action related to the solar energy supply chain.

Find the policy strategies to address the vulnerabilities and opportunities covered in this deep dive assessment, as well as assessments on other energy topics, in the Department of Energy 1-year supply chain report: "America's Strategy to Secure the Supply Chain for a Robust Clean Energy Transition."

For more information, visit www.energy.gov/policy/supplychains.

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1 Solar Photovoltaics

1.1 The Solar Photovoltaic System

To create a grid-connected photovoltaic (PV) system, multiple PV modules (panels) are electrically interconnected and mounted to a support structure. The module (panel) is the core component of a photovoltaic (PV) system. The vast majority of global PV module shipments (96% in 2020) use crystalline silicon (c-Si) technology, made from melting chunks of polysilicon into ingots (i.e., blocks of polysilicon), slicing those ingots into thin wafers, converting the wafers into PV cells (which convert light into energy), and then assembling a series of cells into a PV module. The remaining PV module shipments mostly use cadmium telluride (CdTe) technology, which is typically manufactured by directly depositing the CdTe cell onto the glass of the PV module. A higher percentage of CdTe is installed in the United States (16% compared to 4% globally), with c-Si representing the remaining 84% (Feldman and Margolis 2021).

Additional components are added to manage the flow of electricity. Inverters, which convert direct current (dc) electricity from the modules into alternating current (ac) for connection to the grid, are the most important and expensive balance-of-system component. Other components include wiring, meters, junction boxes, ac and dc disconnects, combiner boxes, transformers, electrical panels, and mounting structures.

System components and designs vary by installation type (Figure 1). For example, the mounting structures used for residential rooftop PV systems can differ substantially from those used for commercial rooftop systems, and the mounting structures used for both categories of rooftop systems are much different than those used for ground-mounted systems. Increasingly, batteries are being combined with PV systems, which requires additional or substitute components such as battery-based inverters and charge controllers.

Beyond hardware components, various activities are required to create PV systems, such as customer acquisition, land acquisition, system installation by trained installers, permitting, and grid interconnection. These activities result in “soft” costs, which make up more than half of total system costs for residential and commercial PV installations.

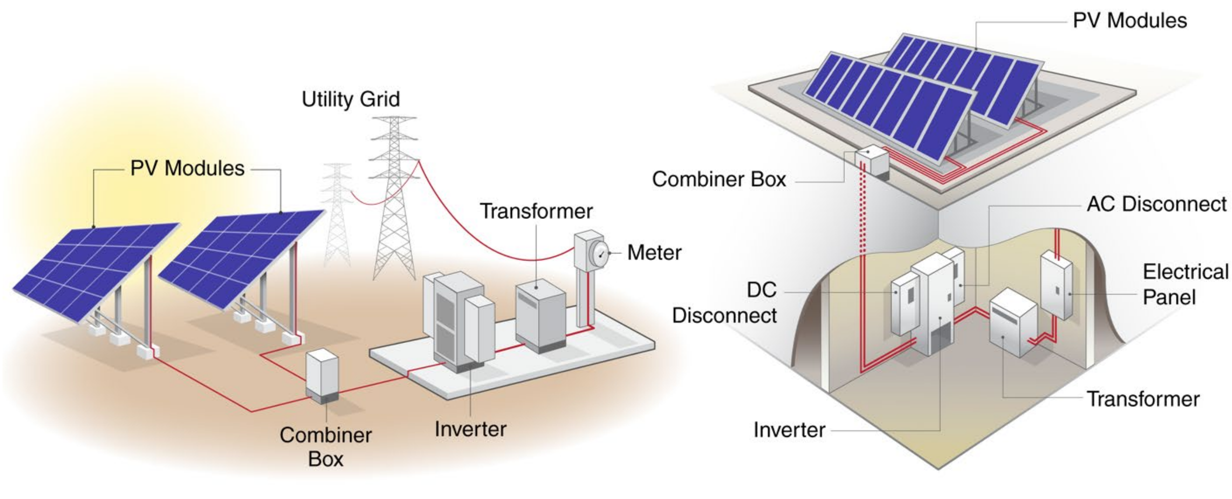


Figure 1. Illustrations of a utility-scale PV system (left) and a commercial rooftop system (right).

1.2 U.S. Solar Photovoltaics Strategy

Solar photovoltaics is an important technology in U.S. efforts to reduce greenhouse gas emissions and minimize climate change impacts. Decades of innovation and cost reductions have made PV one of the lowest-cost forms of electricity generation, and PV deployment has grown in concert with falling prices (Figure 2).

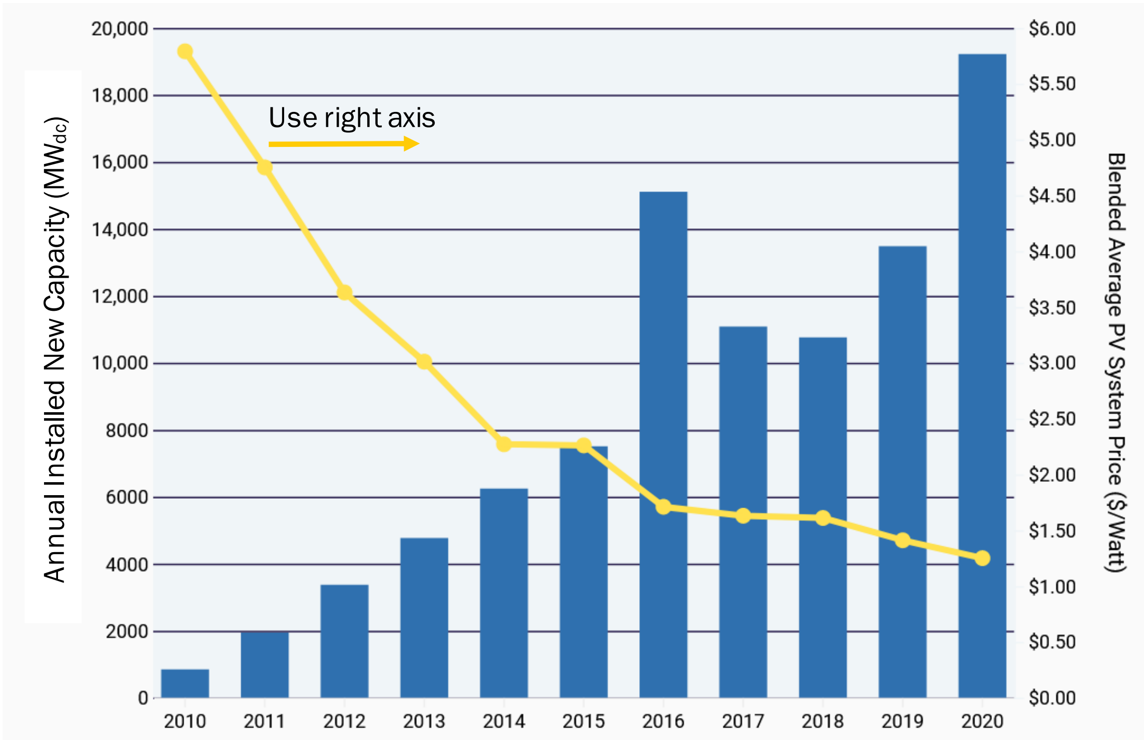
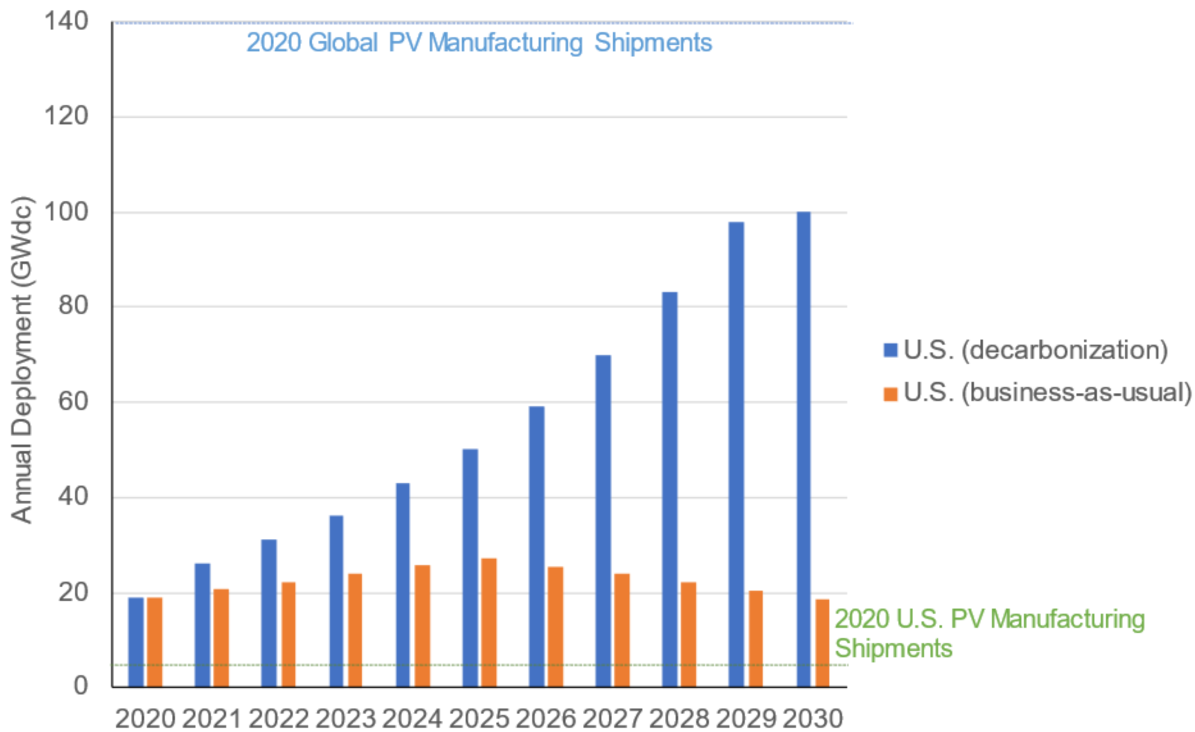


Figure 2. U.S. PV price reductions and annual deployment growth.

Source: ("Solar Industry Research Data" n.d.)

In 2010, solar power represented approximately 5% of new U.S. electric generation capacity additions; by 2020, it had grown to 40% and EIA expects it to further grow above 50% in 2022 (EIA 2021a; 2021b; 2022). Solar power is a critical, affordable, and reliable energy option for America, supplying more than 8% of energy generation in six U.S. states (with California leading the way at almost 23%) (Feldman and Margolis 2021; IEA 2021).

Despite this growth, decarbonizing the electricity sector in the United States would require significant acceleration of annual PV deployment. Compared with 19 gigawatts (GW_{dc}) of PV deployed in the United States in 2020, annual PV deployment would need to double in the early 2020s and to quintuple by the end of the decade in the most aggressive grid decarbonization scenario, as demonstrated in Figure 3 (Margolis et al. 2021). This would greatly dwarf current U.S. PV manufacturing and represent a significant portion of current global PV manufacturing shipments. That said, global shipments are projected to grow to close to 200 GW_{dc} per year by 2030, in a business-as-usual case, and could grow above 500 GW_{dc} by 2030 under a global decarbonization scenario (BloombergNEF 2021; IEA 2020).



Source: (Adapted from Margolis et al. 2021)

Further substantial technological and cost improvements are expected over the coming years which should facilitate the growth of the PV sector. In addition, the modularity of PV enables deployment at a wide range of scales—from a few kW_{dc} on residential rooftops to one or more GW_{dc} in utility-scale solar parks—and creates unique roles for PV in the buildings, industrial, and transportation sectors. In such a decarbonized scenario with continued PV cost reductions, solar power could supply 40% or more of U.S. electricity demand, dramatically accelerating the decarbonization of buildings, transportation, and industry; and doing so without increasing the price of electricity.

The solar-driven clean energy transition could yield broad economic benefits in the form of jobs and workforce development. The solar industry already employs around 230,000 people in the United States, at an average wage that is higher than the national average for most comparable positions. With such a dramatic increase in domestic demand, there is potential for significant expansion in U.S. PV manufacturing. At the growth rate necessary to achieve power-sector decarbonization by 2035, the U.S. solar industry could employ 500,000–1,500,000 people by 2030.

Recently, the vast majority of PV modules installed in the United States were imported (Figure 4), with U.S. manufacturing of c-Si and CdTe modules together supplying just 14% of U.S. PV installations in 2020.

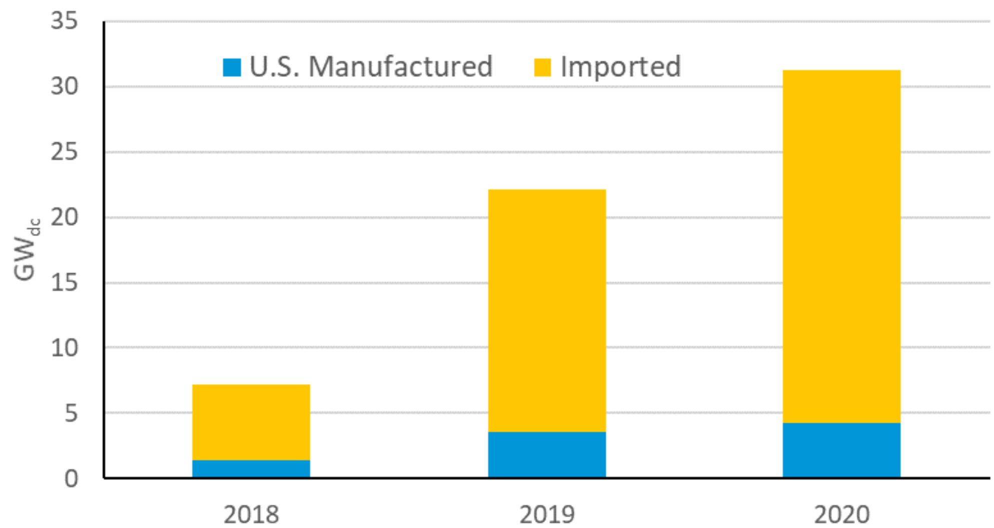


Figure 4. U.S. PV module production and imports.

Figure 5 and Figure 7)

More than 75% of the modules imported in 2020 (counting both c-Si and CdTe) came from just three Southeast Asian countries: Malaysia, Vietnam, and Thailand (Figure 5). These Southeast Asian manufacturers rely heavily on an upstream Chinese supply chain.

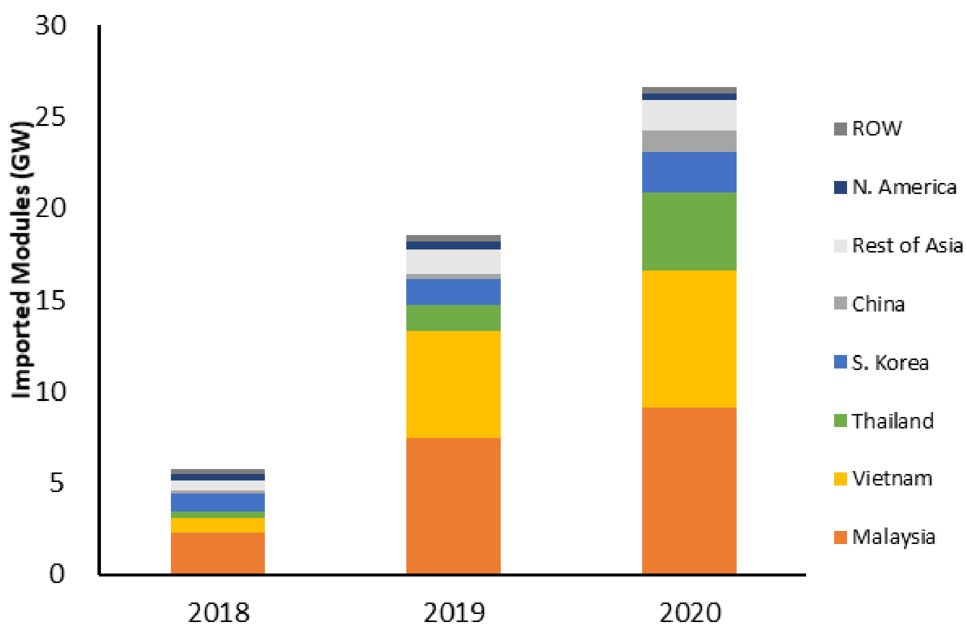


Figure 5. U.S. PV module imports by region.

In addition, all of the silicon solar cells that are assembled into modules in the United States are imported (Figure 6). The United States has no operating capacity for making silicon solar cells. Considering both imported c-Si modules and domestic c-Si module assembly, about 75% of the silicon solar cells installed in the United States in 2020 came from Southeast Asia (Vietnam, Malaysia, and Thailand), with the majority of the remainder coming from South Korea.

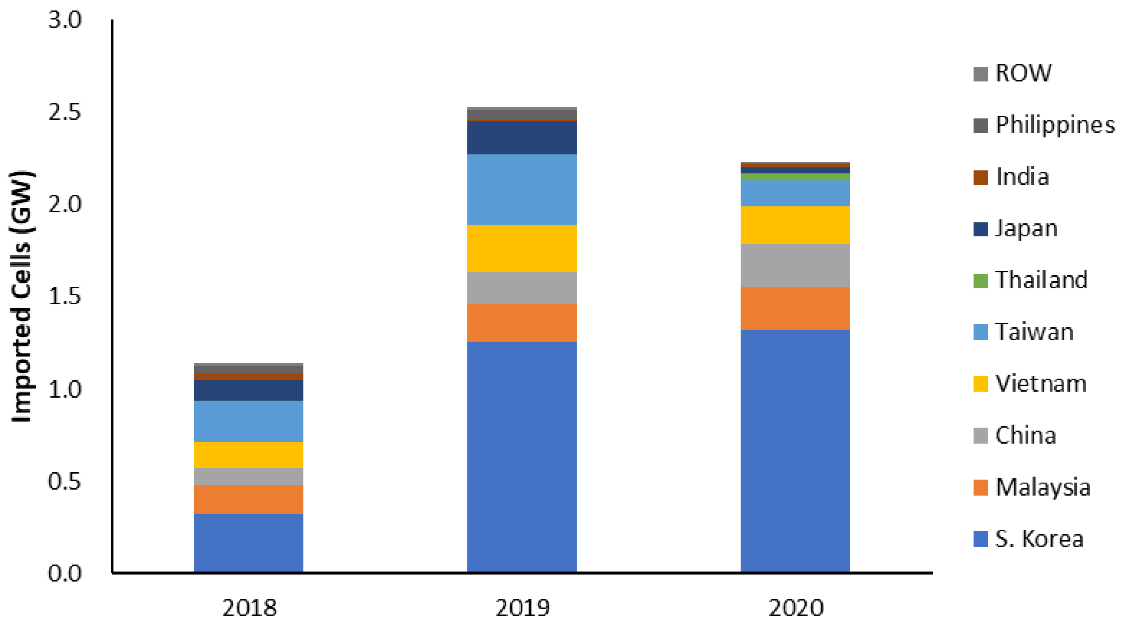


Figure 6. U.S. silicon cell imports by region.

Historically, the U.S. PV market was not as heavily dependent on imports, however from 2010 to 2020, U.S. manufacturers faced multiple challenges related to low-cost imports or imposed tariffs. Capacity for module assembly stagnated for most of the past decade due to market availability of low-cost imported PV modules; first, largely from China, and then mostly Southeast Asia. Wafer production in the United States ended altogether in 2015 due to lower-cost imports. Production of cells varied year to year, but cell producers suffered a series of bankruptcies in 2018, again due to the availability of low-cost imports.

In 2019, cell production started to rebound in part because of the new tariffs; however, the tariffs were not sufficient to enable the existing cell manufacturers to continue and, in Q4 2020, cell production stopped, having produced 198 MW_{dc} for the year. As of this writing, the United States has no active ingot, wafer, or c-Si cell manufacturing capacity. The considerable polysilicon production capacity, which could be a part of the U.S. PV supply chain, is also mostly idle because China, which hosts the vast majority of all wafer manufacturing, placed tariffs on U.S.-produced polysilicon in 2014, forcing them to scale-back production to supply only the semiconductor (integrated-circuit) industry. Over this same period, as U.S. PV manufacturing was shrinking, the U.S. PV installation rate grew from 0.8 GW_{dc} to 19 GW_{dc} (Figure 7).

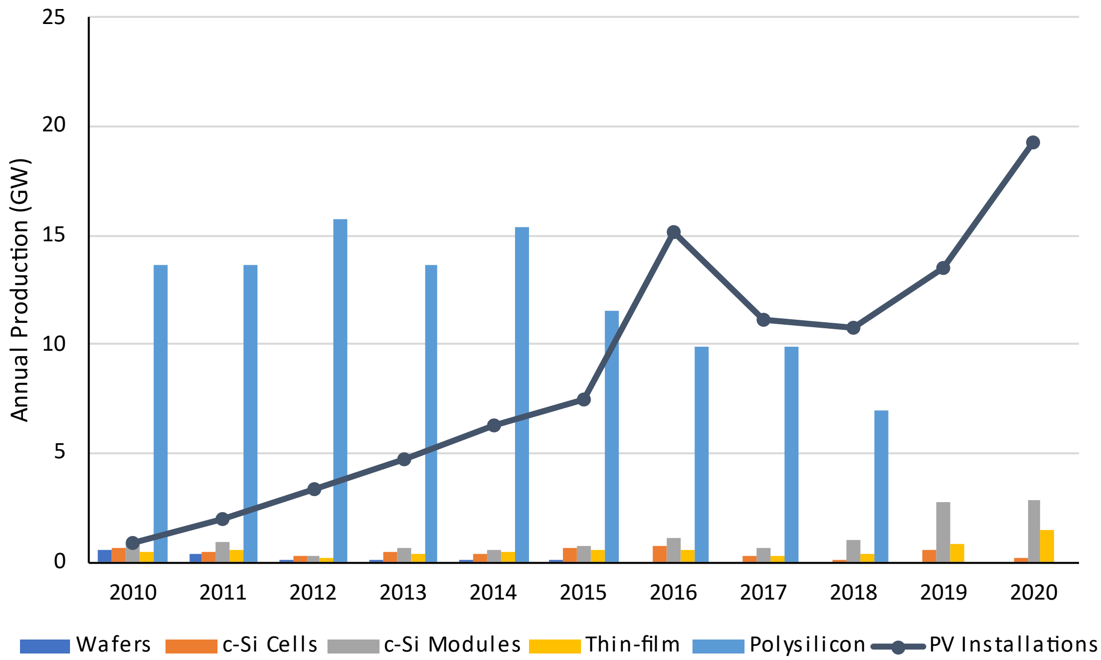


Figure 7. U.S. production of PV components and U.S. PV installations over time.

Using imported cells, U.S. c-Si module *assembly* did began scaling up significantly in 2018 and 2019, due in part to U.S.-placed tariffs on imported modules. In 2020, the United States assembled a record 4.3 GW_{dc} of PV modules, up 24% over 2019, mostly because of a doubling of production capacity by thin-film manufacturer First Solar. If U.S. PV demand growth continues, there may be an opportunity for further domestic manufacturing expansion, particularly given the disruptive nature that global politics can have on the PV supply chain. The impact of restrictions imposed in 2021 on importing solar products potentially traceable back to a company in China linked to human rights abuses illustrates the importance of having multiple sources of supply. Developing the U.S. PV supply chain could also mitigate challenges related to production disruptions, competing demand from other industries or countries, and global politics (Margolis et al. 2021).

Beyond domestic supply chain growth, to fully realize the benefit of solar power to society, its costs and benefits must be distributed equitably, the entire supply chain must be operated in a safe and socially responsible manner, the input materials must be produced without forced labor, and recycling at end-of-life must become standard practice.

Like all energy technologies, solar power generates negative externalities throughout its life cycle, though they are trivial compared to the externalities of fossil fuel technologies that solar technology displaces. The negative externalities of solar power can be mitigated through measures to promote a circular economy in solar manufacturing, installation, and disposal. For example, periodic repairs can extend solar system lifetimes beyond the conventional useful life of 20–30 years and degraded solar panels can be transferred and reused in applications compatible with lower system output. By extending useful lifetime, repair and reuse can delay the need for new resource extraction and manufacturing and delay end-of-life disposal. Further, certain solar system components and materials can be recycled, avoiding raw material extraction and disposal (Margolis et al. 2021).

Solar energy also presents an opportunity to remedy historic injustices in the energy sector. Low- and medium-income communities and communities of color have been disproportionately harmed by the fossil-fuel-based energy system, with exposure to poor air quality and other harmful pollution disproportionately higher in communities of color. Further, low- and medium-income communities and communities of color have historically had to dedicate a greater share of household income toward energy expenses than white and higher-income households. Solar deployment—at the scale necessary to decarbonize the U.S. electricity sector—presents an opportunity to maintain the benefits of the modern energy system while distributing mitigated costs and larger rewards more equitably. The growth in the use of solar technologies presents many potential benefits including climate change mitigation, improved air quality, job creation, and local wealth building. New approaches to energy policy and development may be needed to ensure that the benefits of the zero-carbon system are equitably distributed (Margolis et al. 2021).

1.3 The Global Role of Solar Photovoltaics

A significant portion of PV-component supply, varying by the stage of the supply chain, comes from China. While a considerable (but minority) portion of cells, modules, and polysilicon can be sourced outside of China, the global PV supply chain is almost entirely dependent on ingot and wafers from China. Additionally, many of the other pieces of the module supply chain, such as the manufacturing of production-facility equipment and balance-of-module components (e.g., glass, aluminum frames), are predominantly located in China. China also manufactures a significant share of balance-of-PV-system components, including inverters (which convert the dc output from PV modules to ac power used by the electrical grid) as well as aluminum and steel used for mounting PV modules.

Current PV module manufacturing capacity is well above current deployment levels. By 2035, a high-decarbonization scenario would require significant expansion of several parts of the supply chain (Figure 8). Regardless of capacity increases, existing manufacturing capacity will likely be replaced or refurbished by lines that will produce more efficient and/or cheaper panels.

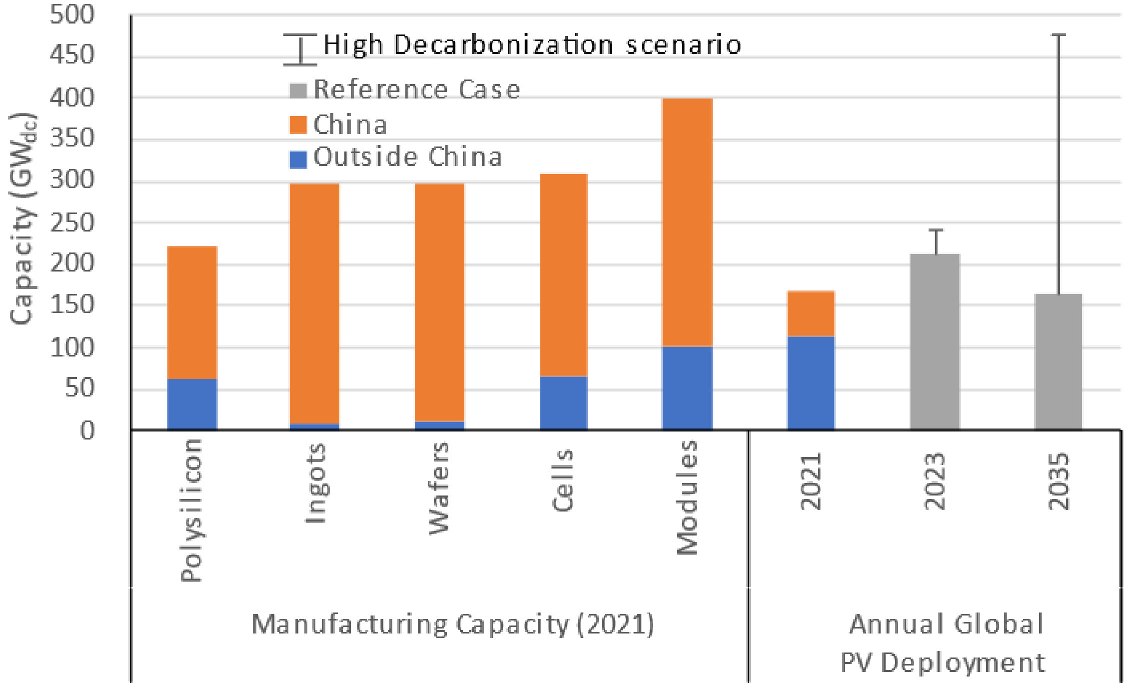


Figure 8. PV manufacturing capacity and deployment, inside and outside China.[1]

Within China, PV production is clustered in a handful of provinces, representing 80%-93% of total Chinese manufacturing and 64%-81% of total global manufacturing (Table 1, Figure 9). Some provinces span multiple PV manufacturing steps, but many tend to focus on one manufacturing step.

Labor, electricity price, and proximity to shipping correlate with provincial strength and manufacturing needs. Western Chinese provinces, with cheap labor and electricity, have high levels of manufacturing for steps that use significant amounts of electricity (polysilicon, ingots) or labor (ingots, wafers). Eastern provinces, with easier access to global shipping and proximity to Chinese populations, are more likely to have PV manufacturing steps later in the process, in preparation for the exports or domestic end-use development (wafers, cells, modules). Some provinces have significant market share across components, due to the benefits of integrating manufacturing steps, and economies of scale associated with larger-scale facilities and supply chains.

Forced labor in the mining and processing of raw materials in China's Xinjiang province adds a new dimension of uncertainty to the solar supply chain's reliance on Chinese production. Metallurgical-grade silicon (MGS) and the coal used to produce electricity have been highlighted by the U.S. government as direct beneficiaries of government-sponsored forced-labor programs in that region.

[1] Assumes 3 grams of polysilicon per watt.

Table 1. Chinese PV manufacturing by component and province.

Province Rank in China	Polysilicon	Ingots	Wafers	Cells	Modules
1	Xinjiang	Inner Mongolia	Jiangsu	Jiangsu	Jiangsu
2	Inner Mongolia	Yunnan	Yunnan	Zhejiang	Zhejiang
3	Jiangsu	Ningxia	Inner Mongolia	Sichuan	Anhui
4	Sichuan	Jiangsu	Jiangxi	Shaanxi	Hebei
5	Qinghai	Sichuan	Ningxia	Henan	Jiangxi
Chinese Fraction of Global Manufacturing Capacity by Component	72%	98%	97%	81%	77%
Top-5 Provinces Fraction of Chinese Manufacturing Capacity	93%	83%	81%	80%	84%
Top-5 Provinces Fraction of Global Manufacturing Capacity	67%	81%	78%	65%	64%

Source: (BloombergNEF 2021)

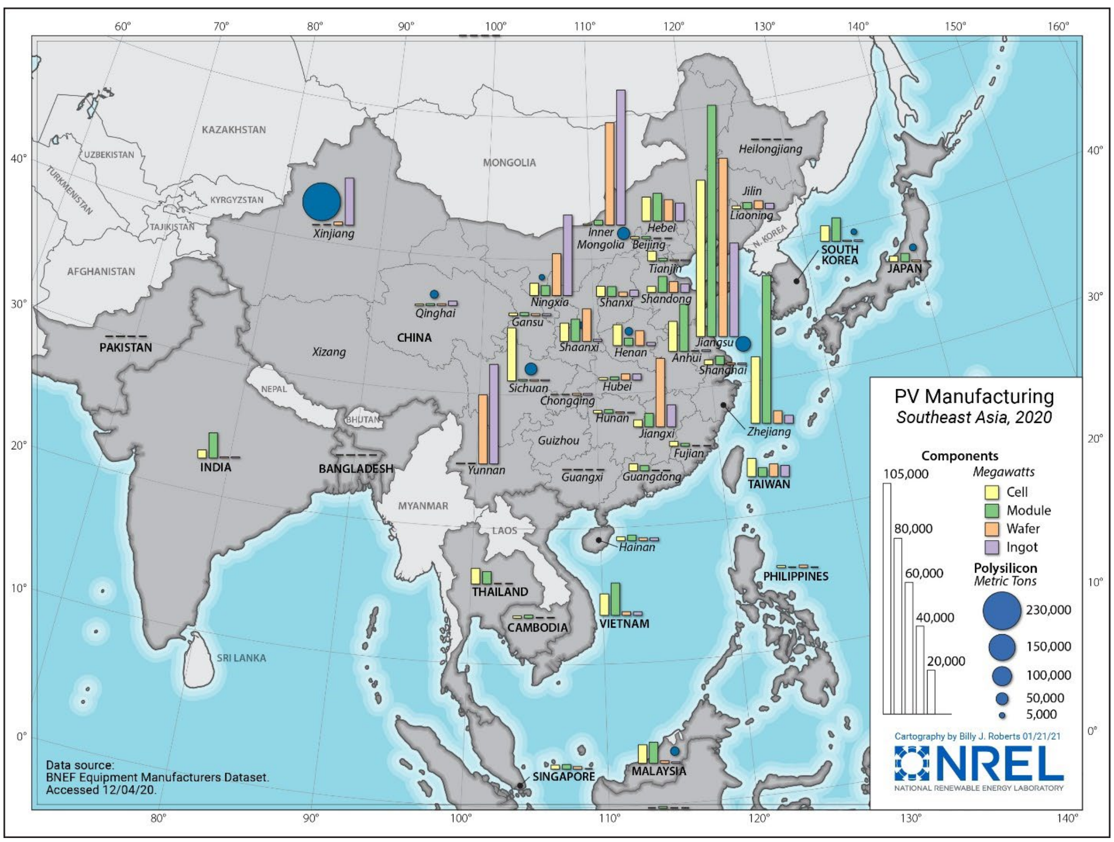


Figure 9. PV manufacturing in Southeast Asia, 2020.

Source: (BloombergNEF 2021f)

Due to China's low labor costs, concentrated supply chain, and non-market practices, it has been difficult for the United States to compete against China across c-Si PV components. The capital cost of production facilities is a minor additional factor in China's favor, with capital expenditure representing 8% of the production cost in China versus 10% in the United States. Figure 10 compares Chinese and U.S. production costs across the c-Si PV supply chain.

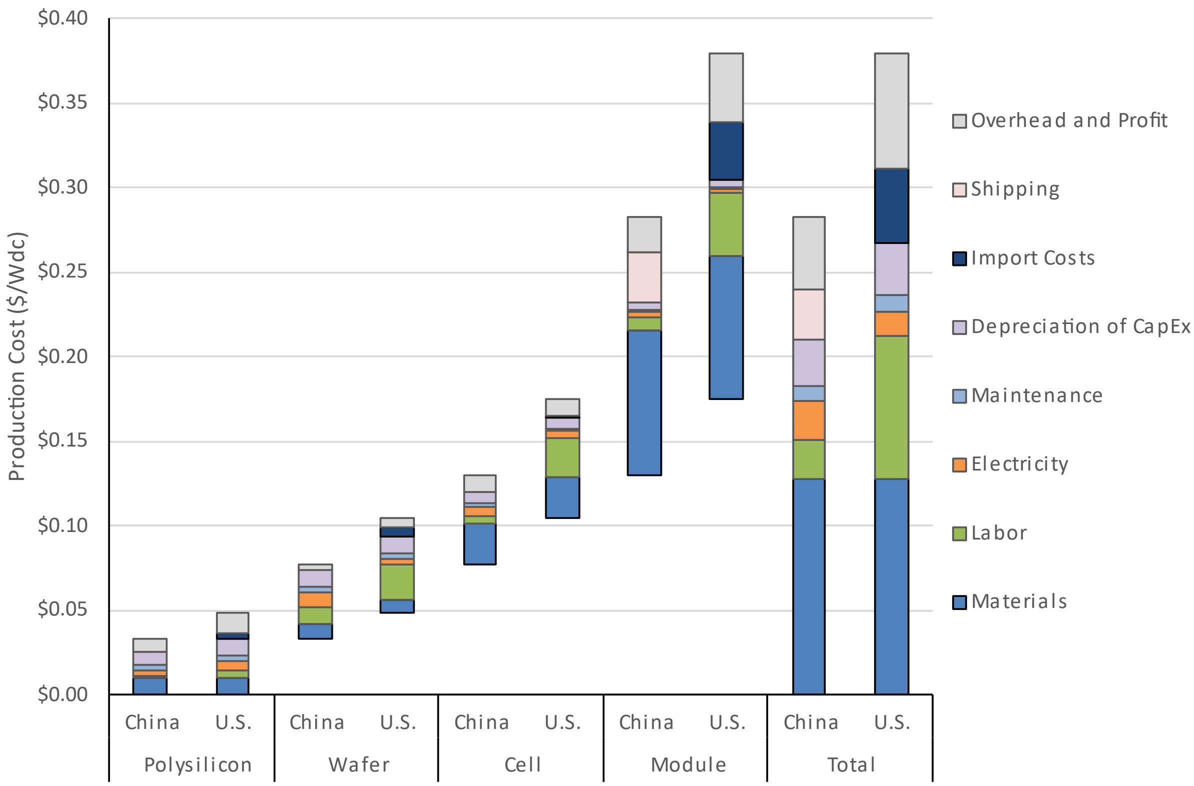


Figure 10. Production costs for c-Si PV manufacturing in the United States and China.

Source: NREL

Labor expenses are the principal source of difference between calculated PV manufacturing costs in the United States and China, particularly for labor intensive manufacturing steps (see Table 2). Labor costs represent 22% of total U.S. manufacturing costs versus 8% in China, 33% of U.S. cell manufacturing costs versus 8% in China, and 36% of U.S. wafer manufacturing costs versus 23% in China.

There are pathways to reduce the cost delta by introducing more automation in the United States. These include more-automated approaches being developed by ingot and wafer factories, as well as more-automated approaches being used to manufacture state-of-the-art cell and module technologies. Automation should be considered as part of a holistic workforce approach that accounts for job quality and the ability of incumbent workers to maintain their livelihood, in addition to a company's long-term growth plan. Such a strategy has proven to be successful for the production of CdTe panels in the United States. As demonstrated in Figure 11, the cost to produce a CdTe in the United States is approximately the same as that of Southeast Asia, when accounting for shipping.

Table 2. Labor cost drivers across the c-Si and CdTe supply chain.

Labor Cost Drivers	c-Si Supply Chain				CdTe Module Production
	Polysilicon	Ingot and Wafer	Cell Conversion	Module Assembly	
Labor Intensity (Direct full-time employees (FTE) per MW_{dc} of production)	0.035—0.070 (40—85 MT per year per FTE for Siemens to FBR. @ 2.8 g/W)	0.40—0.80 (Labor intensity in U.S or Europe to China)	0.15—0.45 (Advanced technology to PERC)	0.50—0.70 (Advanced technology to PERC)	0.40—0.60
Direct Manufacturing Jobs at 1 GW_{dc} Scale	35—70	400—800	150—450	500—700	400—600
Assumed Hourly Labor Rates for Cost Models ($2020 USD)	$4.1—5.0 per hour for direct operators in China $6.2—7.5 per hour for first-line supervisors in China Housing, cafeteria, and insurance expenses included. $14.3—22.0 per hour for direct operators in electronics assembly in the United States $23.3—38.8 per hour for first-line supervisors in the United States Additional 35% benefits expense assumed for workers in the United States				

Source: NREL update of (Smith et al. 2021)

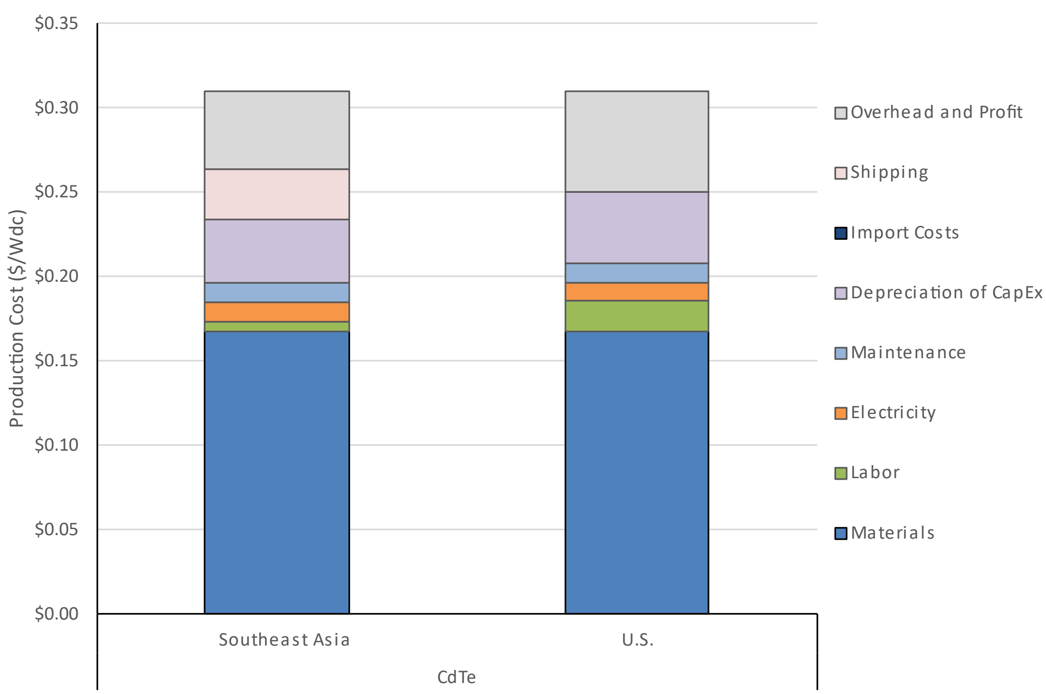


Figure 11. Production costs for CdTe PV manufacturing in the United States and Southeast Asia.

Source: NREL update of (Smith et al. 2021)

Because of the current gaps in the domestic PV supply chain, virtually all c-Si manufacturing inputs are imported (i.e., "Import Costs" in Figure 10), from the aluminum frame and glass to the PV cells. These import costs add 11% to the total U.S. PV manufacturing costs. A build-up in domestic PV supply chain would significantly reduce these costs. The time to build new facilities, minimum scale of facilities, and capital expenditures, vary by manufacturing step (Table 3), with certain steps less expensive and faster (module assembly) to scale than others (ingot and wafer).

Table 3. Fixed cost drivers across the c-Si and CdTe supply chain.

Fixed Cost Drivers	c-Si Supply Chain				CdTe Module Production
	Polysilicon	Ingot and Wafer	Cell Conversion	Module Assembly	
Initial Capital Expenditure ($USD per Watt of annual capacity)	$0.11-0.14/W ($40—50/kg, 2.8 g/W)	$0.08-0.10/W ($0.54/wafer, 6.0 W for M6)	$0.05-0.13/W (PERC to Advanced technology)	$0.05-0.08/W (Standard to Busbarless)	$0.28-0.36/W (430-W series)
for equipment:	$0.06—0.08/W	$0.06—0.07/W	$0.03—0.10/W	$0.03—0.05/W	$0.25—0.30W
for balance-of-plant or factory	$0.04—0.06/W	$0.02—0.03/W	$0.02—0.03/W	$0.02—0.03/W	$0.03—0.06/W
1 GW_{dc} Investment	$110—140M	$80—100M	$50—130M	$50—80M	$280—360M
for equipment:	$65—80 M	$60—70 M	$30—100M	$30—50M	$250—300M
for balance-of-plant or factory	$45—60 M	$20—30 M	$20—30M	$20—30M	$30—60M
Time to Build (Engineering to production)	3—4 years (All-new, not retrofit)	1—3 years	1—3 years	1—3 years	1—3 years

Source: NREL update of (Smith et al. 2021)

2 Supply Chain Mapping

Figure 12 illustrates the steps in the c-Si supply chain, from polysilicon to modules, which are physically attached to mounting structures and electrically attached to inverters. This chapter provides supply chain details for each step, followed by a section addressing cadmium telluride thin-film technology.

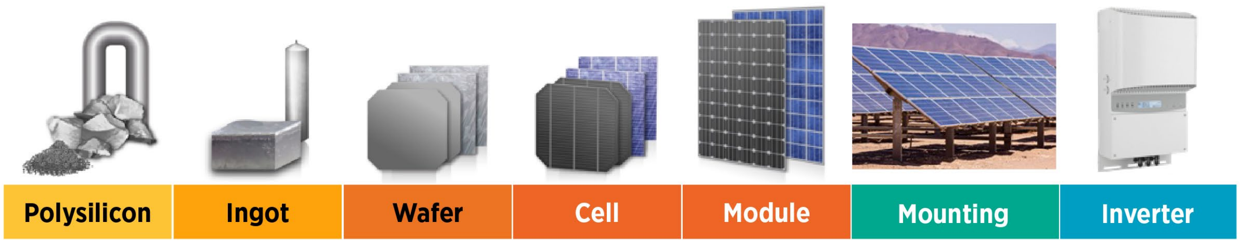


Figure 12. Principal sectors of the c-Si supply chain.

Source: NREL

2.1 Input Materials

2.1.1 Metallurgical-Grade Silicon

2.1.1.1 Technology Overview

The silicon incorporated into c-Si modules initially comes from silicon dioxide (or silica), the second most abundant mineral in the Earth's crust (Honsberg and Bowden 2019). Silica occurs naturally in the form of quartz, but there are limitations on the type of quartz (and quartz mines) that can be used, due to the need for high levels of purity. While some elements, such as aluminum and calcium, are easy to extract from silica, other elements—such as iron, phosphorus, titanium, and boron—have deleterious effects on solar cell performance and are very difficult to remove; therefore, manufacturers of metallurgical-grade silicon (MGS) must be selective with the quartz they use. Sand, for example, is made of quartz but tends to have too many impurities. There are typically two ways quartz is mined for silica:

1) Riverbeds often have quartz from broken mountain ranges. Quartz can be collected from such sites, but there can be environmental considerations for active waterbeds due to the connection with water supply. This type of mining is common in the United States, as are other dry excavation and mining approaches.

2) Quartz veins are often found and mined below ground. This can be a dangerous process as fine quartz dust particles from mining can be lethal if inhaled. This type of quartz mining requires great care and typically also leaves a big scar where the land was blasted.

While quartz is the main input to MGS refining, it is relatively inexpensive and represents less than 10% of the cost. For this reason, companies do not typically explore for high-quality quartz mines, but rather find them when looking for something more valuable, such as gold (gold is often associated with quartz). Therefore, the amount of world reserves for quartz is unknown; however, there does not appear to be any shortage globally. While quartz can be transported, sourcing quartz close to where it is needed minimizes shipping costs. China, the leader in MGS production, does not have abundant resources of quartz. Conversely, Spain and Brazil have the lowest-cost quartz. India has good quartz but high energy costs, making MGS production uneconomical.

In addition to quartz, low-ash coal and woodchips are necessary for producing MGS, and these are somewhat specialized materials. Low-ash coal can be found in the United States for domestic MGS production, but a significant portion of international MGS production relies on low-ash coal from the Cerrejón mine in Colombia. There are also key washing operations in the Netherlands, Spain, and Portugal. Charcoal may be a substitute for Colombian coal.

Figure 13 shows the principal input materials and process for MGS production. Quartz, or silicon dioxide, is made into MGS by removing the oxygen using carbon (i.e., coal and woodchips), which produces the byproduct carbon monoxide, which can later be processed into carbon dioxide. This process is very energy intensive and requires the use of an electric arc furnace; 10–15 MWh of power are required for each ton of MGS produced.

Many producers of MGS can also make ferrosilicon by adding in iron during the process. As most silicon production is actually ferrosilicon production, capacity could be switched over, and even brownfield existing sites could currently pick up any solar demand. Unless there are restrictions against particular production locations (e.g., Xinjiang or China more broadly), MGS is not believed to be a bottleneck material.

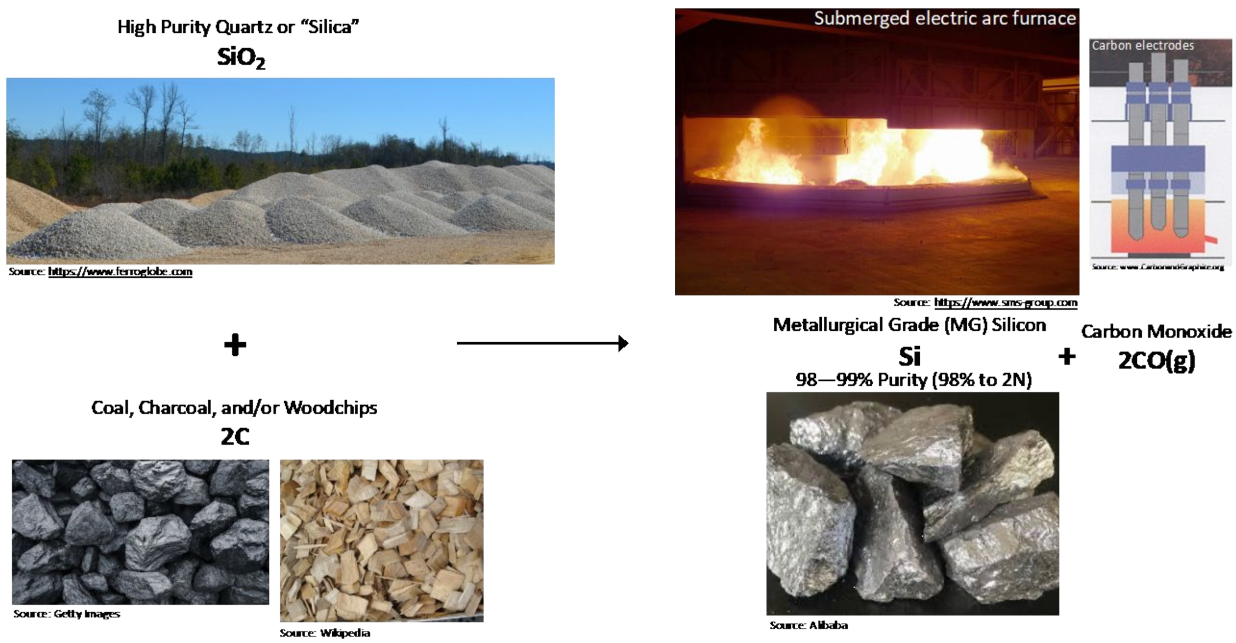


Figure 13. Principal input materials and process for MGS production.

Source: NREL

MGS is used to make polysilicon for solar wafers and semiconductors, silicones, and aluminum alloys (Figure 14). While the process is in principle flexible, polysilicon producers oftentimes impose expectations of MGS chemistry (impurity tracing) and size. To guarantee supply and purity levels, MGS manufacturers often backwardly integrate, owning a significant portion of the mines in which they source quartz. Additionally, because of the energy-intensive nature of the process, MGS processing typically occurs in locations with abundant and cheap sources of electricity including the United States, Malaysia, Norway, and the Xinjiang region of China. In 2021, the U.S. government determined that Hoshine Silicon's MGS operation in Xinjiang was benefiting from forced labor and imposed a Withhold Release Order (WRO) to prevent products incorporating Hoshine's MGS from being imported into the United States (see Section 3.2.3).

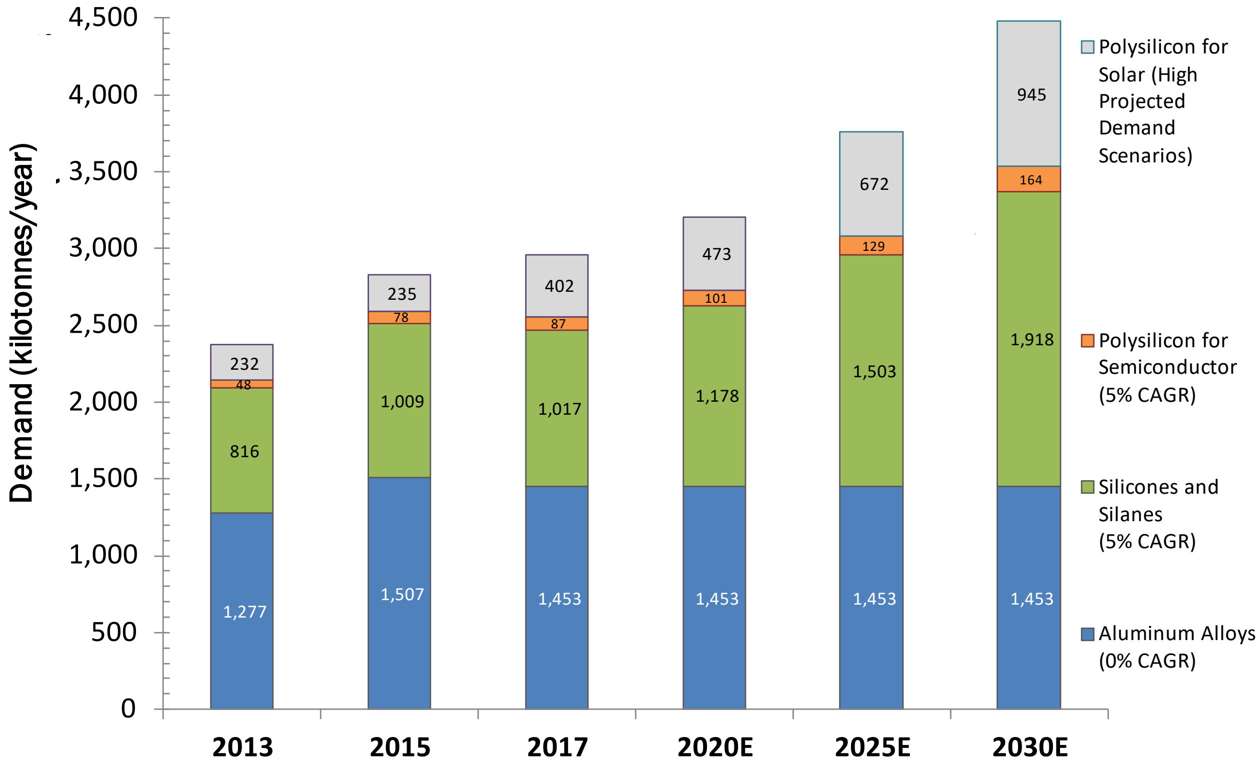


Figure 14. Global demand for MGS by application.

Sources: USGS, Sandia, CRU Group, BloombergNEF, ITRPV, NREL

The competing uses for MGS are silicones and aluminum alloys. Growth in demand for aluminum alloys is difficult to determine currently. On the one hand, demand should increase due to population growth; however, there could also be less demand for aluminum as recycling becomes more efficient globally.

Silicon demand from the solar industry is a function of deployment targets and silicon utilization. Based upon technology advancements outlined within the International Technology Roadmap for Photovoltaic (ITRPV), the net MGS utilization is expected to drop from 3.4 g/W in 2020 to 2.1 g/W by 2030 (J Trube 2021).

2.1.1.2 Industry Overview

There are currently about 15 countries with MGS capacity (Figure 15) (BGS 2021; USGS 2021b). These include: China, Norway, Iceland, Brazil, the United States, France, Canada, Australia, Malaysia, Russia, Kazakhstan, Bosnia and Herzegovina, Laos, and Thailand (U.S. International Trade Commission 2018). South Africa had production facilities, but those recently closed. Production in Malaysia began in 2019 due to access to a new hydropower hub. Location is limited to places with cheap and abundant electricity, access to quartz (domestically or near a port), and access to buyers without prohibitive trade restrictions.

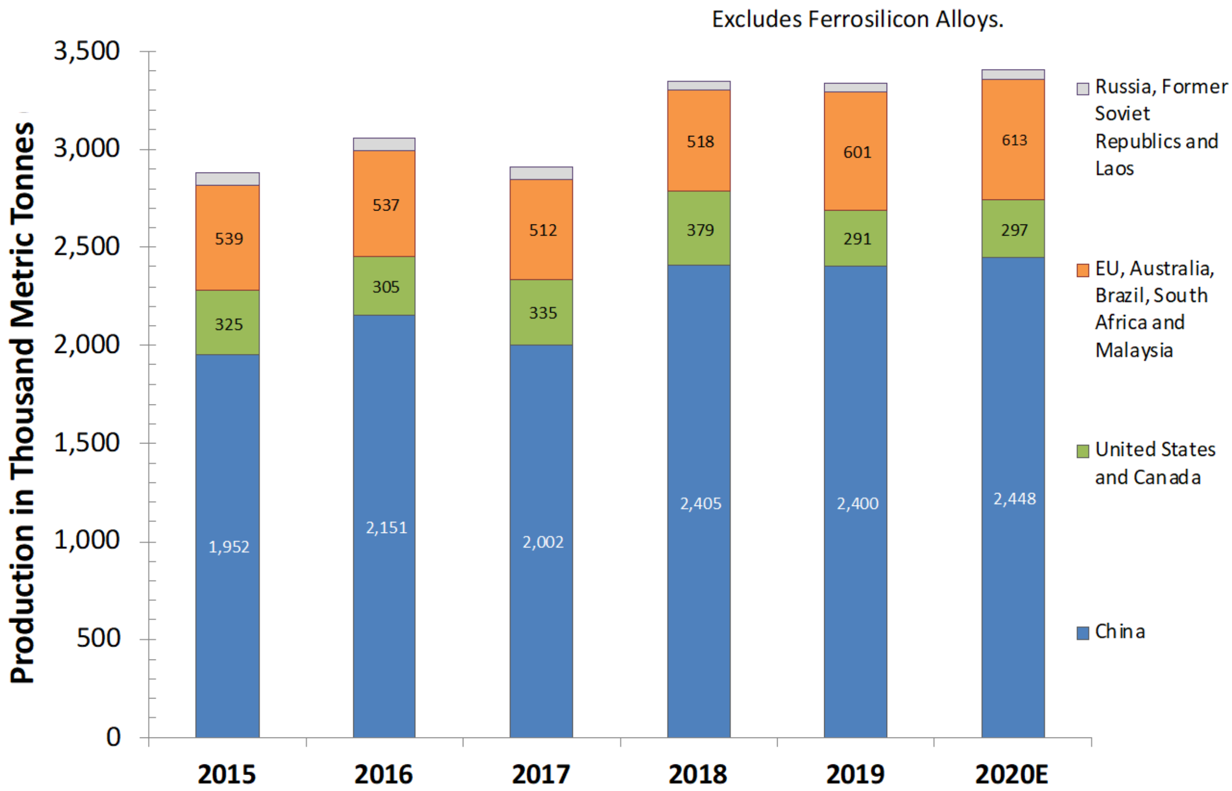


Figure 15. Principal locations of MGS production.

Sources: USGS, British Geological Survey

China currently has around 70% of global MGS production capacity and hundreds of companies of varying size (USGS 2021b; BGS 2021). As of 2017, the top 10 Chinese producers owned approximately 35% of domestic capacity and the top five approximately 25% (Normann 2018). Non-Chinese silicon manufacturers are consolidated, with the top 10 manufacturers holding 96% of non-Chinese manufacturing capacity (Figure 16).

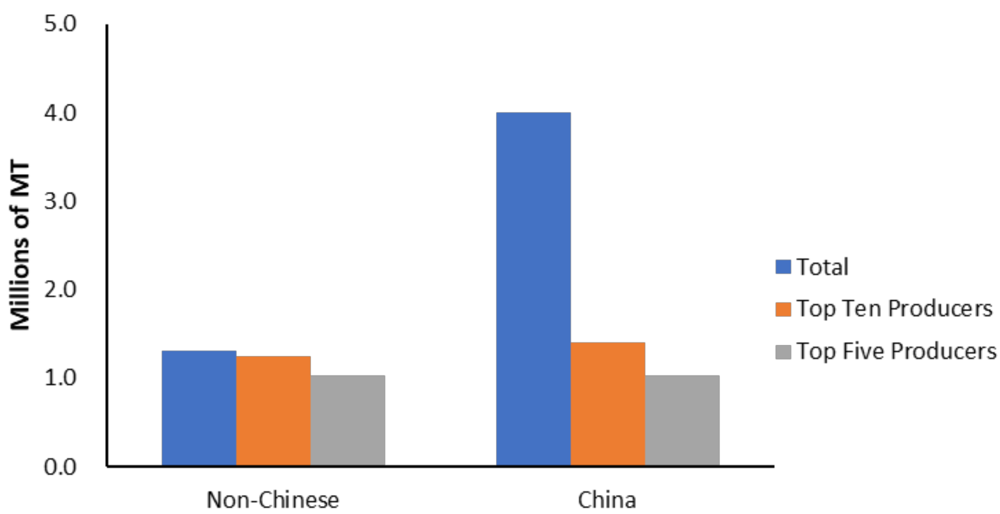


Figure 16. China and non-China MGS manufacturing capacity, 2017.

Source: (Normann 2018)

There are currently four companies with seven plants producing MGS in North America, as shown in Figure 17, but the Dow Corning plant has been shut down for some time. Many of the plants improve their competitiveness and keep their greenhouse gas emissions low by sourcing inexpensive hydropower electricity (even in coal-rich West Virginia).

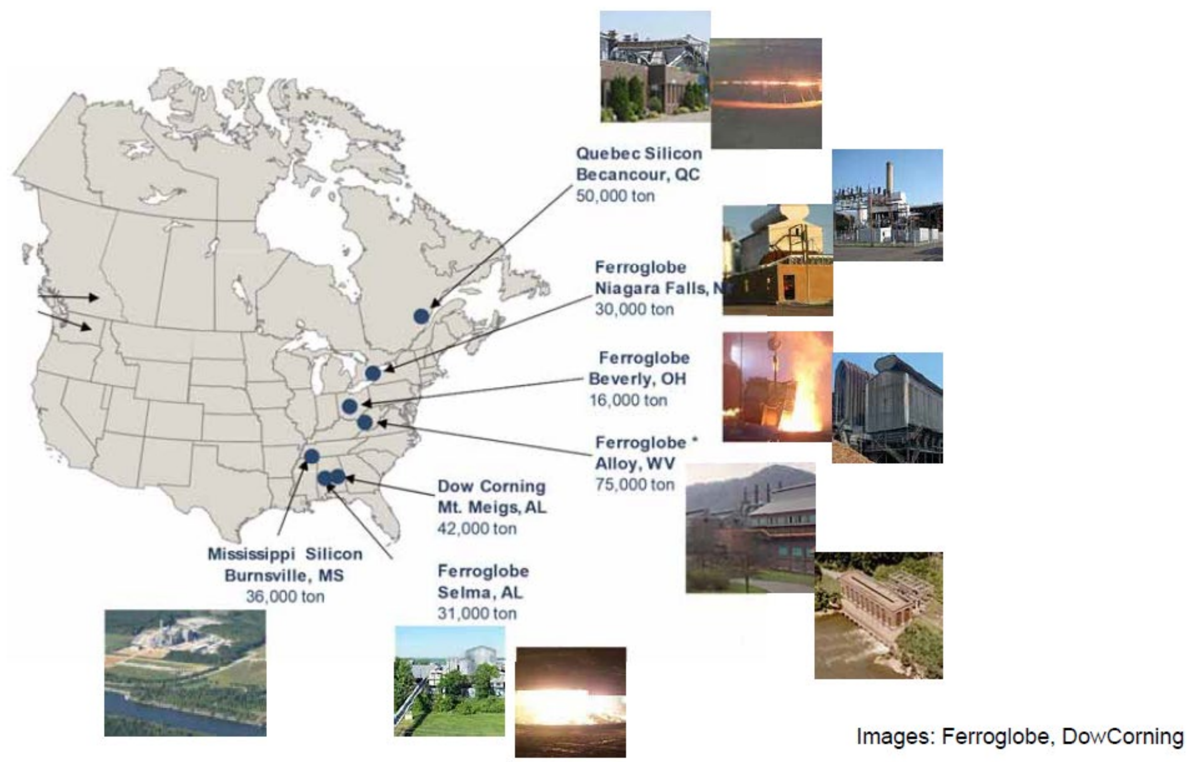


Figure 17. North American MGS plants.

Source: (Chalamala 2018)

2.1.2 Glass

2.1.2.1 Technology Overview

The flat glass used for PV module assembly typically has low iron content for optimal transmissivity of sunlight and is both tempered and anti-reflective coated. Silica sand is typically reported to be the primary input material for solar-grade glass (Heidari and Anctil 2021).

- The front glass typically used on crystalline silicon PV modules (also known as "coverglass") is typically 3.2-mm rolled glass, which is slightly dimpled on one side to improve encapsulant adhesion. This glass is produced between two rollers, one of which is patterned.
- The front glass on thin-film PV modules is typically 3.2-mm float glass produced on a float line, due to the need for a highly flat surface to act as a superstrate or substrate.

Rear glass for thin film or bifacial c-Si modules is typically 2.0-mm soda lime glass, since it does not need high optical transmittance and is less expensive.

2.1.2.2 Industry Overview

Float lines are most common in China and the United States as shown in Figure 18, but little detail is known about the distribution of rolled glass production, aside from the fact that most PV coverglass is produced in China. The United States currently does not have significant excess capacity to produce rolled glass, though float glass lines may be able to be built in a relatively short time, as demonstrated by First Solar's exclusive glass line in Ohio.

Figure 18. Flat glass production by country and number of float lines, 2017.

Source: (B. Smith and Margolis 2019)

Float glass is generally reported to be more expensive than rolled glass, and larger facilities are necessary to achieve the necessary economies of scale. A single float line would produce approximately 2 GW_{dc} of coverglass per year and would require a capital investment of approximately $150 million. To produce the low-iron pattern glass that is typically used as coverglass for c-Si PV, the float line would have to be slowed down considerably, which worsens the economic performance of the float line. Because rolled glass has a higher proportion of labor costs as compared to float glass, it is much cheaper when produced in areas with low-wage labor, such as China.

2.1.3 Encapsulant

2.1.3.1 Technology Overview

In a PV module, front and back layers of encapsulant film form a protective barrier around the PV cells, essentially laminating the cells. The predominant resins used to make encapsulant are ethylene vinyl acetate (EVA), which is primarily used for monofacial PV modules, and polyolefin elastomers (POE), which is primarily used for bifacial or thin-film modules. EVA is synthesized by polymerizing vinyl acetate monomers and ethylene (B. Smith and Margolis 2019). Natural gas is the primary feedstock to produce both ethylene and POE.

Typically, EVA or POE is produced by a petrochemical company in resin form and sold to a film extruder which extrudes the resin into the film needed in the module assembly process. These two steps are typically not vertically integrated, though some vertically integrated firms exist, such as Hanwha and Mitsui.

2.1.3.2 Industry Overview

Generally, resin is produced globally, but extrusion capabilities are concentrated in China (Figure 19). Some Southeast Asian countries have encapsulant production established by Chinese corporations to support the module industry in those countries. Similarly, encapsulant extrusion exists in India, but is often owned by Chinese companies. Hangzhou First (or “First Applied Material”) is the largest global encapsulant producer, though it also supplies backsheets. HIUV, Sveck, and Cybrid are also major encapsulant producers in China, while Borealis is a smaller producer in Austria.

The United States has significant capability to produce encapsulant resin, but extrusion capabilities are less common. DOW Chemical is focused on POE resin for PV applications, though it produces EVA resin as well. Natural gas is the feedstock for both POE and ethylene, so low U.S. gas prices can be an advantage for U.S. production.

Figure 19. Largest EVA-producing countries, 2017.

Source: (B. Smith and Margolis 2019)

2.1.4 Backsheets

2.1.4.1 Technology Overview

Backsheets are used in monofacial c-Si modules as the final back layer of the module, but some clear backsheets are now starting to be used as the backing for bifacial c-Si modules as well. Backsheets are intended to electrically insulate the module and protect it from moisture and wind damage.

The materials used in backsheets vary significantly across the market (Figure 20). Almost all backsheets use polyester (PET), typically in some combination with polyvinyl fluoride (PVF), polyvinylidene fluoride (PVDF), polyethylene, or less commonly polyolefin or polypropylene (Chunduri and Schmela 2020).

Like encapsulants, backsheet materials are typically first produced as bulk resins and are then extruded into films. Backsheets are typically made of three films laminated together: the inner layer (touching the encapsulated cells), the core (middle) layer, and the outer layer which is exposed to air. The core layer is typically PET, while the outer layer is frequently PVF or PVDF. Firms often operate as independent laminators by purchasing films and laminating desired stacks together into backsheets.

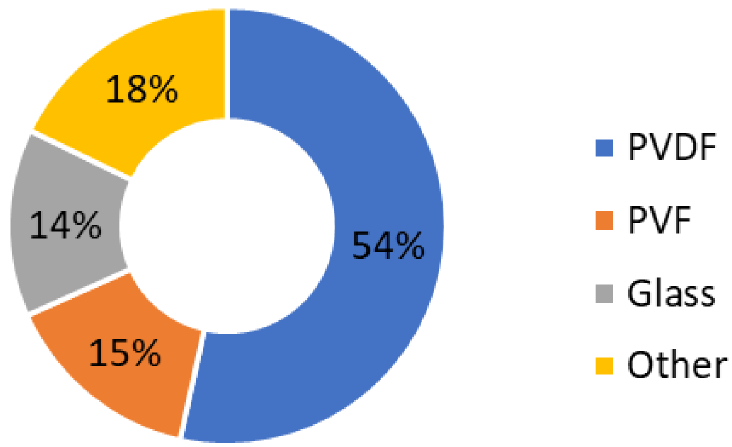


Figure 20. Market share of backsheet materials, 2019.

Source: (Chunduri and Schmela 2020)

2.1.4.2 Industry Overview

PVDF-based backsheets are reported to dominate the backsheet market; Fumotech, ZTT, and Arkema are major suppliers of PVDF resin. Some examples of vertical integration include ZTT in China, which produces PVDF resin and consumes about 50% of its own resin to produce completed backsheets (Chunduri and Schmela 2020). Conversely, Cybrid was first known as a major backsheet supplier and now operates a PVDF resin production facility. DuPont reports that all its PVF (Tedlar) production occurs in the United States, and approximately 50% goes to PV backsheet applications. It supplies the extruded film to backsheet laminators. Jinko and LONGi, two of the largest PV module producers, use PVF-based backsheets for most of their products.

There are a few major PET suppliers, mostly located in China, though the DuPont-Asia PET supplier is located in Japan. DTF is a major supplier of the PET core layer for backsheets.

Very few backsheet laminators exist in the United States, but examples include Dunmore, Tomark Worthen, and FLEXcon. Most laminators are located in China, with some appearing in India more recently.

2.1.5 Aluminum Frames

2.1.5.1 Technology Overview

The aluminum used in PV module frames or PV system racking can either be sourced from primary extraction (mining) or secondary extraction (recycled content). Module frames and aluminum racking (typically used for residential systems) have similar production processes, which rely on extrusion and anodization or other coatings (Figure 21).

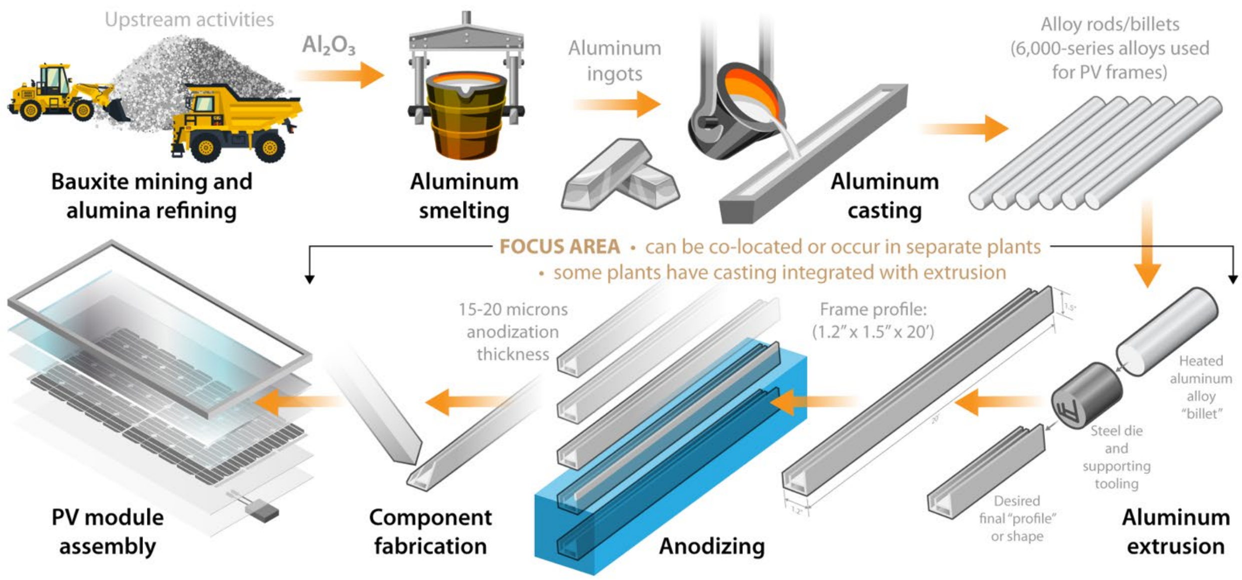


Figure 21. Production process for aluminum module frames, assuming primary aluminum extraction.

Source: NREL

The raw input aluminum must be alloyed appropriately for its intended application. Alloying occurs during the casting stage when smelted ingots are cast into billets. The most popular extrusion alloy class, which is typically used in solar applications, is the 6000 series (Werner 2013). This alloy class is created by varying a combination of magnesium and silicon, depending on the strength required by the end use of the extruded aluminum profile. Once the desired alloy has been produced, it is extruded into the desired shape, then coated and cut (fabricated) as needed.

The general structure of the aluminum extrusion industry encompasses production of the desired alloy, extrusion into the desired shape, then coating or anodization, and finally fabricating or cutting as needed. Extrusion, coating/anodization, and fabrication processes are often co-located but may occur in separate facilities operated by different firms.

2.1.5.2 Industry Overview

Some countries subsidize aluminum, which would result in PV frames and racking at lower cost. Both extrusion and anodizing use large amounts of water, for cooling as well as cleaning and rinsing. Stricter regulations regarding water treatment will add to the cost of producing PV frames and racking. The United States has significant capacity to produce aluminum for frames.

The prices of steel and aluminum in the United States rose in 2018 following the implementation of two tariffs (see Section 3.2.2). A Section 301 tariff on Chinese solar products imported into the United States was placed in spring and summer of 2018; and a Section 232 tariff on steel and aluminum imported to the United States from various countries was imposed starting in the spring of 2018 (Figure 22). China produces more than half the world's aluminum and steel (U.S. Congressional Research Service 2021). The price increases subsided in 2019 with the exclusion of some countries from the Section 232 tariffs (U.S. Congressional Research Service 2021), but since the start of the coronavirus pandemic, supply-chain logistics combined with the tariffs, and other import quotas, have caused domestic shortages in the United States and significant price increases.

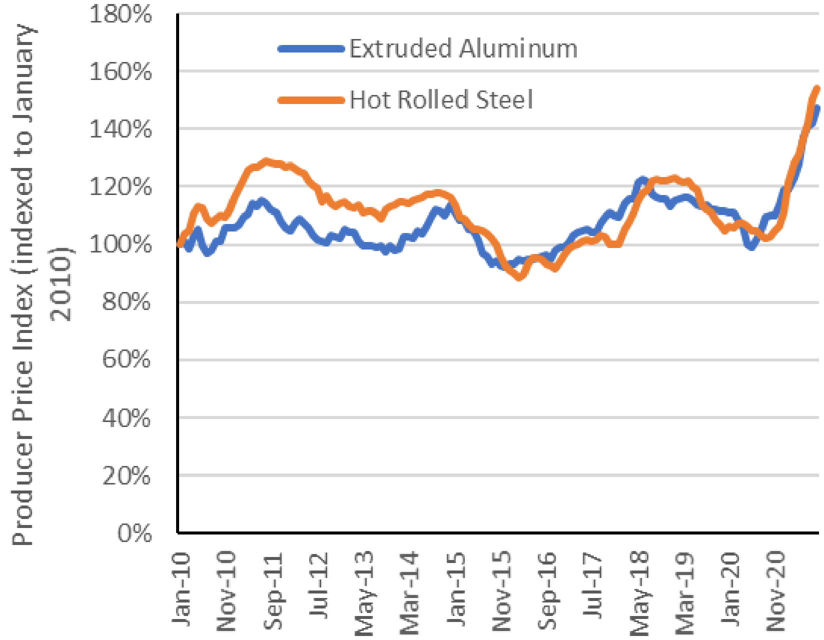


Figure 22. Producer price index for extruded aluminum and hot rolled steel.[2]

Source: (FRED n.d.)

2.2 Polysilicon Refining

2.2.1 Technology Overview

Polysilicon is the high-purity product obtained by refining MGS. PV is the primary consumer of polysilicon (greater than 80% of demand), and the other principal end use is for consumer electronics and semiconductors (Figure 23). Whereas MGS is 99% pure ("2 nines" or 2N) silicon, polysilicon for PV typically has a purity of 8N–11N. Numerous variations in polysilicon production techniques exist, but the two general approaches with the largest market shares are the Siemens chemical vapor deposition method (greater than 90% market share) and the fluidized bed reactor (FBR) method (3%–5% market share). Figure 23 shows the steps to produce polysilicon from MGS, based on the Siemens process.

The Siemens process generally entails passing a gaseous trichlorosilane (TCS) or silane precursor over heated silicon filaments housed within bell-shaped reaction vessels, which deposits pure silicon onto the filaments. Recovered compounds are recirculated and can be used to synthesize new precursors. The end results of this process are U-shaped silicon rods, which are later broken into chunks and sealed in plastic bags with an inert gas such as argon.

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[2] Steel includes: "Hot Rolled Steel Bars, Plates, and Structural Shapes." Aluminum includes: "Extruded Aluminum Rod, Bar, and Other Extruded Shapes."

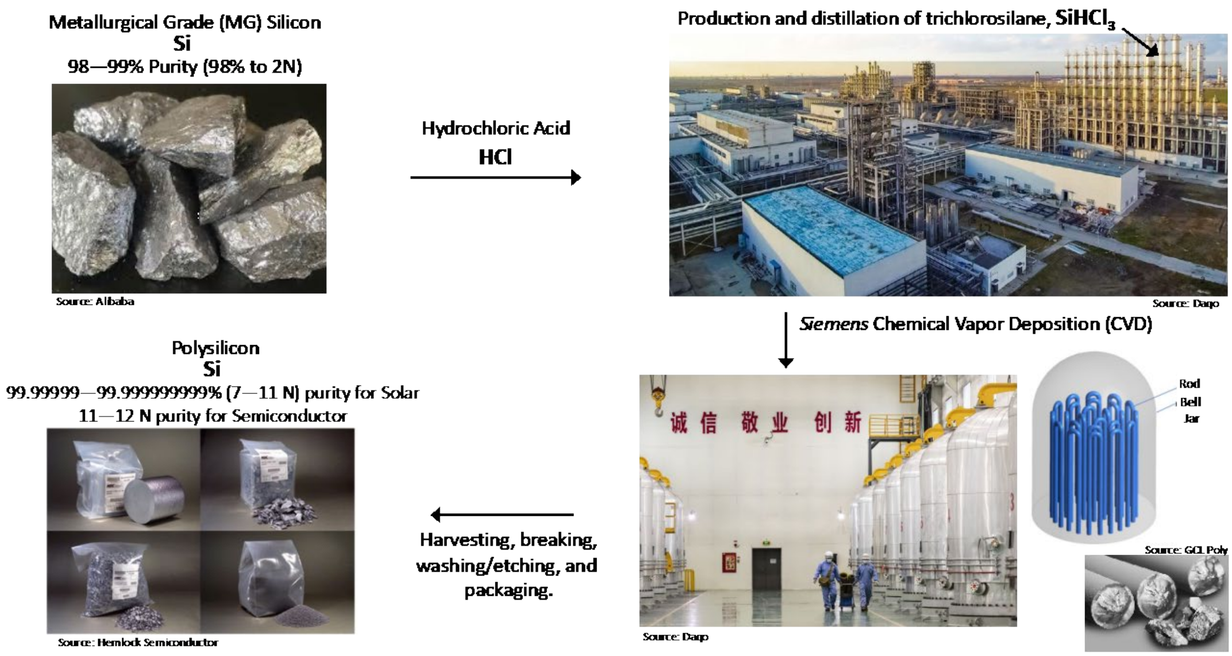

Figure 23. Steps to produce polysilicon from MGS, Siemens chemical vapor deposition method.

Source: NREL

In the FBR process, a bed of silicon beads floats on the fluidizing gases silane and hydrogen, which flow upward through an inverted cone-shaped reaction vessel. Through controlling the temperature differential between the fluidized silicon beads and the reactor walls, silicon layers are deposited onto the beads. As beads become heavy, they fall to the bottom of the cone for collection, ultimately yielding granular polysilicon. This granulated form can facilitate subsequent steps in the c-Si PV manufacturing process. Compared with polysilicon chunks from the Siemens process, the granules fill ingot crucibles more quickly and efficiently, and they are better suited to continuous-Czochralski (Cz) ingot pulling, which can contribute toward PV efficiency and cost advantages. The decision between polysilicon chunk vs. FBR beads must consider impurity differences between the suppliers and the processing capabilities of the ingot production equipment.

2.2.2 Industry Overview

Before 2005, the solar industry sourced most of its polysilicon supply via scrap from the semiconductor industry. As demand for PV grew rapidly, in large part due to the German feed-in tariff beginning in 2004, there was a shortage of polysilicon, which significantly increased its price (Figure 24).

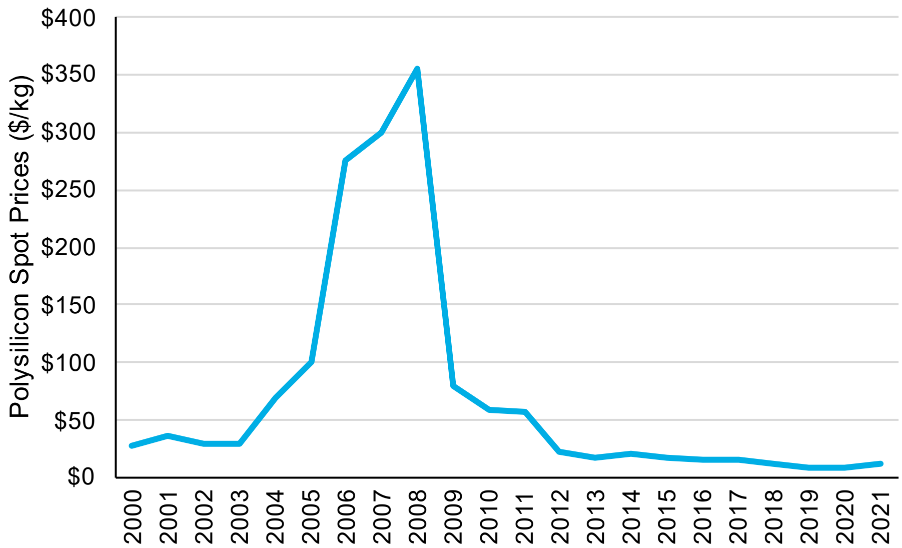

Figure 24. Polysilicon prices.

Source: (BloombergNEF 2021b)

Polysilicon production requires large capital investments to build a plant, large corporate investment to learn and refine the production process, highly skilled labor to operate the plant, and low electricity costs due to the large amount of energy needed to produce polysilicon. These requirements limit the geographical locations suitable for polysilicon production.

Virtually all polysilicon production capacity is located in 10 countries, with China having 72% of total global capacity (Figure 25) (BloombergNEF 2021f). With greater than 96% of ingot capacity, virtually all buyers of solar-grade silicon are located in China.

Polysilicon prices increased threefold from $6.27/kg in June 2020 to $28.46/kg in June 2021 (BloombergNEF 2021a). The price increase has been attributed to a supply/demand imbalance caused by significant capacity expansion in wafer and cell manufacturing. Now that polysilicon is the limiting factor, downstream entities (wafer and cell producers) have been stockpiling polysilicon supplies in anticipation of growing demand, especially a ramp-up in utility-scale deployment in China. Although new polysilicon capacity came online in early 2021, shortages are expected to persist in the short term until polysilicon capacity expansions come online in 2022–2023. Based upon projects that have been announced or are under construction, polysilicon manufacturing is expected to double in capacity, with most of the new plants located in China.

Many of the new plants built in the past two years have manufacturing capacities of 30,000-70,000 metric tonnes (MT) of polysilicon per year, and there have been announcements for plans to build plants with capacities greater than 100,000 MT (BloombergNEF 2021f).

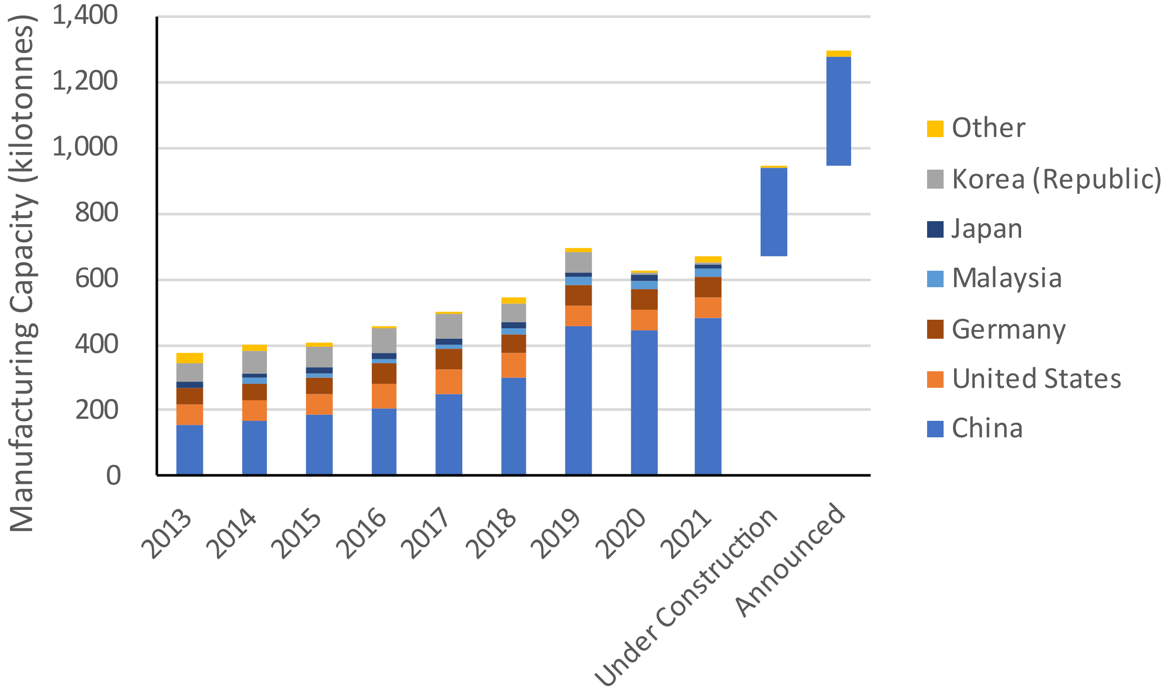

Figure 25. Global polysilicon annual manufacturing capacity.

Source: (BloombergNEF 2021f)

Before 2017, most of the polysilicon manufacturing was located in Jiangsu, the leading province for other solar manufacturing steps. Since then, Chinese companies have strived to continue lowering the price of polysilicon by locating manufacturing in regions with cheaper land, electricity, and labor. There has been considerable build-out of polysilicon in the western provinces of Inner Mongolia, Sichuan, Quinghai, and in particular, Xinjiang. Xinjiang currently hosts 54% of Chinese polysilicon manufacturing and 39% of global manufacturing (Figure 26). Based upon projects that have been announced or are under construction, polysilicon manufacturing is expected to increase considerably in Inner Mongolia, Sichuan, and to a lesser extent Xinjiang.

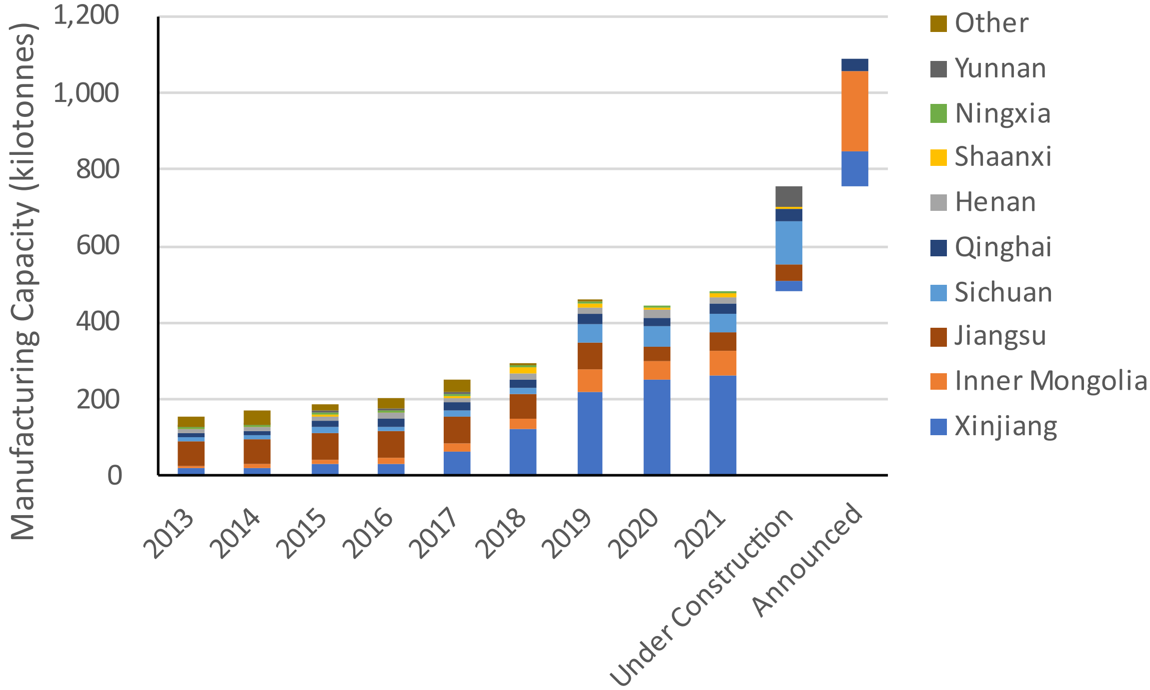

Figure 26. Polysilicon annual manufacturing capacity by Chinese province.

Source: (BloombergNEF 2021f)

Outside of China, Germany and the United States have the largest polysilicon manufacturing capacity (Figure 25). Plants outside China are typically smaller in size, with the largest plants having capacities between 20,000-40,000 MT (BloombergNEF 2021f). The principal advantage of U.S. and German polysilicon firms has been their ability to deliver semiconductor-quality (11N and greater) material.

South Korea also benefited from the proximity to China and historically had significant polysilicon manufacturing capacity. As polysilicon prices declined from 2010 to 2020, most polysilicon production in South Korea waned due to low margins within the industry, and the inability to get the same low electricity tariffs as those found in Western China (Bernreuter n.d.). Malaysia, on the other hand, grew its manufacturing capacity with the help of low electricity prices from abundant natural gas and new hydroelectric facilities. The South Korean company OCI, which was in the process of ramping down its South Korean operations, has been a critical technology partner for establishing polysilicon production in Malaysia. A small amount of manufacturing capacity has been announced in Saudi Arabia and Iceland.

Ten manufacturers produced 96% of global solar polysilicon in 2020 (Figure 27). Until 2005, the vast majority of polysilicon was produced by seven German, U.S., and Japanese firms with operations in those three countries. Italy also produced polysilicon for the semiconductor industry. After 2005, with the rapid growth in demand for polysilicon from the solar industry, other companies began to gain significant market share. OCI, a South Korean chemical company, began developing its own polysilicon production process in 2000 (Bernreuter n.d.). OCI, as well as some Chinese companies, grew with the help of the polysilicon shortage from 2006-2008 as well as proximity to the growing demand for polysilicon wafer producers in China.

In 2020, the top 10 manufacturers consisted of seven Chinese companies, one German company (Wacker – which has plants in Germany and the United States), one U.S. and Japanese company (Dow and Shin-Etsu Handotai collectively owning Hemlock – which is headquartered and has plants in the United States), and one South Korean company (OCI – which has a solar-grade plant in Malaysia and an electronic-grade polysilicon plant in South Korea).

Tongwei, Daqo, and Xinte, three of the five leading producers of polysilicon, benefit from long-term contracts with the largest wafer manufacturer in the world, LONGi, which produced 34% of global wafers in 2020 (BloombergNEF 2021e). Tongwei also benefits from being a leading supplier of cells and modules. GCL, the third largest producer of polysilicon, also benefits from being the third largest producer of PV wafers.

Wacker has been helped by a German trade agreement with China, which made imports from the German plants exempt from punitive import duties that are applied to U.S. and South Korean producers (see Section 3.3). Dow and Shin-Etsu Handotai (owners of Hemlock) are vertically integrated upstream, producing MGS.

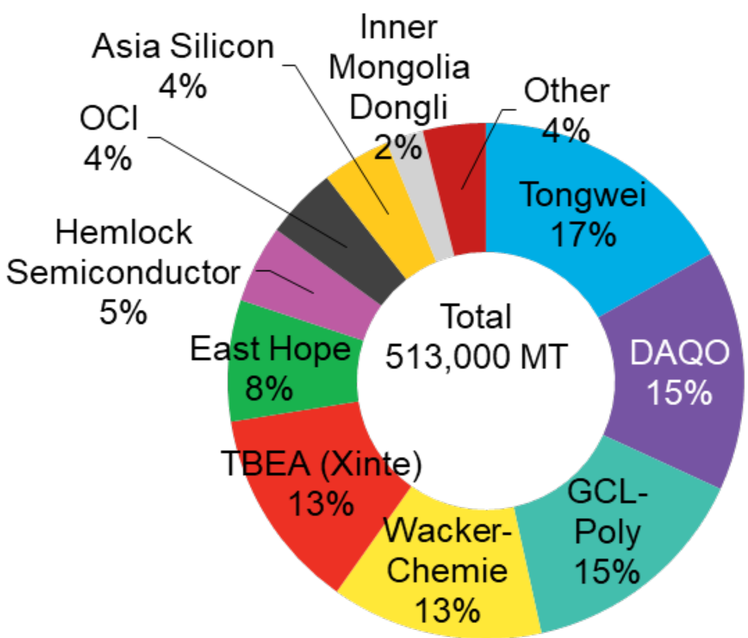

Figure 27. Polysilicon production, by manufacturer, 2020.

Source: (BloombergNEF 2021e)

Four polysilicon companies operate in the United States: Hemlock, with 35,000 MT of annual production capacity in Michigan; Wacker, with 20,000 MT in Tennessee; REC Silicon, with 4,000 MT in Montana, and a 16,000 MT plant in Washington, which shuttered in 2018; and Mitsubishi, with 1,500 MT in Alabama (BloombergNEF 2021f). Hemlock, Wacker, and REC were awarded manufacturing tax credits under Section 48C and subsequently expanded capacity (obamawhitehouse.archives.gov, n.d.). U.S. plants are operating significantly under capacity since Chinese duties (see Section 3.3) were placed on U.S. polysilicon in 2014 (Figure 28). Some production is being sold to the semiconductor industry.

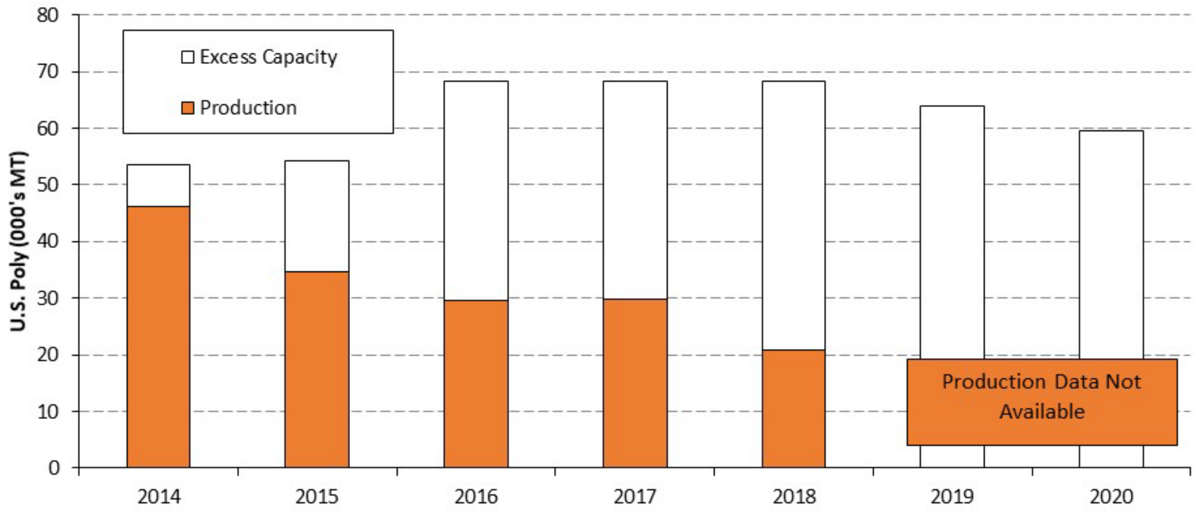

Figure 28. U.S. polysilicon production and excess manufacturing capacity.

Source: (Wood Mackenzie & SEIA 2021)

2.3 Ingots/Wafers

2.3.1 Technology Overview

The two primary methods for manufacturing PV wafers from polysilicon feedstock are the continuous-Czochralski (Cz) process for monocrystalline wafers (Figure 29) and the directional solidification (DS) process for multicrystalline wafers (Figure 30). Both approaches involve melting the polysilicon at 1410°C in a crucible designed to minimize contamination, then solidifying the melt to grow a rectangular-block ingot comprised of centimeter-sized crystals (DS) or a single-crystal cylindrical ingot (Cz).

A typical cylindrical monocrystalline ingot in 2010 was around 140 kg in size and led to cropped (squared) ingots that were 1.5–2.0 m long, with a flat-edge width of 156 mm and a cross-sectional area standardized to 237 cm^2. After accounting for wafer thickness, kerf (silicon sawdust generated when slicing the ingot into wafers) and yield losses, and cell efficiencies around 16.5%, the net silicon utilization was around 7–8 g/W at that time. By 2020, industry-typical ingot mass had increased to 400–450 kg, and ingots larger than 800 kg had been demonstrated at pilot scale. Two separate movements for wafer size standardization also began in 2020, to either the M10 size (182 x 182 pseudo-square with a diagonal of 260 mm) or the G12 size (210 x 210 full square with a diagonal of 297 mm). These larger sizes are following the development of 300 mm Cz ingots for the semiconductor industry. Solar and semiconductor ingot capabilities now range from 200 mm diameter ingots around 5.5 m in length (400–450 kg) to 300 mm diameter ingots greater than 5 m in length at pilot scale (800 kg). About 4 days are required to produce a Cz ingot at the typical growth rate of 1 mm per minute.

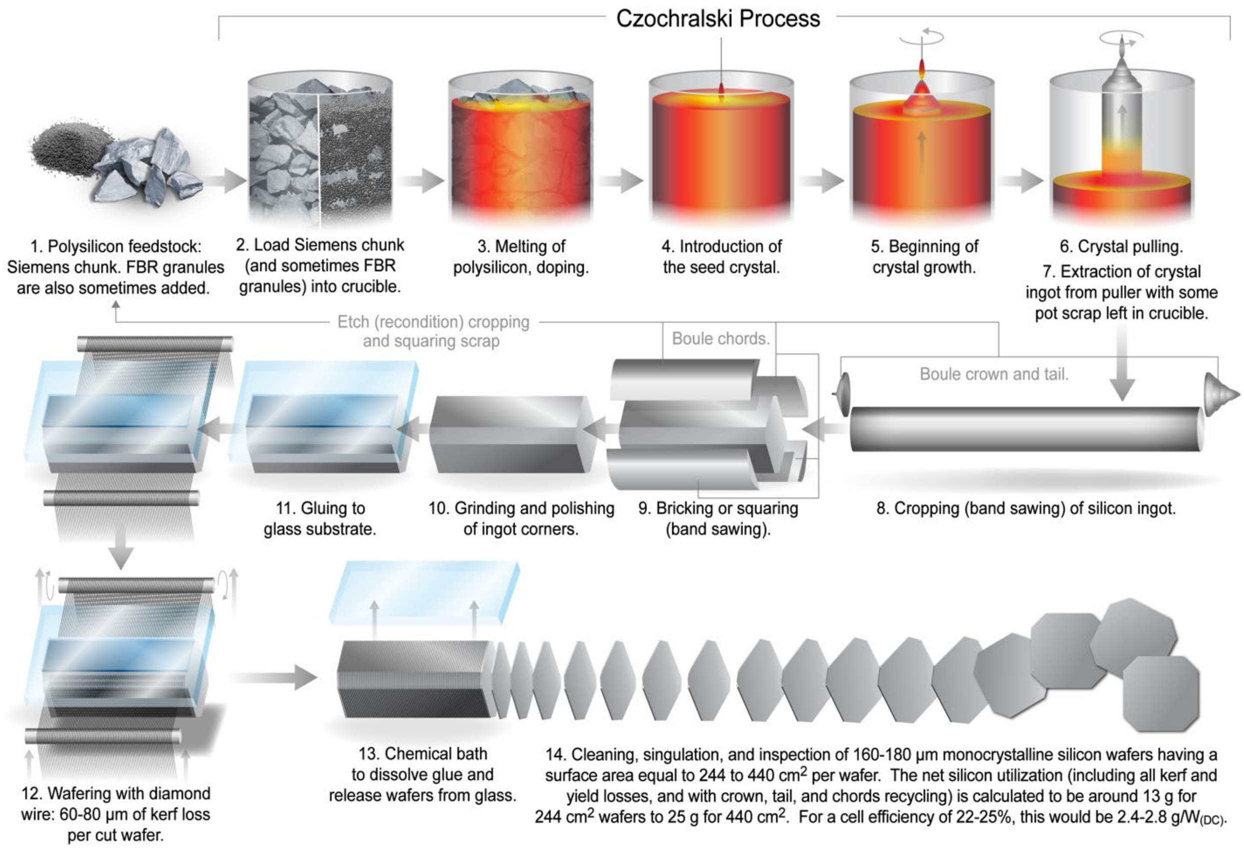

Figure 29. Process flow for making monocrystalline-silicon wafers via Cz crystal growth.

Source: NREL

The DS process produces shorter but much wider rectangular-block ingots. After the polysilicon is melted, the bottom surface of the crucible is cooled at a certain rate to create a temperature gradient that induces the DS process. As in the Cz process, sections of DS ingots produced during cropping and squaring can be remelted for later ingot generations, except for the contaminant-heavy topmost section. The square ingots are easily sawn into square wafers that enable cells to occupy essentially the entire PV module area. About 3 days are required to produce a typical multicrystalline silicon ingot including melting, DS, and cool down.

Whether formed by DS or Cz, the resulting ingot must be sliced into thin wafers, typically 180 micrometers thick. Diamond-coated wires are typically used that wrap around the ingot many times and cut all of the wafers in parallel, simultaneously. About one-third of the ingot is wasted as sawdust in the sawing process.

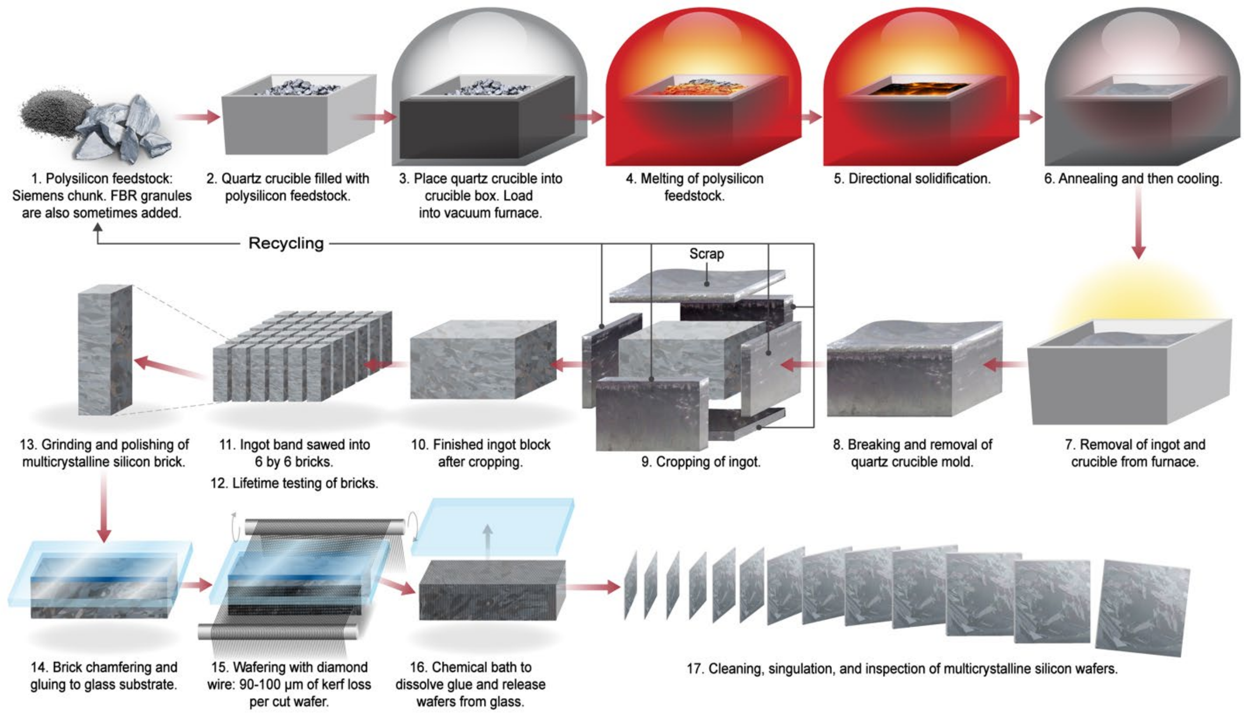

Figure 30. Process flow for making multicrystalline-silicon wafers via directional solidification (DS).

Source: NREL

2.3.2 Industry Overview

Beginning with polysilicon melting, producing ingots requires a lot of energy. The ingot production process alone requires greater than 70% of the total energy to produce a wafer. Therefore, it is advantageous to site ingot production near large, inexpensive sources of energy, and global ingot capacity reflects these trends. Because wafers are cheap to transport, it is not necessary to locate these facilities near cell manufacturing plants (though this often occurs). Ingot growth and wafer sawing benefit heavily from economies of scale. Therefore, it is advantageous to site an ingot/wafer plant in a location with cheap electricity, low labor rates, large industrial scale, and access to abundant sources of polysilicon.

Virtually all ingot and wafer manufacturing is located in China (Figure 31) and half of global capacity located in just eight plants (BloombergNEF 2021f). Many of the new plants built in the past two years have manufacturing capacities of 20-50 GW_{dc} per year. This concentration of ingot and wafer capacity was a direct result of intensive Chinese government support for expansion of this sector over the period 2000 – 2010, during which an estimated $50 billion was invested in Chinese solar production facilities.

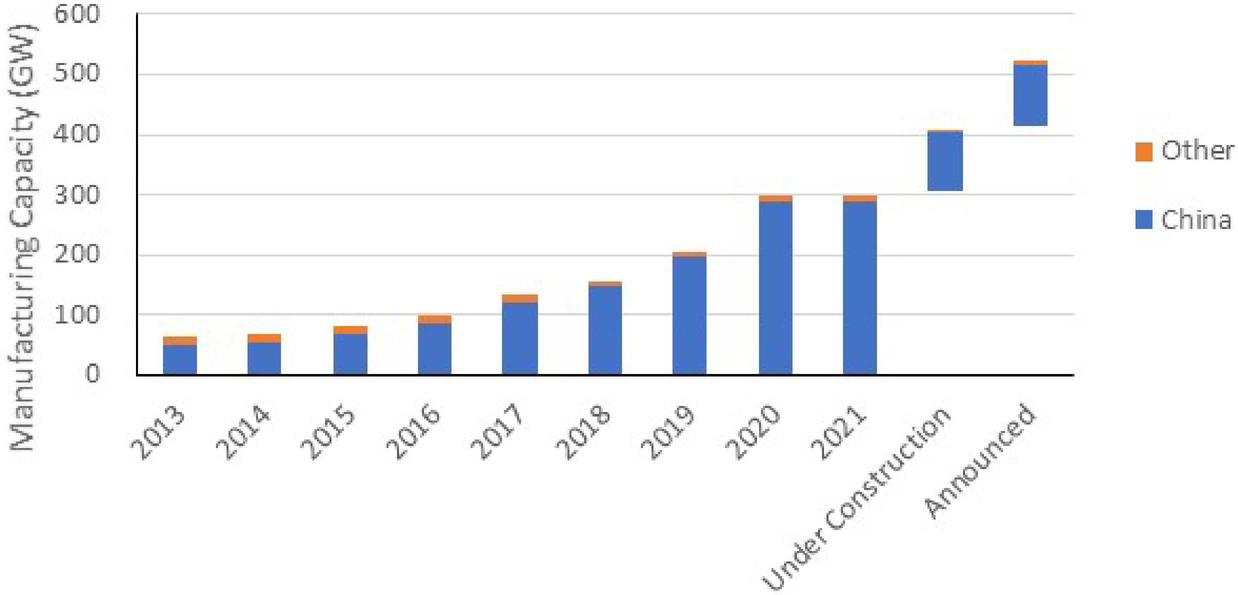

Figure 31. Wafer manufacturing capacity in China vs. other locations.

Source: (BloombergNEF 2021f)

There is no dominant province or region within China for ingot and wafer manufacturing. Seven Chinese provinces have over 10 GW_{dc} of wafer manufacturing capacity (Figure 32). Some are in the western provinces, but Jiangsu, with 28% of Chinese wafer capacity, is just north of Shanghai. It is also a domestic hub of cell and module manufacturing.

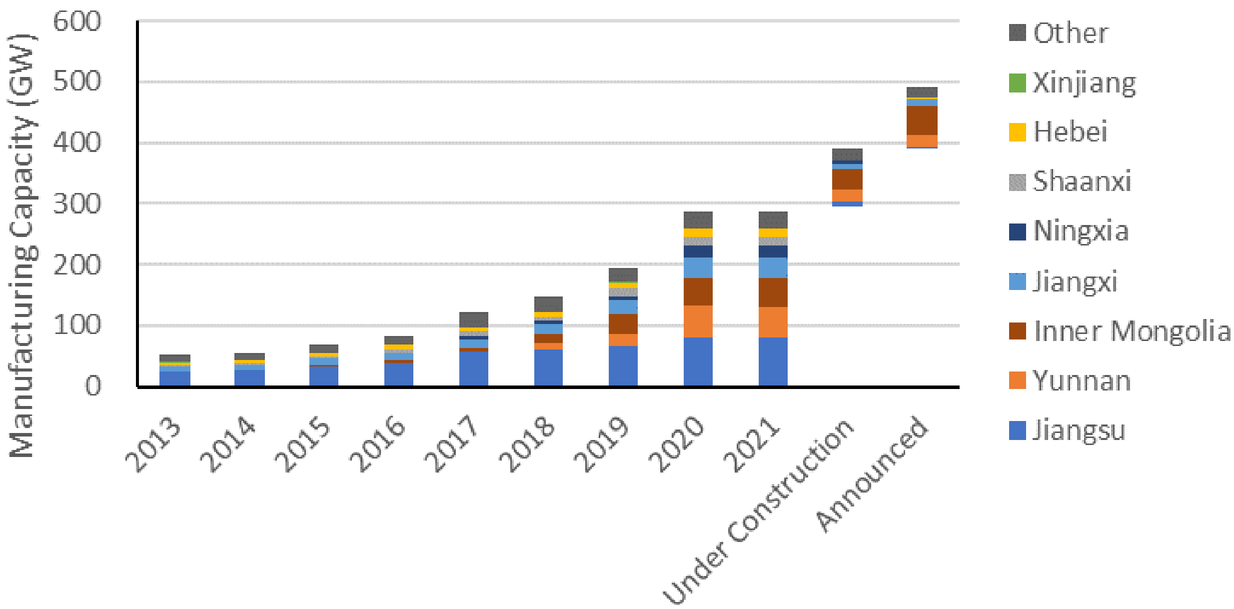

Figure 32. Wafer manufacturing capacity by Chinese province.

Source: (BloombergNEF 2021f)

Outside of China, there is only 10 GW_{dc} of wafer manufacturing capacity, mostly in East Asia (Figure 33). The Chinese company Jinko Solar recently announced it would build a 7 GW_{dc} ingot and wafer facility in Vietnam to service its cell and module factory in Malaysia and its module assembly in the United States. The company stated that it had made plans to build the factory in 2020, before the current U.S. trade restrictions on material from Hoshine Silicon (Bellini 2021a).

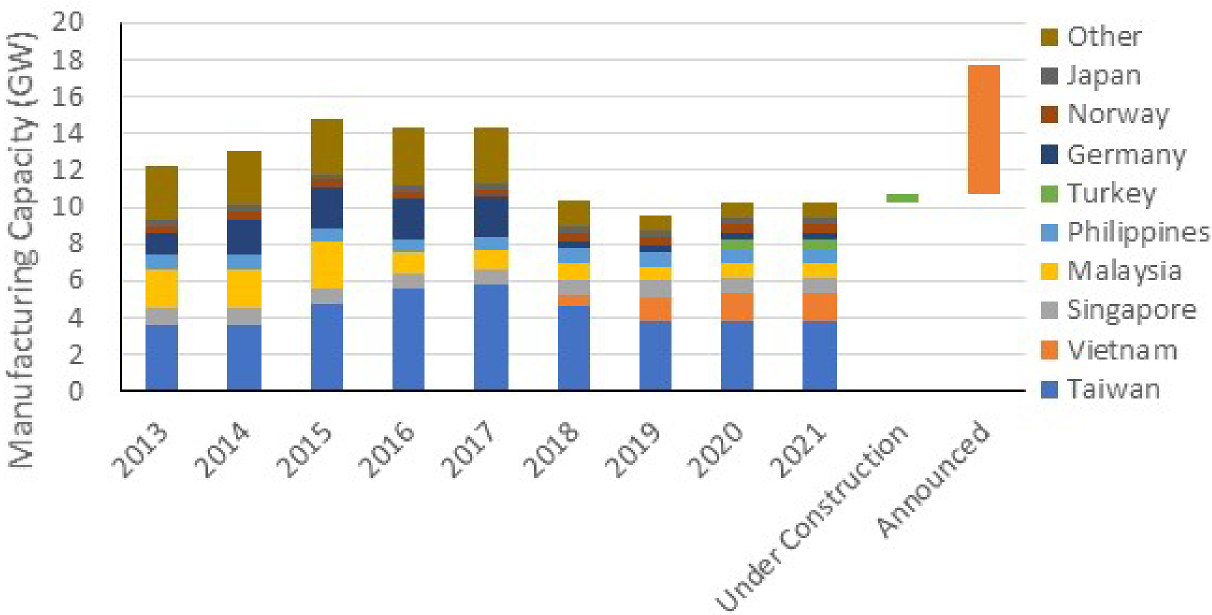

Figure 33. Wafer manufacturing capacity outside of China.

Source: (BloombergNEF 2021f)

Ten Chinese manufacturers produced 98% of global solar wafers in 2020, with three companies (LONGi, Zhonghuan, and GCL) producing 71% (BloombergNEF 2021e). From 2016 to 2020, these three companies grew their collective manufacturing capacity from 29 GW_{dc} (29% of global capacity) to 173 GW_{dc} (58% of global capacity) (Figure 34). The large growth from these companies followed the rapid growth in market share of monocrystalline PV modules.

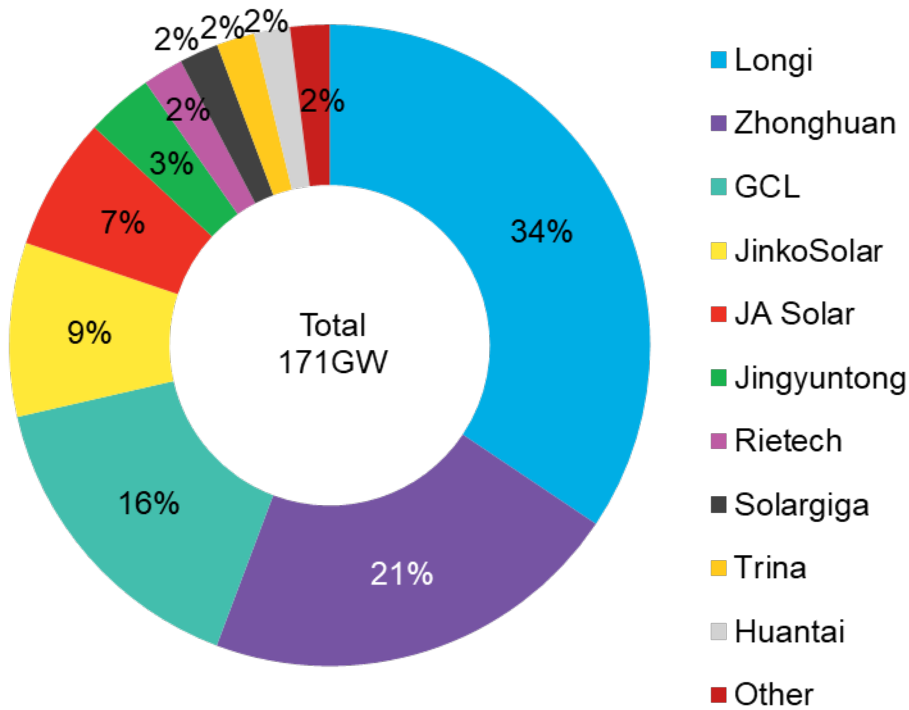

Figure 34. Wafer manufacturing capacity by company, 2020.

Source: (BloombergNEF 2021e)

By 2010, the United States had built its wafer manufacturing capacity to over 700 MW_{dc}, able to supply over 80% of domestic installations that year (Figure 35). The facilities were typically part of a fully integrated manufacturing process, from wafers to modules (though at one point MEMC, which bought SunEdison, was only making wafers, with synergies to its polysilicon production). But these facilities could not compete on cost with Chinese wafers, which benefitted from 50 times greater scale. By 2016, all U.S. wafer production had stopped, and many of these companies had gone out of business.

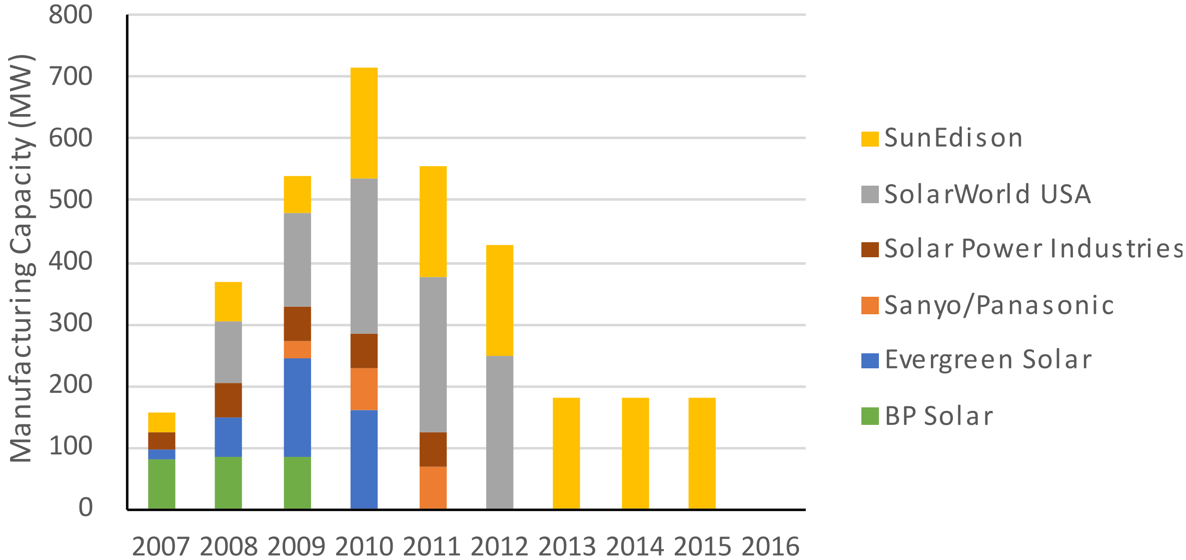

Figure 35. U.S. wafer manufacturing capacity.

Sources: (Wood Mackenzie Power & Renewables 2018; Wood Mackenzie & SEIA 2021)

The company 1366 Technologies received a $150 million loan guarantee from the U.S. Department of Energy in 2011 to build a novel wafer manufacturing facility that would avoid the step of slicing ingots to make wafers by casting wafers directly (U.S. Department of Energy n.d.). The “direct wafer” process was designed to require less silicon use, save time and money, and better compete with Chinese wafer manufacturers through automation over cheaper labor. 1366, however, never constructed a commercial scale wafer facility in the United States, instead forming a partnership with South Korean company Hanwha Q Cells to establish pilot production in Malaysia (Bellini 2019). In 2021, 1366 merged with Hunt Perovskite Technologies to form CubicPV, with the aim of developing a novel perovskite-silicon tandem-cell technology.

2.4 Solar Cell Fabrication

2.4.1 Technology Overview

Wafers are converted into cells through a series of wet chemical treatments, high-temperature gaseous diffusions, coating depositions, and metallization steps. The steps and the tools used vary based on cell architecture. Figure 36 shows the process for the full-area aluminum back surface field (Al-BSF) cell structure that was the dominant cell structure prior to 2018. Figure 37 shows the process for the passivated emitter and rear cell (PERC) structure, which—because of cell efficiency advantages over the standard Al-BSF architecture—now dominates the market. The PERC process is like the Al-BSF process, with a few more steps. Additional architectures designed to provide efficiency advantages over standard cells are also emerging. Regardless of the architecture, inspections at the start of the manufacturing line and electrical testing at the end of the line are used to identify cells that must be discarded. The tools and expertise needed to manufacture standard and PERC cells at high volume with guaranteed efficiencies are widely available.

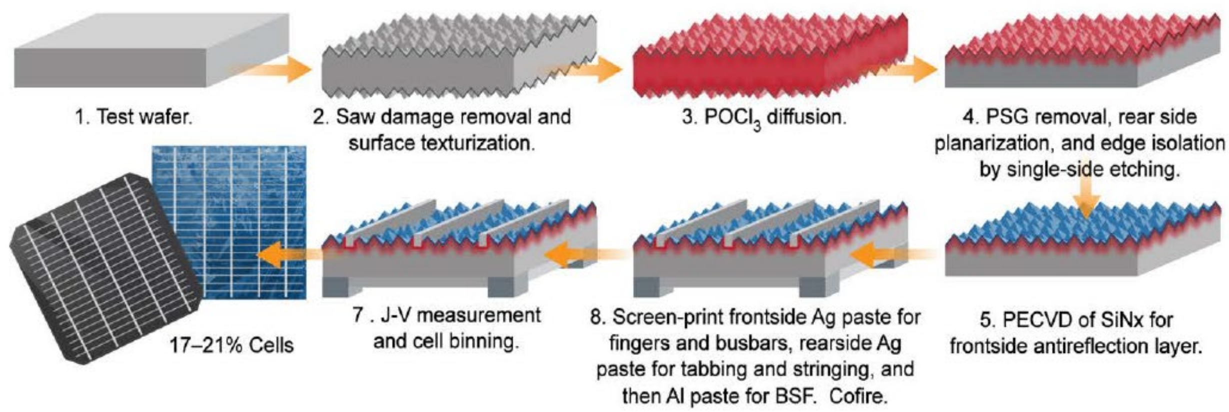

Figure 36. Process flow for manufacturing standard full-area Al-BSF cells.

Source: NREL

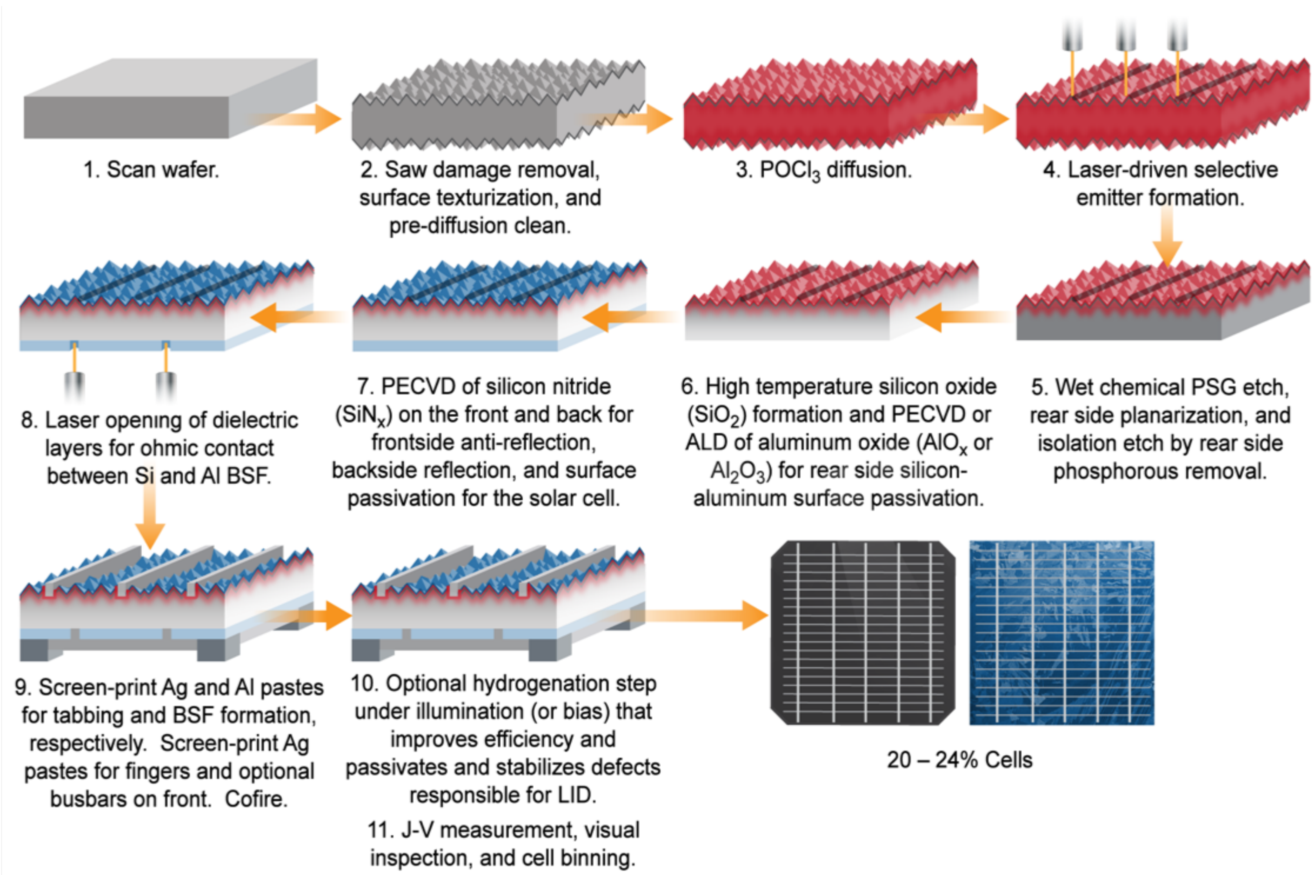

Figure 37. Process flow for manufacturing standard full-area PERC cells.

Source: NREL

Silver is an important component in c-Si solar cells, as it is used in the form of screen-printable paste to make electrical contact to the silicon material. In 2019, silver accounted for about 10% of cell cost (Bellini 2021b). Silver can be mined as a principal product, extracted as a byproduct or coproduct at other metal extraction operations, or recovered from secondary sources (USGS 2021a). For PV applications, silver is refined to high purity levels, processed into a fine powder, and immersed in solvent to create a paste for screen-printing applications (Yüce et al. 2019).

In 2019, the PV sector accounted for approximately 10% of global silver demand (Bellini 2021b). However, the amount of silver used per cell has declined over time even as cells have become larger in area, dropping from 521 milligrams per cell in 2009 to 111 milligrams per cell in 2019 (Marsh 2021). This trend is expected to continue (Keen 2020).

2.4.2 Industry Overview

Solar cell fabrication has become a very automated process and thus typically benefits from locations with a sufficient labor pool of manufacturing engineers and machine laborers; government support of manufacturing through cheap land, electricity, and tax breaks to incentivize companies with sufficient access to capital to procure the equipment and land; and access to a supply chain of affordable machines.

While not always the case, cell manufacturing is often collocated with wafer and module manufacturing due to synergies in the manufacturing process, procurement of equipment and land, taking advantage of captive demand, and economies of scale. As of July 2021, approximately 27% of cell manufacturing capacity was collocated with wafer capacity, and 61% was collocated with module capacity (Figure 38). Still, over 100 GW_{dc} of cell manufacturing is sited alone.

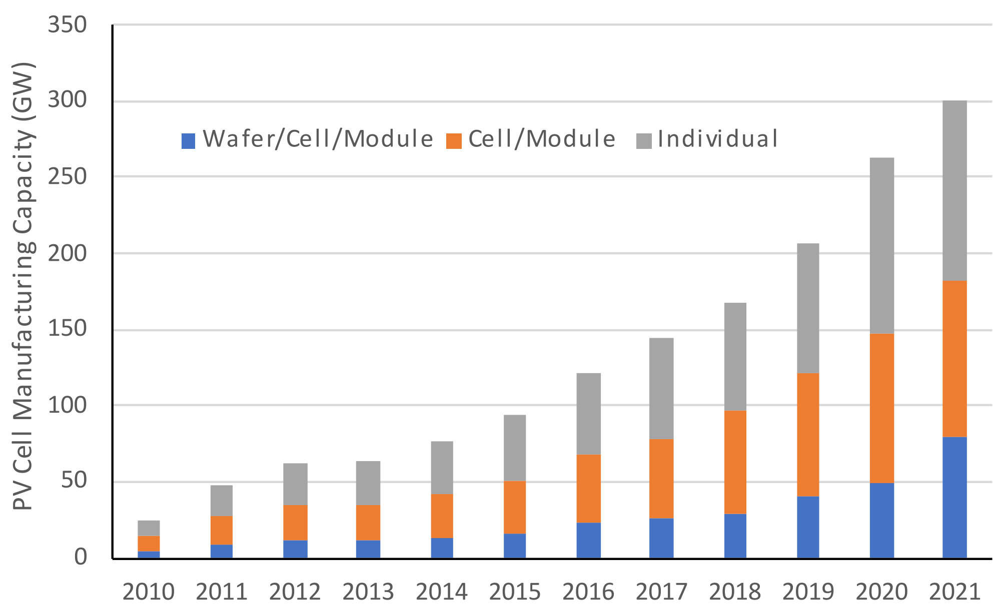

Figure 38. Co-location of cell manufacturing with wafer and module manufacturing.

Source: (BloombergNEF 2021f)

Over 80% of cell manufacturing is located in China and based upon factories that have been announced or are under construction, this percentage will likely increase, with cell manufacturing significantly increasing from 300 GW_{dc} to over 500 GW_{dc}. Cell manufacturing plant size continues to increase, with most new plants with a stated capacity above 5 GW_{dc}, and now many over 20 GW_{dc} (Figure 39). Looking forward, most of the plants that are under construction or announced are 1–20 GW_{dc} in size.

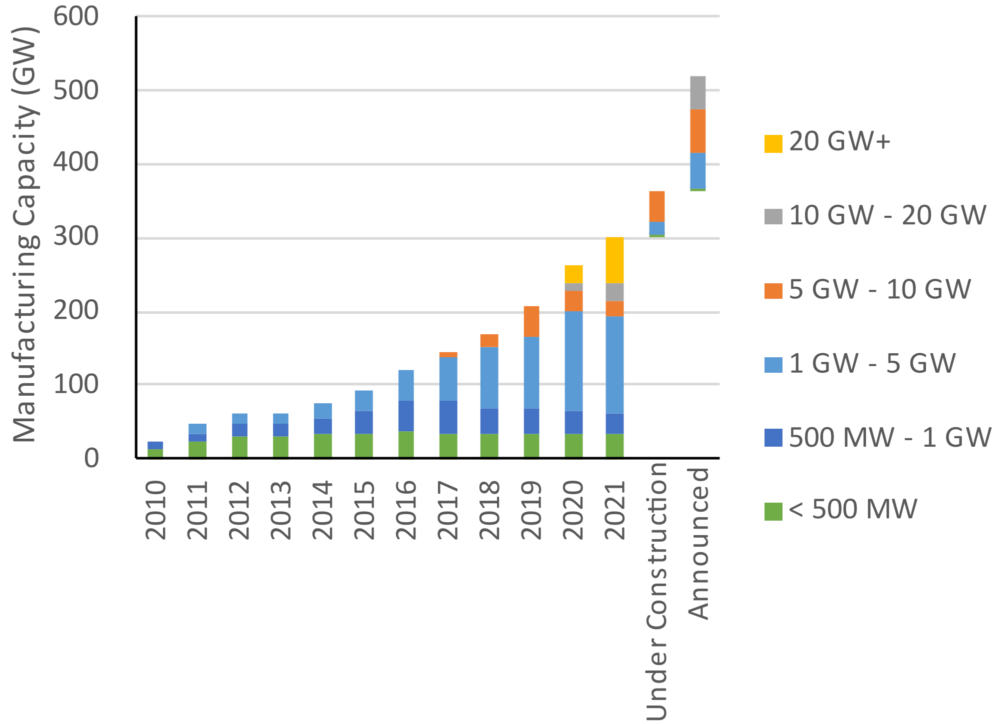

Figure 39. Cell manufacturing capacity by plant size.

Source: (BloombergNEF 2021f)

Jiangsu currently hosts 41% of Chinese cell manufacturing and 33% of global manufacturing, and is home to large amounts of polysilicon, wafer, and module manufacturing capacity. Despite this large market share, a significant level of capacity is located outside of this region (Figure 40). Additionally, there is significant module assembly capacity located around the globe, making the level of buyer or supplier power significantly more difficult, and this section of the supply chain more diverse.

The two leading provinces, Jiangsu and Zhejiang, are both located on the coasts, making shipping internationally easier. However, a relatively large amount of cell production is located elsewhere in China as well. Because China has represented 30%-50% of global demand of PV modules, a significant portion of production is shipped domestically.

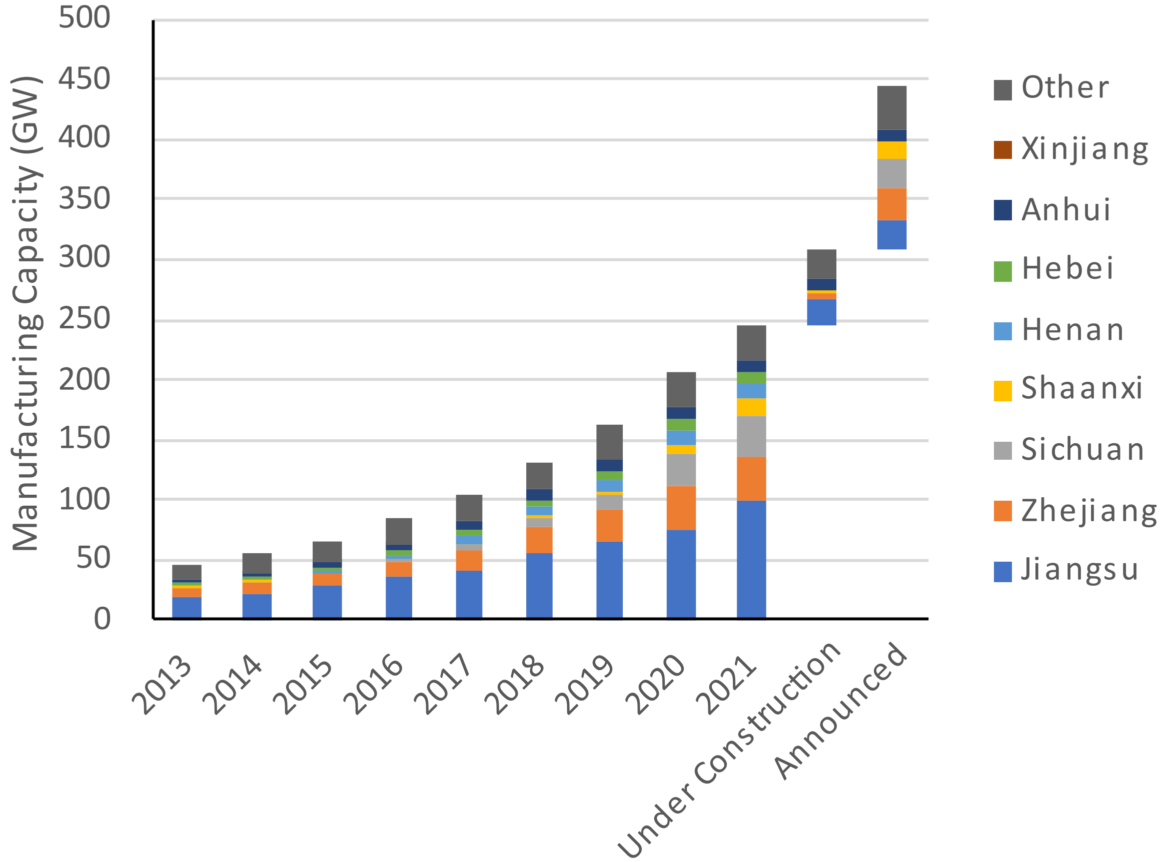

Figure 40. Cell manufacturing capacity by Chinese province.

Source: (BloombergNEF 2021f)

Outside of China, there is 50-60 GW_{dc} of cell manufacturing capacity, mostly in East Asia (Figure 41). Manufacturing capacity outside of China is expected to further grow, based on projects that have been announced or are under construction, mostly in the leading non-Chinese countries of Vietnam and Malaysia. Most of the leading non-Chinese cell manufacturing countries are located near China, likely making it easier, cheaper, and faster to get wafers from China. Additionally, many of the manufacturing facilities in these countries are owned by Chinese companies or have parent Chinese companies.

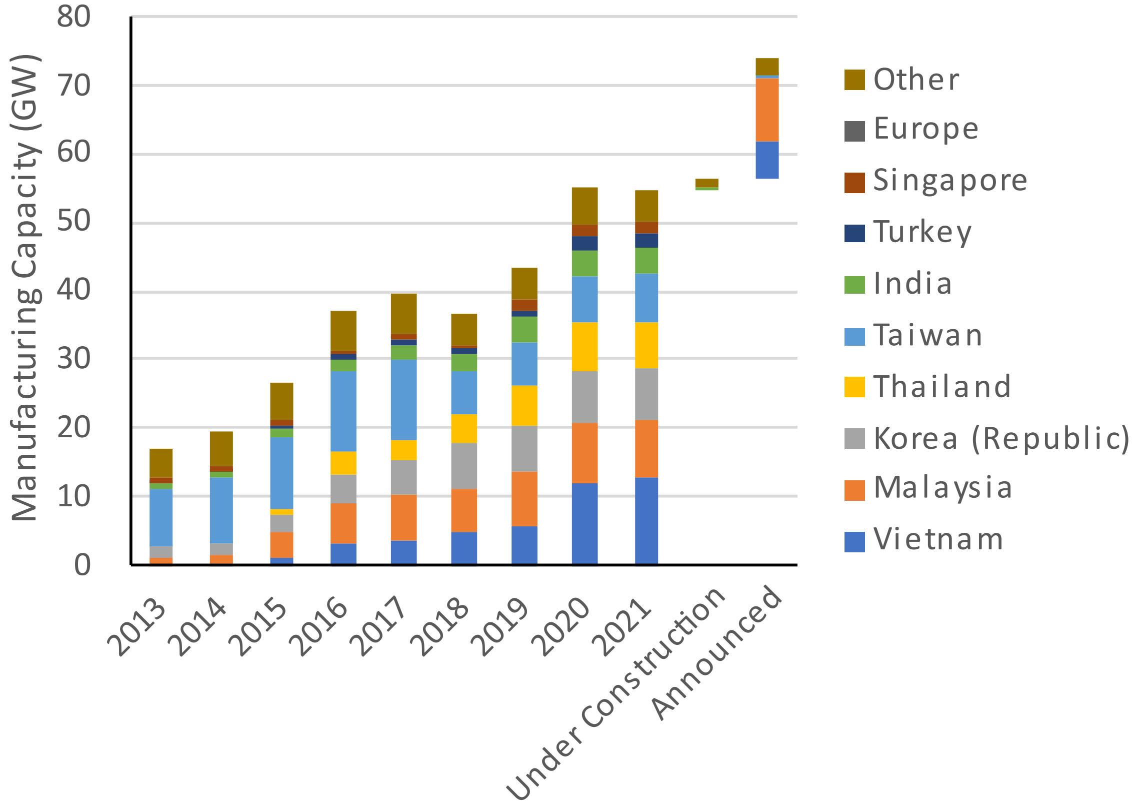

Figure 41. Cell manufacturing capacity outside of China.

Source: (BloombergNEF 2021f)

In 2020, 68% of cells produced came from the top 10 manufacturers, all but one of which (Hanwha Q Cells) was Chinese (Figure 42). While this does represent market concentration, it is much less so than in manufacturing steps before cells. The three leading suppliers, Tongwei, LONGi, and Aiko Solar, have collectively grown their manufacturing capacities from 3 GW_{dc} in 2015 to 71 GW_{dc} in July 2021 (and up from 37 GW_{dc} in 2019) (BloombergNEF 2021f).

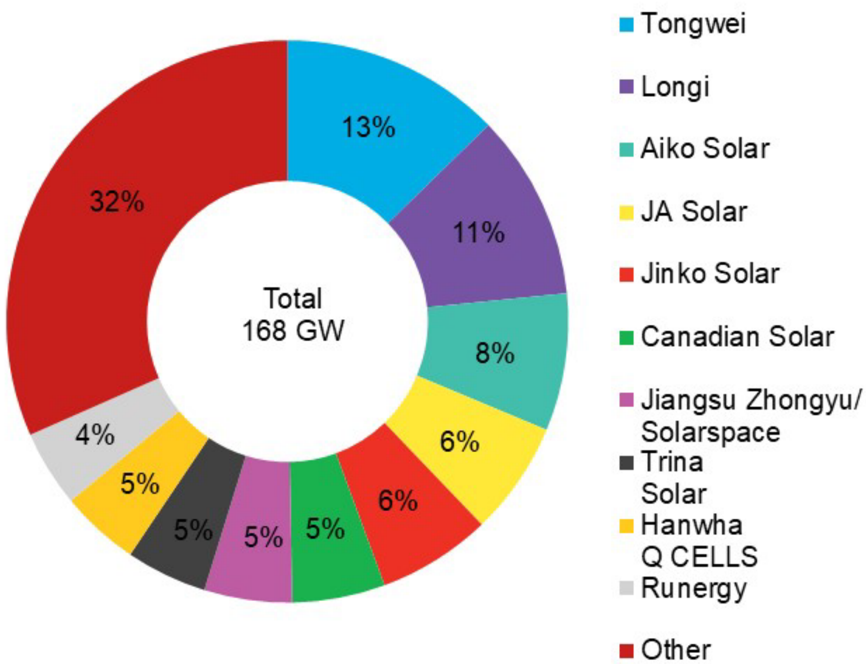

Figure 42. Cell production by manufacturer, 2020.

Source: (BloombergNEF 2021e)

There is significant vertical integration for cell manufacturers. Of the companies with 300 GW_{dc} of manufacturing capacity, these companies also owned 169 GW_{dc} of wafer and 332 GW_{dc} of module capacity. 41% of the cell manufacturing capacity is from a company with wafer, cell, and module capacity, and 81% is from a company with cell and module capacity (BloombergNEF 2021f). Figure 43 provides the wafer, cell, and module manufacturing capacities of some of the leading cell and module manufacturers. While some only focus on one piece of the value chain, many of them have significant investment in all three.

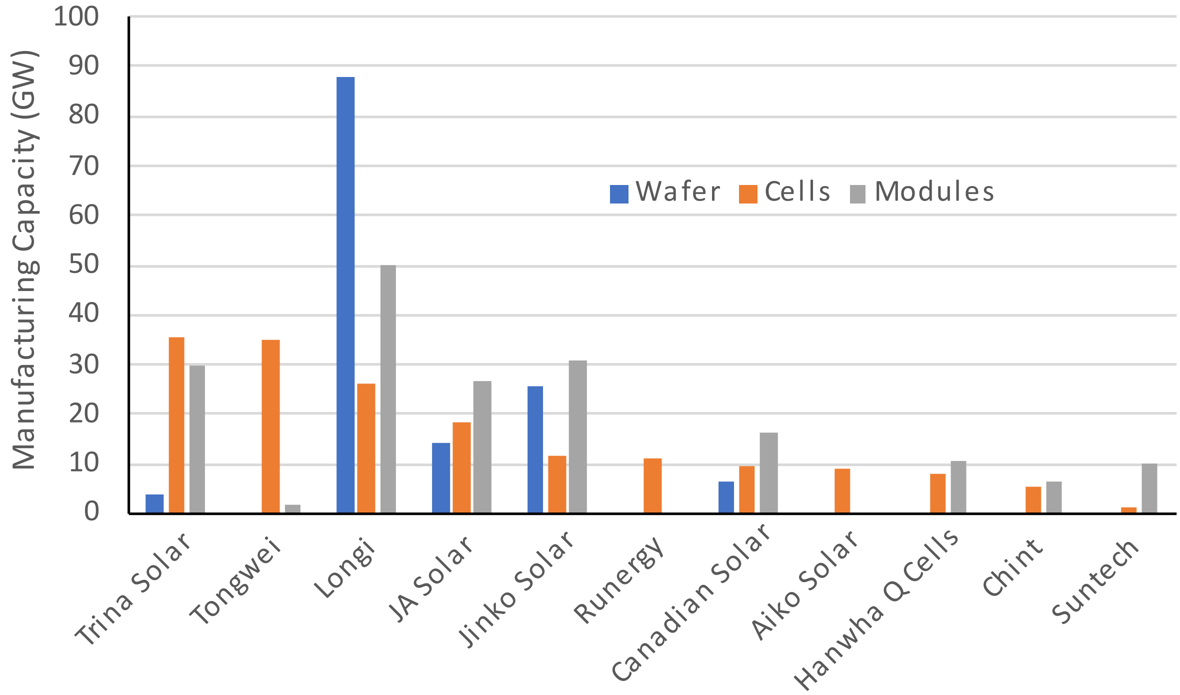

Figure 43. Wafer, cell, and module manufacturing capacities of some leading cell and module manufacturers.

Source: (BloombergNEF 2021f)

U.S. cell manufacturing was driven mostly by six companies, with only three (SolarWorld, Suniva, and Tesla) achieving capacities above 400 MW_{dc} (Figure 44). Two of the six companies (Evergreen and Suniva) went bankrupt (Hoium 2017). Silicor Materials, Tesla, and Mission Solar closed the U.S. cell manufacturing portion of their businesses, though Mission Solar and Tesla continue to assemble modules from imported cells (Lombardi 2011; Jester 2016; Hall 2021; Wood Mackenzie & SEIA 2021). SolarWorld was sold to SunPower, which briefly operated the facility in Oregon before it was closed in 2021.

Companies reported they were not able to compete at the price levels of imported cells and modules when Section 201 safeguard tariffs were put in place in 2012 and 2015 (Congressional Research Service 2018), but low-cost modules and cells still came into the United States from other countries (United States International Trade Commission 2021). By 2018, when Section 301 tariffs were placed on all imported modules, many of these companies were already bankrupt, had exited the cell manufacturing industry, or were still unable to compete with the help of the safeguard tariffs. In the case of cells, the Section 201 tariffs do not apply to the first 2.5 GW_{dc} of imported cells; a cap which was not reached in the first three years of tariff implementation (United States International Trade Commission 2021). As of the end of 2020, there was no PV cell production in the United States (Wood Mackenzie & SEIA 2021).

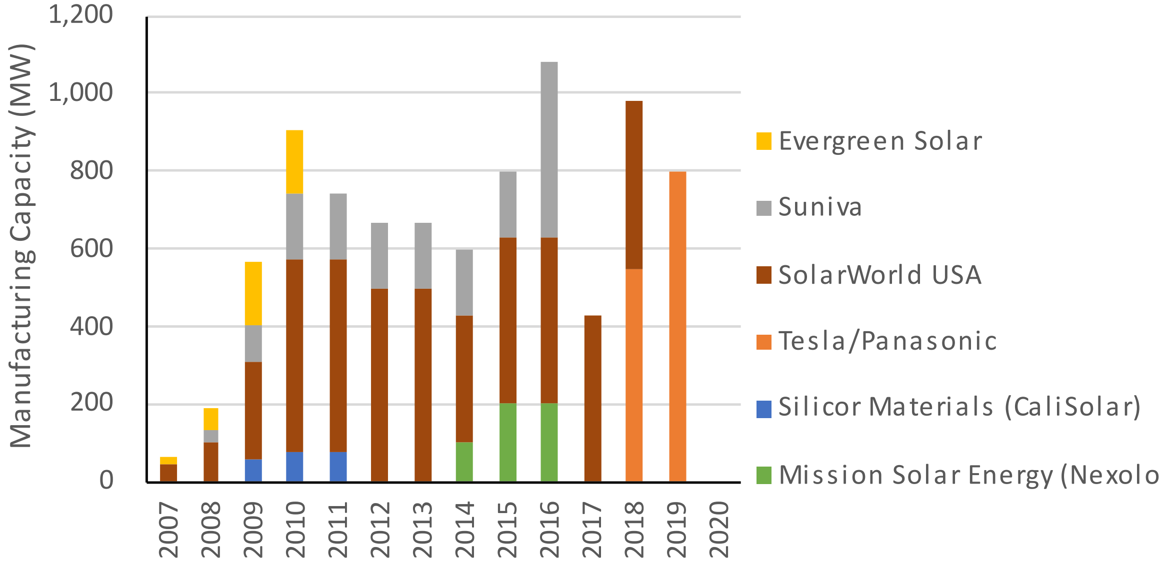

Figure 44. U.S. cell manufacturing capacity.

Sources: (Wood Mackenzie Power & Renewables 2018; Wood Mackenzie & SEIA 2021)

2.5 Module Assembly

2.5.1 Technology Overview

Module assembly entails electrically connecting cells into strings, arranging parallel cell strings into an array, electrically connecting the strings with metallic ribbons, mounting the array onto a layer of encapsulant on top of a sheet of glass or backsheet, and laminating another sheet of encapsulant and front glass onto the whole assembly (Figure 45). The typical front and back encapsulants are thermoplastic material that melts when heated during the lamination process to encase the entire assembly between a sheet of glass on the front and a backsheet or another sheet of glass on the back.

The ribbons are fed through a hole in the back glass or backsheet and interwoven on the back of the module within a junction box, which contains diodes to reduce cell mismatch and serves as the point of contact between modules in an installed system. Finally, an extruded aluminum frame is typically put around the perimeter of the module. Some firms have been developing glass-glass modules without an aluminum frame, while monocrystalline and multicrystalline busbarless, 72-cell, 96-cell, frameless, and glass-glass module options (including but not limited to options using bifacial cells) are also available.

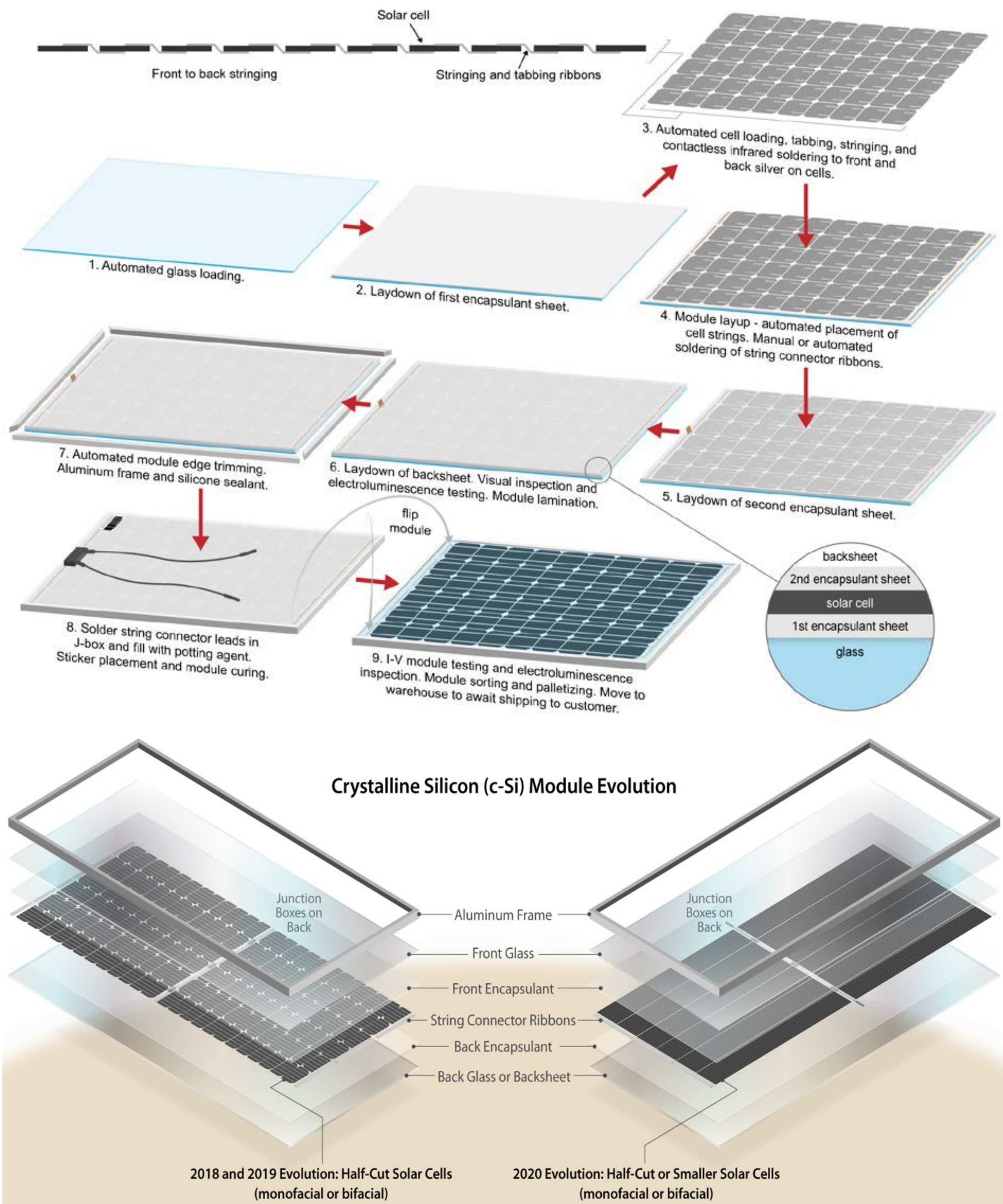

Figure 45. Process flow (top) and finished product (bottom) for standard 60-cell monocrystalline-silicon module assembly.

Source: NREL

2.5.2 Industry Overview

There are varying degrees of automation within the module production process, and unlike other parts of the c-Si value chain, this step is more assembly than manufacturing. Because of this, it does not require the same level of technical skill, and assembly lines can be built in relatively short periods of time. Most of the components are relatively cheap to ship, including the aluminum frame and glass. Therefore, provided a manufacturing site has access to the PV supply chain, they can manufacture modules relatively inexpensively and without much capital expenditure or labor development. While there are economies of scale to this process, many locations around the world, including the United States, have encouraged local manufacturing, and module assembly represents a relatively large part of the cost of a final module, without the need for large government development support.

While not always the case, module manufacturing is often collocated with wafer and cell manufacturing due to synergies in the manufacturing process, procurement of equipment and land, taking advantage of captive demand, and economies of scale. 77% of module manufacturing is located in China. Based upon projects that have been announced or are under construction, this percentage will likely increase, with module manufacturing increasing from 400 GW_{dc} to over 600 GW_{dc}. Still, almost 100 GW_{dc} of module capacity is located outside of China. Module manufacturing plant size continues to increase, with most new plants with a stated capacity above 5 GW_{dc} in size, and now many over 20 GW_{dc} (Figure 46). Looking forward, most of the plants that are under construction or announced are 1 – 20 GW_{dc} in size. That said, there appears to be continued construction of plants with manufacturing capacities less than 5 GW_{dc}.

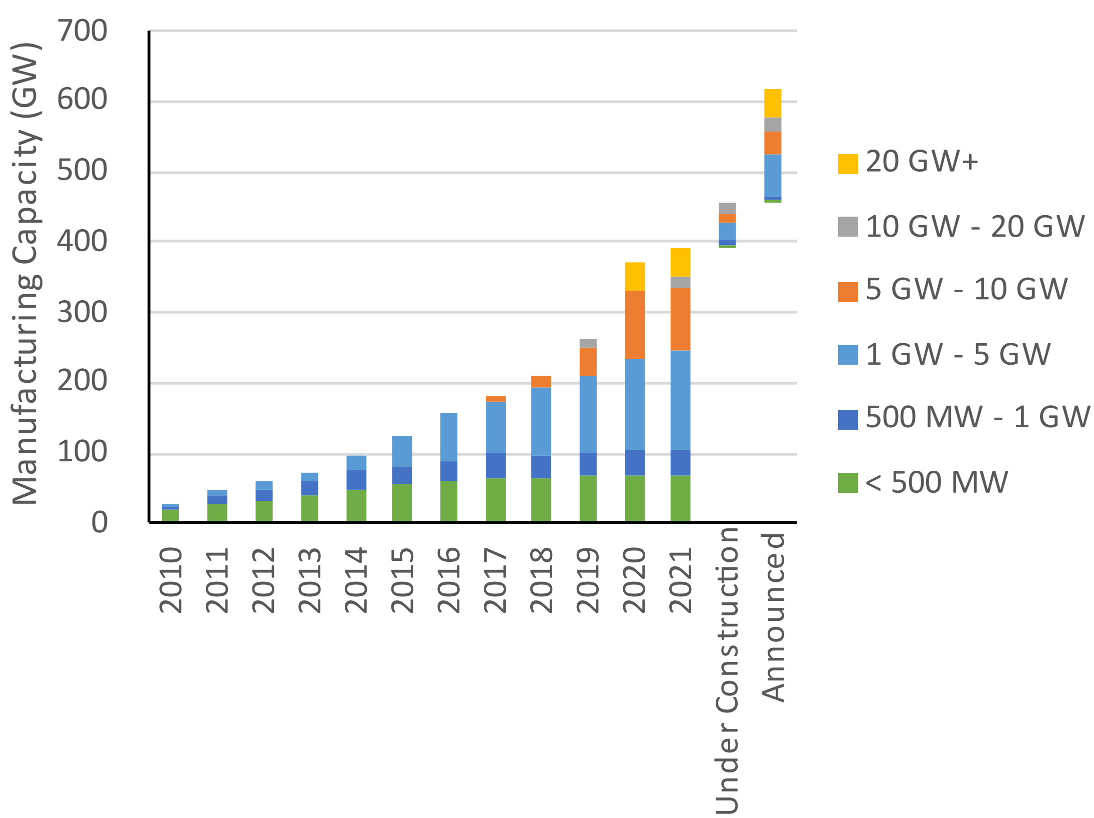

Figure 46. Module manufacturing capacity by plant size.

Source: (BloombergNEF 2021f)

Jiangsu and Zhejiang currently host 68% of Chinese module manufacturing (Figure 47) and 52% of global manufacturing, and are home to large amounts of polysilicon, wafer, and cell capacity. These provinces are both located on the coasts, making shipping internationally easier. Despite this large market share, a significant level of capacity is located outside this region. Because China has represented 30%-50% of global demand for PV modules, a significant portion of production is shipped domestically. Additionally, there is significant manufacturing capacity of modules located around the globe, making the level of buyer or supplier power significantly more difficult, and this section of the supply chain more diverse.

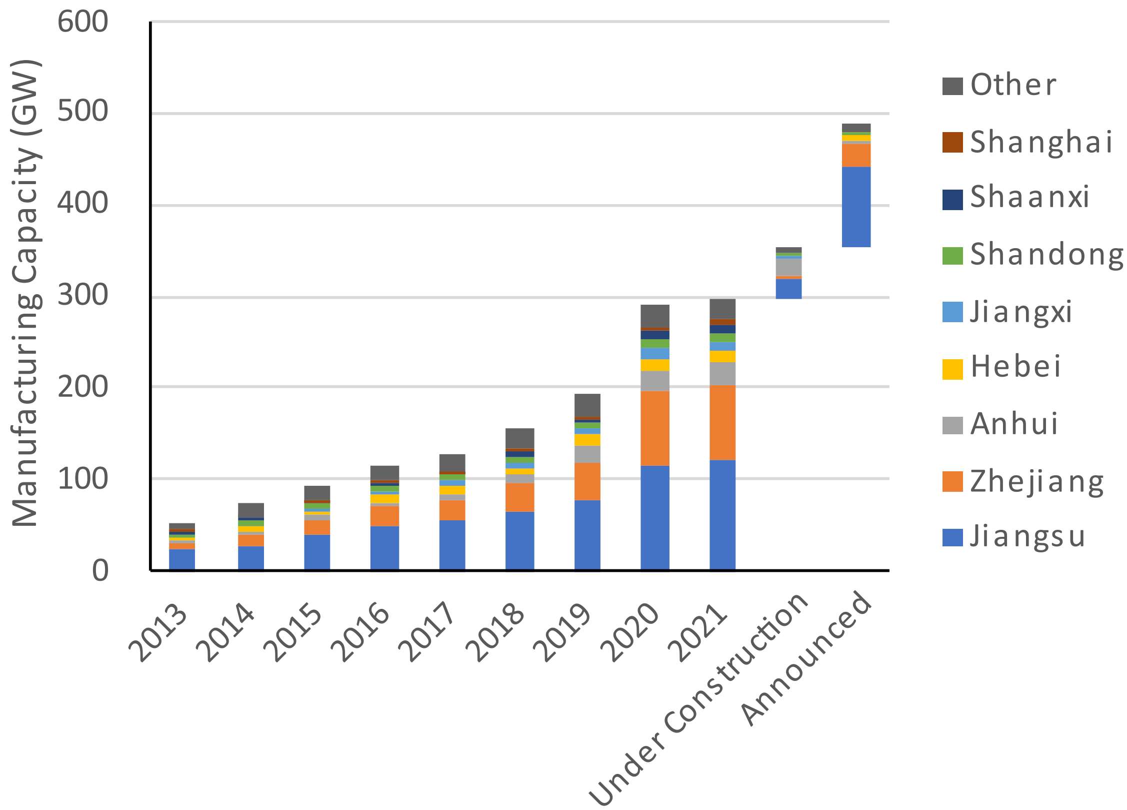

Figure 47. Module manufacturing capacity by Chinese province.

Source: (BloombergNEF 2021f)

Outside of China, there is 90-100 GW_{dc} of module manufacturing capacity (Figure 48). Much of it is in Asia, but there are significant levels of module manufacturing capacity located near areas of large PV demand, such as Europe and the United States. Manufacturing capacity is expected to further grow, based on projects that have been announced or are under construction, mostly in Asia.

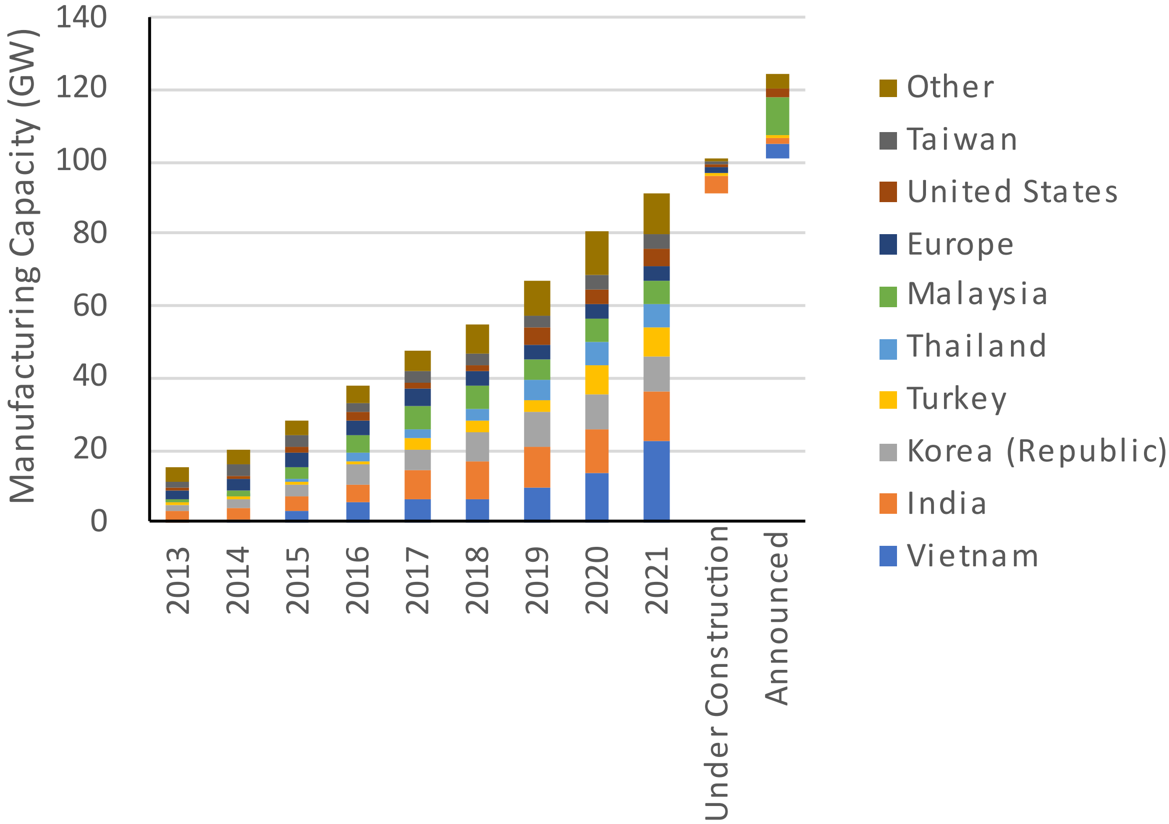

Figure 48. Module manufacturing capacity outside of China.

Source: (BloombergNEF 2021f)

In 2020, 69% of modules produced came from the top 10 manufacturers, all but two (Hanwha Q Cells, First Solar) of which were Chinese (Figure 49). While this does represent market concentration, it is much less so than in manufacturing steps before cells.

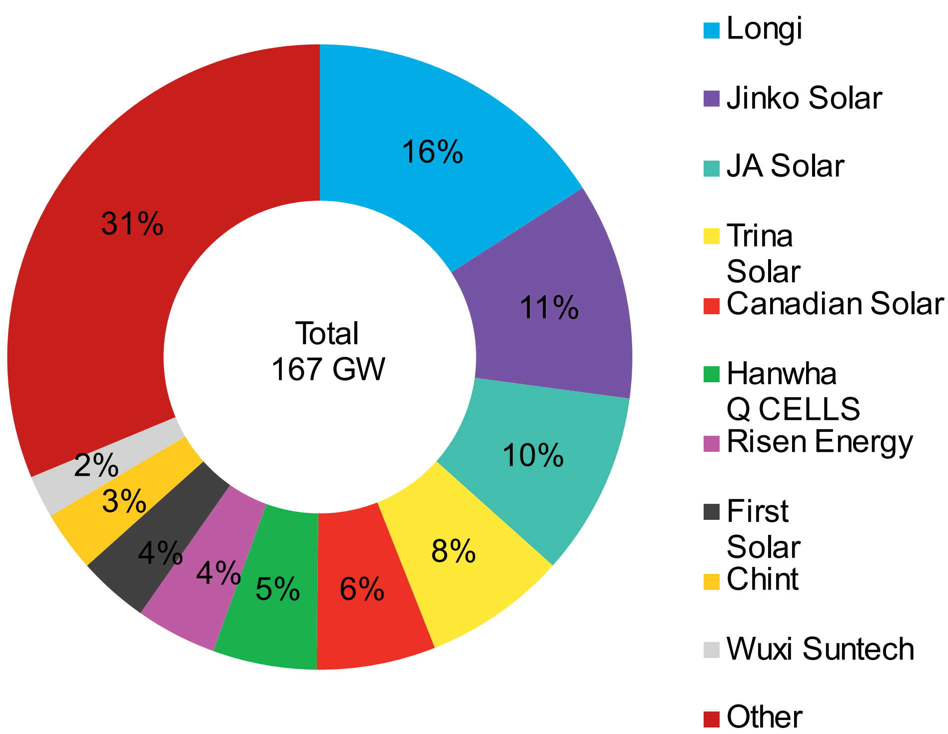

Figure 49. Module production by manufacturer, 2020.

Source: (BloombergNEF 2021e)

There is significant vertical integration for module manufacturers. See Figure 43, which provides the wafer, cell, and module manufacturing capacities of some of the leading cell and module manufacturers. While some only focus on one piece of the value chain, many of them have significant investment in all three.

U.S. module manufacturing has consisted of dozens of manufacturers over the past twenty years, but much of the capacity was operated by a few companies. U.S. module assembly grew rapidly until 2010, due to increasing demand for PV modules. Over a third of module assembly capacity came from the German company SolarWorld, which also manufactured wafers and cells in the United States (Wood Mackenzie Power & Renewables 2018).

As PV module prices dropped precipitously in 2010 (Figure 50), many of these companies could no longer compete and closed operations. Module capacity grew again starting in 2015 with the institution of tariffs on Chinese panels and continued growth in the United States PV market (Congressional Research Service 2018). However, the United States was eventually able to import low-cost PV modules from other low-cost Asian countries, and many of the companies, including SolarWorld, ceased operations.

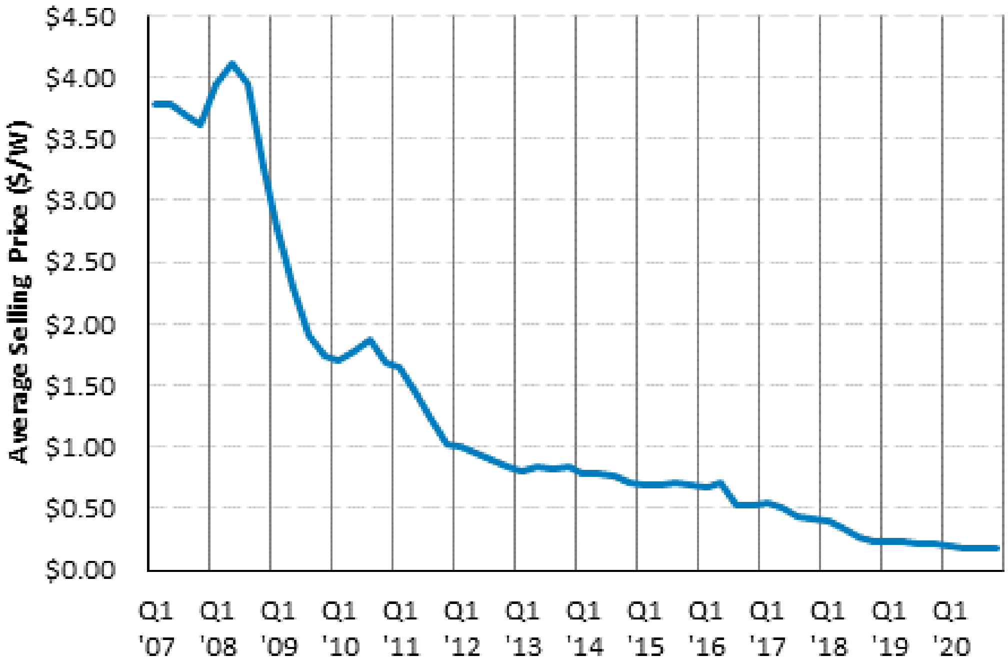

Figure 50. Average module selling price.

Sources: (BloombergNEF 2021a; Chin et al. 2012; Shah 2019)

In 2018, Section 201 tariffs were put in place, putting a 30% duty on virtually all imported modules (over the years, this tariff has dropped to 15%) (Reuters 2020). As a result of these tariffs, U.S. c-Si module assembly capacity more than doubled (Figure 51).

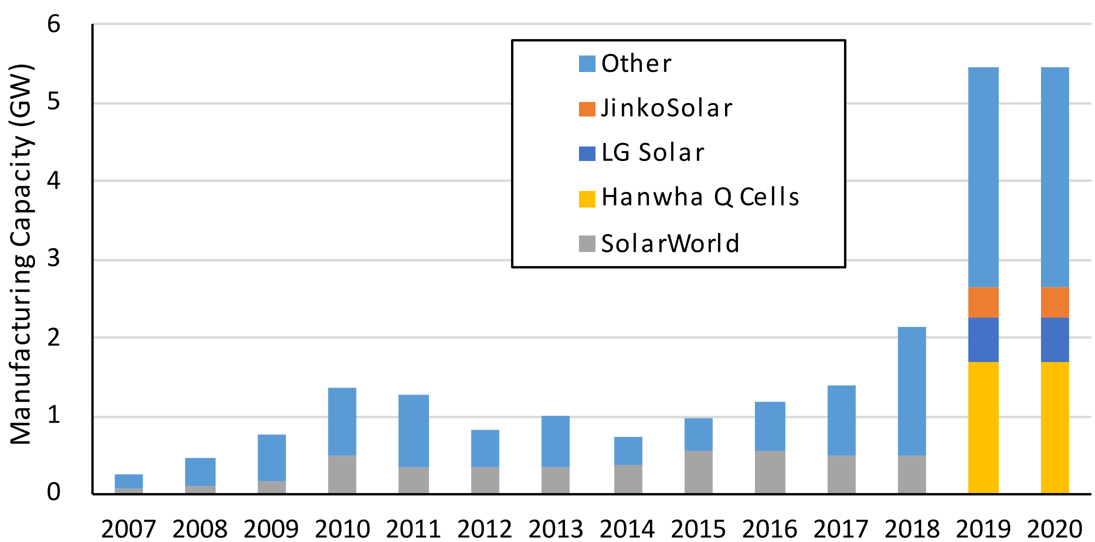

Figure 51. U.S. module manufacturing capacity.

Sources: (Wood Mackenzie Power & Renewables 2018; Wood Mackenzie & SEIA 2021)

Despite the increase in capacity and subsequent increase in PV modules produced in the United States, these facilities continue to operate with significant excess capacity (Figure 52). In the past three years of the Section 201 tariff, module production and PV cell imports have been around the same level as the 2.5 GW_{dc} PV cell tariff exemption.

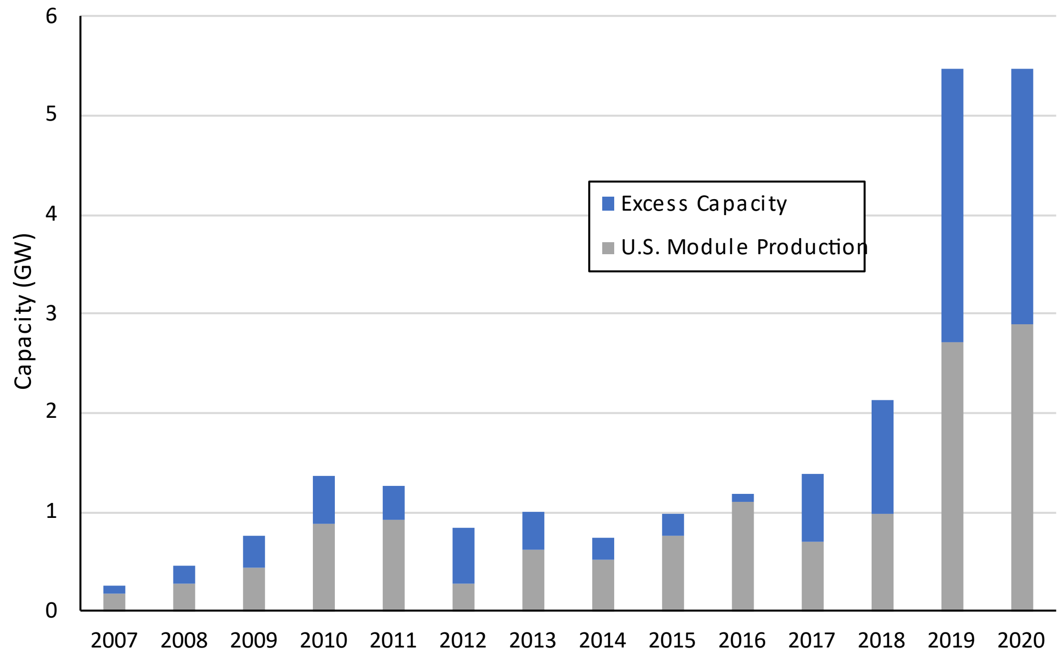

Figure 52. U.S. module production and excess production capacity.

Sources: (Wood Mackenzie Power & Renewables 2018; Wood Mackenzie & SEIA 2021)

2.6 Mounting Structures

2.6.1 Technology Overview

PV mounting structures hold PV panels in place, securing them from wind, and ideally providing air circulation underneath to keep them cool (allowing the cells to operate more efficiently). A significant portion of mounting structures is made of galvanized or stainless steel, which is composed of iron, with small amounts of carbon, manganese, silicon, phosphorus, sulfur, and oxygen. In addition to steel, aluminum is used, as well as the raw materials in electrical components, such as silicon, copper, and petroleum-based material. Other parts are manufactured using galvanized or stainless steel, but also some aluminum, electrical equipment, motors, and possibly concrete. Most of the labor spent installing PV systems, particularly utility-scale PV, involves assembling the mounting structure.

There are four primary mounting structures deployed in the United States: single-axis tracking ground-mount systems, fixed-tilt ground-mount systems, penetrating rooftop systems, and ballasted rooftop systems. Single-axis tracking systems attach the modules to a horizontal torque tube that is oriented on a north-south axis that rotates the modules from east-facing in the morning to west-facing in the evening. Fixed-tilt systems typically orient the modules facing towards the south tilted at an angle above horizontal equal to the local latitude. Rooftop systems for flat roofs typically orient the modules between southwest and southeast at a tilt angle of 10 to 20 degrees above horizontal. Rooftop systems for pitched roofs are typically coplanar with the roof. Each of the four systems will be discussed in turn.

PV trackers are used to orient modules more directly toward the sunlight to increase energy production per module. Because trackers represent moving machinery - requiring more material than fixed-tilt racking systems, as well as more land-use and higher operation and maintenance (O&M) costs - they typically represent a cost premium, but this premium is often outweighed by the increase in energy production. Single-axis trackers used to be primarily located in sunny areas, where the performance premium was more substantial. However, since 2013, with the decline in cost premium, single-axis trackers have been increasingly deployed in less sunny locations. Exceptions to this trend tend to involve specific site factors, such as being in hurricane-prone areas, greenfield sites where significant ground penetration is problematic, or on military bases (Bolinger, Seel, and Robson 2019).

Single axis tracker architecture is typically either centralized, with equipment designed to move multiple rows of PV modules at a time (typically 15 to 30), or decentralized, with equipment designed to move one row of modules at a time (Figure 53). Approximately 42% of 2020 tracker shipments used centralized trackers, while 58% used decentralized architecture (Wood Mackenzie Power & Renewables 2021a).

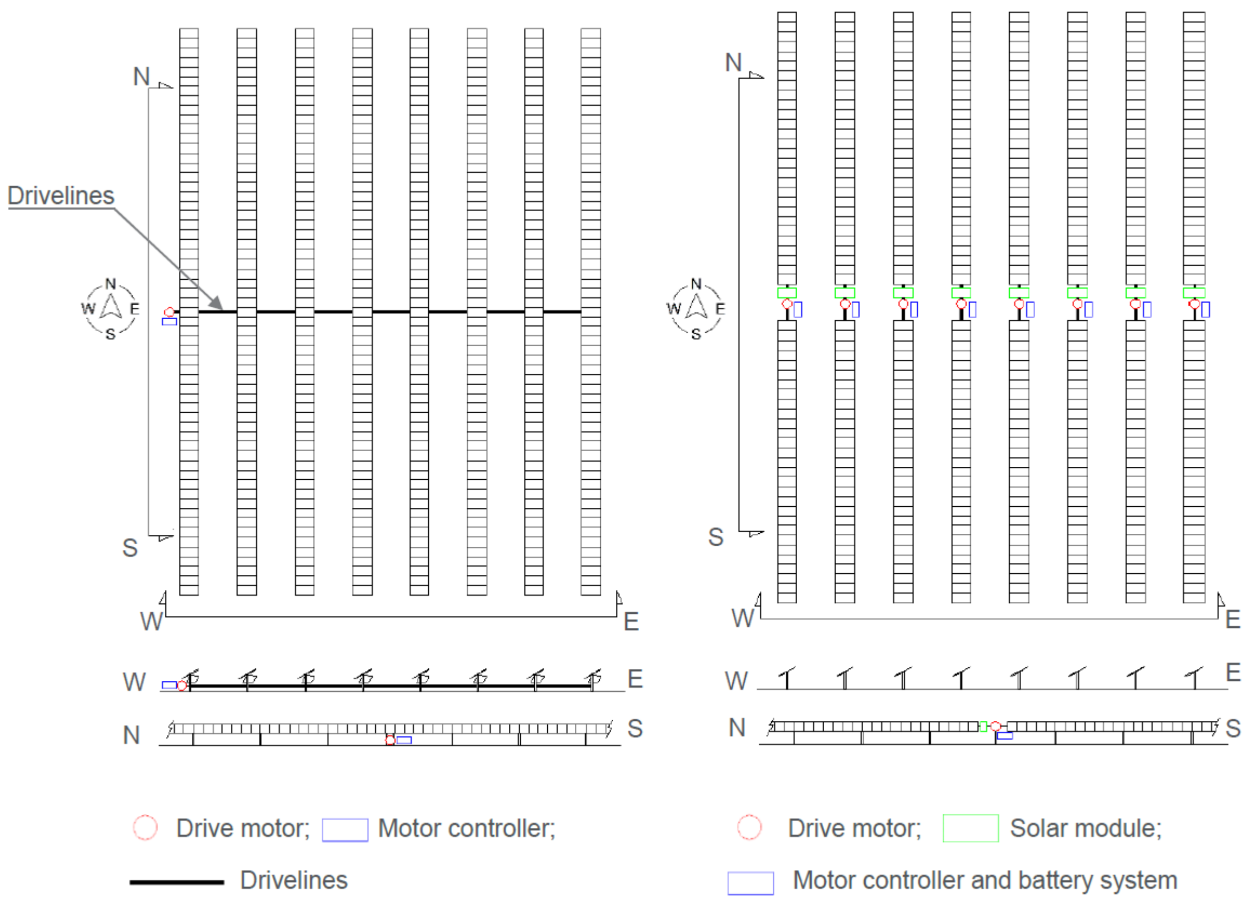

Figure 53. Multi-row (left) and single-row (right) tracking systems.

Source: (RINA Tech and Array Technologies 2020)

Five categories typically make up the components of a single-axis tracking system (Table 4). While the component categorization is similar regardless of tracker design, decentralized and centralized configurations will have different proportions of costs per category. There are over 500 major components per MW_{dc}, with thousands of minor components (e.g., nuts, bolts).

Table 4. Components of a tracking system.

Component	Description	Quantity per MW_{dc}
Structures	Typically made of galvanized steel and some aluminum	
Fasteners	*Galvanized or stainless-steel parts connecting components together (e.g., nuts, bolts)*	
Module rails	*Steel rails connecting PV modules to tracker*	
Foundations	Connects mounting structure to ground	
Support columns (driven piers)	*Steel foundational tracker support, driven into ground with machines*	*12*
Some sites also use concrete or ground screws (also made of galvanized steel)		
Torque Tube and Bearings	Determines the motion of the equipment	
Torque Tube	*A galvanized steel tube, connected to the rails holding the modules. It is rotated by a motor, so the PV panels rotate.*	*1*
Bearings	*Connect torque tube to support columns*	*376*
Drive Train (transmission system)	*Gearbox, gear racks, worm gear, and connecting rods, driveline joints, or slew drive on or near pier that allows torque tube to rotate.*	*34*
Harmonic Dampers	*Shock absorbers*	*68*
Drive Motor	Powers the movement of the rows	1 (centralized) 34(decentralized)
Tracker Control Panel, Power Supply, and Stowing	*Electronics required to perform tracking algorithm, including weather reading, sensors, and communications. Electronics and control also necessary to safety stow trackers in cases of high wind*	

Sources: (RINA Tech and Array Technologies 2020; NREL 2021)

While some preassembly of tracker components does occur, it is weighed against the additional costs of shipping a bigger piece of equipment to the PV project. A significant portion of tracker assembly occurs at the PV installation site. Tracking companies do not do the installation themselves, but rather provide training and field services to engineering, procurement, and construction (EPC) installers, particularly those whose companies have not installed that particular design, or from that particular tracker company.

The cost contribution by component will also vary depending on tracker architecture, as demonstrated in Figure 54. Centralized tracker configurations tend to have higher torque tube and bearing costs due to the need to move multiple rows with one motor, but they save on fewer pieces of redundant electronic equipment.

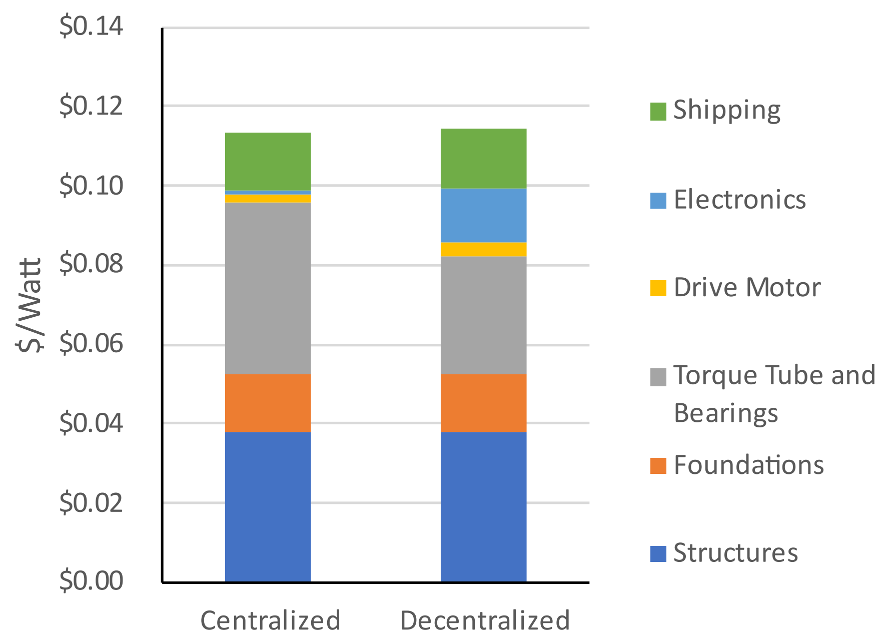

Figure 54. Indicative cost breakdown of trackers, by subcomponent.

Sources: (RINA Tech and Array Technologies 2020; NREL 2021)

PV modules that are mounted at a fixed tilt are configured to optimize system performance over the course of an entire year. The farther away a system is from the equator, the greater the tilt angle for optimal design. The mounting design is based on wind load, with more reinforcements (e.g., higher steel gauge) necessary for windier places.

Fixed-tilt mounting structures typically consist of rails connected to rear and front legs (or a single leg), with clamps holding the modules in place. The legs are typically driven into the ground or held in place with concrete. Virtually all components are made of steel or aluminum.

Slanted roofs typically mount racking on the south, east, or west portion of the roof. Because of the tilt, they often penetrate the roof to affix the racking. Commercial rooftop buildings, however, are often flat with the ability to handle significant weight. In these cases, developers often opt for non-penetrating, ballasted systems, which rely on heavy material (i.e., concrete) to keep systems in place.

Like fixed-tilt mounting, most rooftop racking components are made of galvanized steel or aluminum and consist of rails and clamps. They also typically have splice plates to connect the rails (which can be used for grounding) and either a ballasted foundation (used with concrete as the weight) or a roof penetration system.

2.6.2 Industry Overview

Utility-scale PV represents the majority of PV installed in the United States (46 GW_{dc} vs. 17 GW_{dc} and 10 GW_{dc} for residential and commercial and industrial (C&I), respectively), and within that sector over 70% of installed capacity has used single-axis tracking ground-mount structures (EIA 2021a, Figure 55). Residential PV systems almost exclusively use penetrating rooftop mounting. C&I installations have a mix of fixed-tilt structures for ground mount and ballasted rooftop mounting for large, flat rooftops (Figure 56).

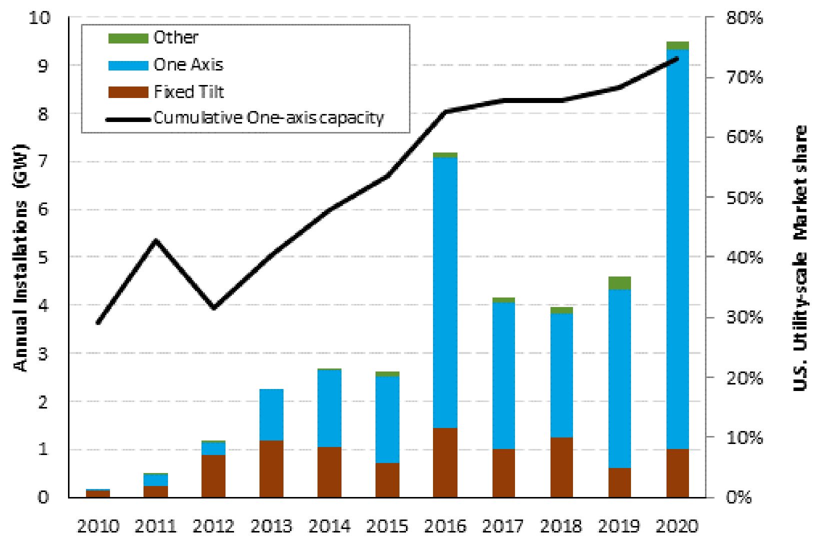

Figure 55. U.S. utility-scale PV installed capacity, by mounting structure.

Source: (Feldman and Margolis 2021)

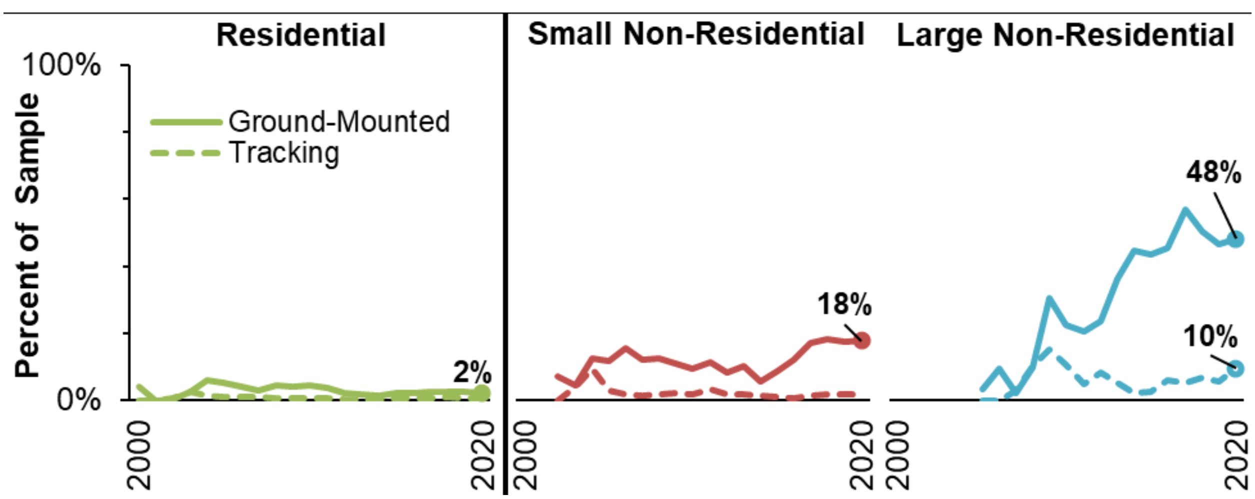

Figure 56. U.S. distributed PV panel mounting trends.

Source: (Barbose et al. 2021)

Single-axis trackers have gained significant market share in large part because of the narrowing premium as compared to fixed-tilt systems, as demonstrated in Figure 57. With the exception of trackers, mounting costs have been relatively flat since 2016. The price of trackers was flat in 2020 and the first quarter of 2021.

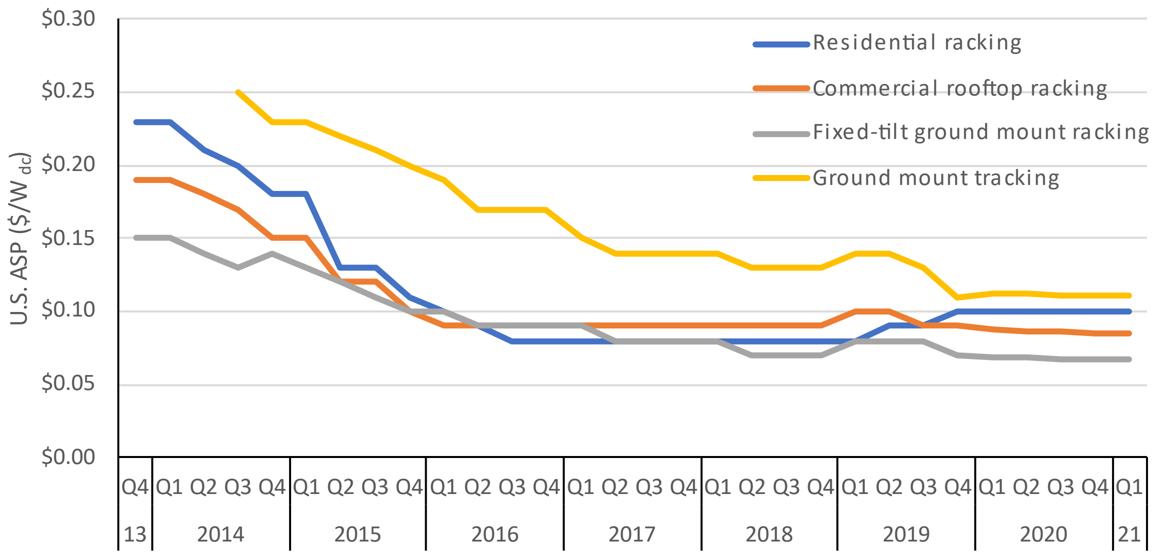

Figure 57. U.S. average PV racking price, by sector.

Source: (Wood Mackenzie & SEIA 2021)

Tracking companies spend a significant portion of their efforts developing intellectual property and managing logistics to bring the pieces of equipment to the PV system site. While there is some manufacturing performed by the companies themselves, a significant portion is made by third-party suppliers. Companies often have agreements with steel and aluminum suppliers for the raw material, and with mills and manufacturing companies that are given the specs to produce the company's parts. Many pieces of the equipment are delivered directly on-site, never coming in contact with the tracking company. Companies look to produce the tracker at the lowest cost to the PV site (including shipping), but they balance this with the competitive advantage of short lead times (getting the equipment to the PV site in a timely manner). Therefore, a company may opt for manufacturing locations that are somewhat more expensive but closer to demand (e.g., U.S., Mexico). This allows companies to deliver products faster than their competitors and provide a quicker turnaround time if there is an error and a part needs to be replaced.

The two largest tracker vendors, globally and in the United States, are the U.S. firms NEXTracker and Array Technologies, collectively representing 70% of 2020 U.S. tracker shipments, and 46% of 2020 global tracker shipments (Figure 58). NEXTracker was originally a U.S. company, and it is still based in San Jose, CA. However, in 2015 it was purchased by Flex, a Singapore-based global electronics manufacturer, with manufacturing facilities in thirty countries. NEXTracker now manufactures on five continents, including major facilities in Mexico (Roselund 2019). However, the second and third largest suppliers of U.S. trackers, Array Technologies (27% of the market in 2020) and GameChange Solar (8% of the market in 2020) are based in the United States (Wood Mackenzie Power & Renewables 2021a). While GameChange Solar appears to only supply projects in the United States, Array Technologies was the second largest global manufacturer of PV trackers in 2020, and exported approximately 16% of its products (Wood Mackenzie Power & Renewables

2021a). All of these U.S. companies control much of the intellectual property incorporated into their products, but they still rely heavily on international suppliers for aluminum and steel.

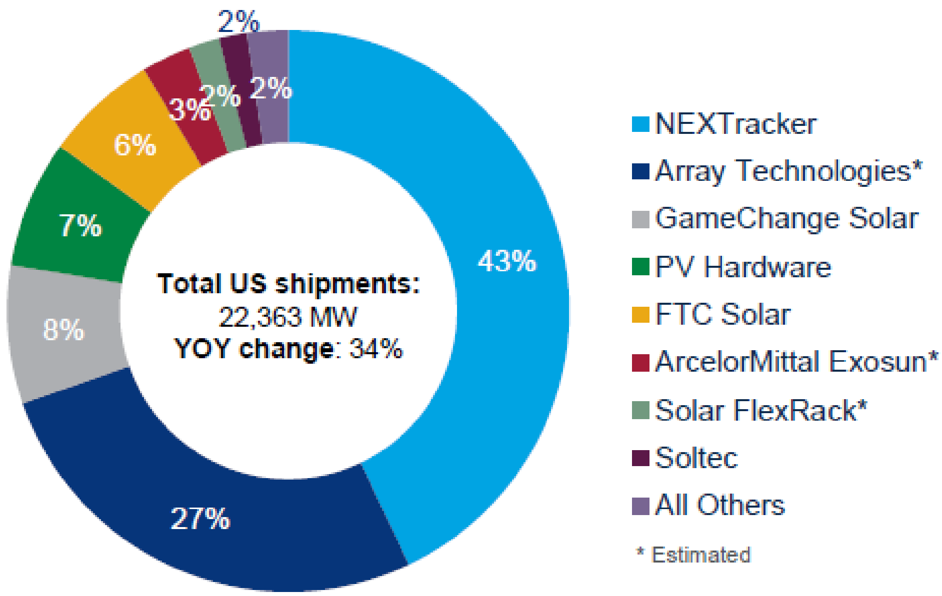

Figure 58. U.S. PV tracker market share rankings by shipment, 2020.

Source: (Wood Mackenzie Power & Renewables 2021a)

There are many fixed-tilt mounting structure suppliers worldwide because there is very little intellectual property associated with the design and therefore a low barrier to entry. Manufacturing plants are typically successful if they achieve sufficient scale and are located near demand to reduce shipping costs (Aboudi 2011). Some PV manufacturers, such as Canadian Solar and Trina Solar, also offer fixed-tilt racking solutions as part of a bundle with their PV modules.

Similarly, while there is a diverse marketplace of products, most of the leading racking companies in the United States distributed PV marketplace manufacture exclusively (Unirac, PV Racking, ProSolar, Quick Mount PV, Oatey, DPW Solar, Tamarack Solar) or in part (IronRidge) in the United States.

However, the Section 232 tariffs have indicated how heavily some domestic racking producers rely on imported raw steel or aluminum pricing. Once the Section 232 tariffs were enacted, multiple firms decreased the amount of racking produced in the United States, since they could no longer afford raw metals, and instead imported finished racking from overseas (Eckhouse and Deaux 2019b).

2.7 PV Inverters

2.7.1 Technology Overview

Inverters are the primary power electronics equipment in PV systems, converting the dc energy generated by PV modules into ac energy used by the electric grid. PV inverters have varying levels of capacity and function, each with its own set of advantages. Generally, they can be divided into the following categories:

- Central inverter: typically, floor or ground-mounted, converting the energy from multiple strings of PV panels, typically range in size between 1 MW_{ac} – 5 MW_{ac} and are used in utility-scale applications.
- Three-phase string inverter: typically installed on a wall or a vertical structure, converting the energy from a single string of a PV array to three-phase energy, typically found in commercial and utility-scale applications.
- Single-phase string inverter: like three-phase inverters but only convert to single-phase power, typically found in homes.
- Module level power electronics: includes both microinverters, which convert the energy from a single module, and dc-dc optimizers, which optimize the power supply for each individual module but work with three-phase or single-phase string inverters.

PV inverters are composed of power electronic semiconductors and power circuits, primarily consisting of the power block (or power module) and passive components; mechanical and structural parts, consisting of the thermal management system (if necessary), and the casing. Figure 59 diagrams the components of a typical inverter and how they are connected.

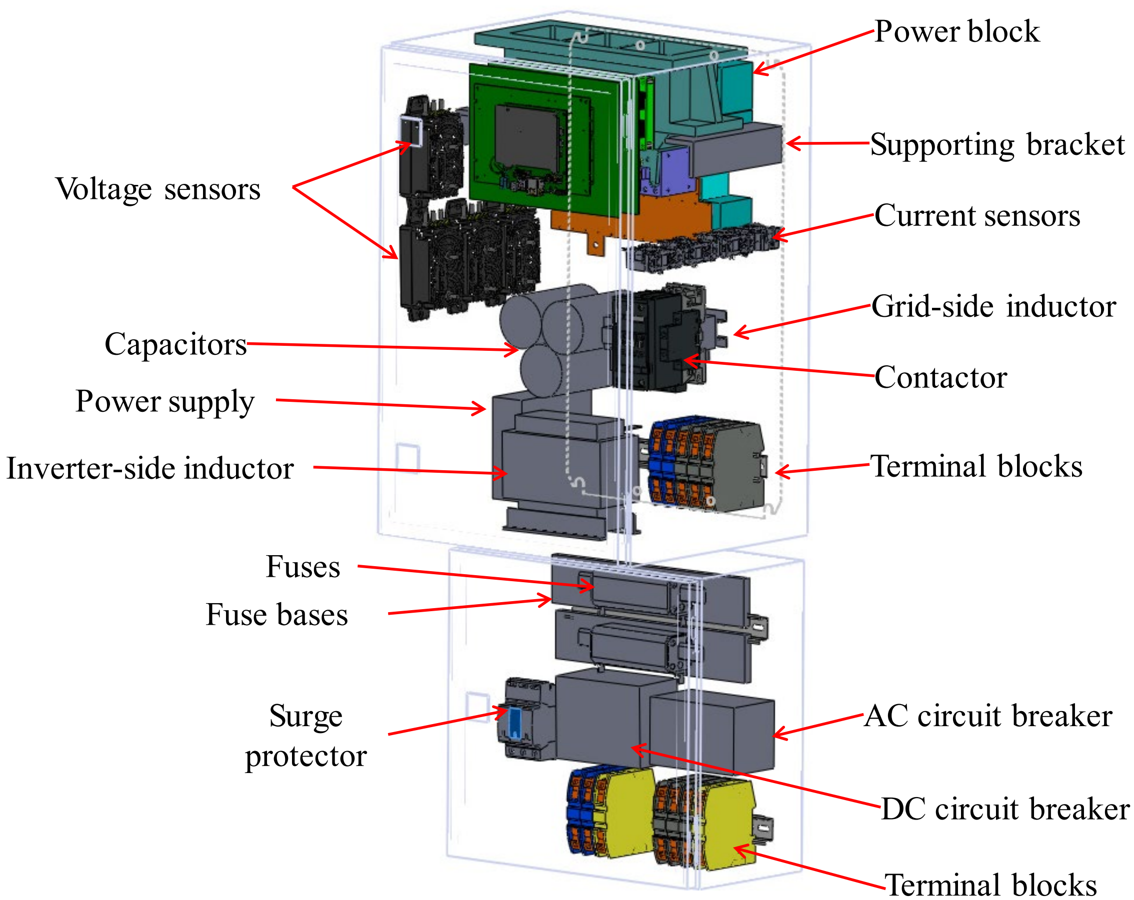

Figure 59. Inverter assembly with supporting components.

Source: (Singh, et al., 2018)

Silicon, copper, aluminum, and petroleum-based material are all processed into forms that can be used to produce the subcomponents, such as semiconductors, transformers, and housing structures. Figure 60 provides a cost breakdown of a silicon carbide (SiC) converter.[3] As shown, the power block, consisting of the semiconductor and electronic component, represents the bulk of the costs, followed by the passive components. Insulated-gate bipolar transistors (IGBTs) are the power devices used in higher power applications, such as for PV inverter power blocks.

Inverter enclosures are typically made of metal and would have a similar supply chain to aluminum and steel. Thermal management systems (i.e., wiring, thermostat, fan) are part of the general electronics supply chain, dominated by Asia.

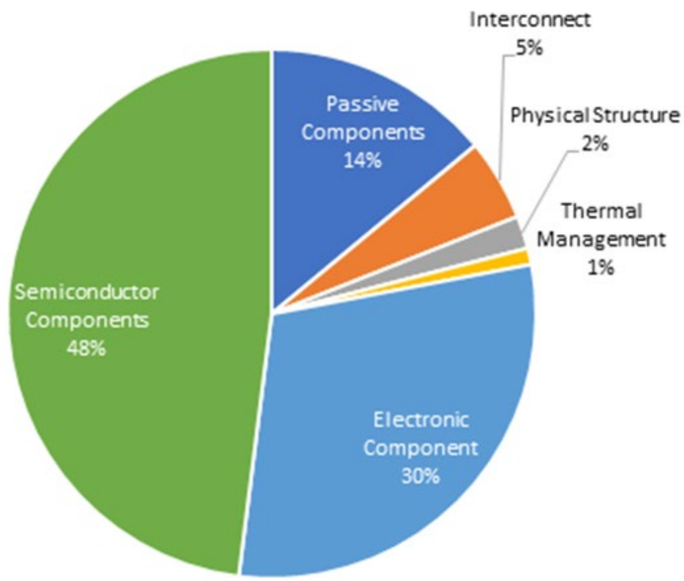

Figure 60. Breakdown of silicon carbide inverter material costs.

Source: (Singh, Reese, and Akar 2019)

2.7.2 Industry Overview

Components including semiconductor power electronics, the power block, and passive components are typically manufactured in separate locations from where they are eventually assembled into an inverter, providing the opportunity for a global supply chain.

The United States, Europe, Japan, and other parts of Asia have many large semiconductor companies generating the intellectual property found in an inverter, as seen in Figure 61.

[3] Silicon carbide technology represents a small portion of PV inverter sales, with most sales using silicon semiconductor equipment. However, the proportions give a rough estimate of component cost contribution.

Figure 61. Geographical headquarters of main power semiconductor companies (non-exhaustive list).

Source: (Yole Developpement 2018)

Despite the large presence of U.S., European, and Japanese semiconductor power electronics companies, most of the manufacturing is done in China and other parts of Asia. From 2012 to 2017, the American presence decreased from 10% to 8% of the market, while China and Asia Pacific accounted for 54% to 58%, a trend that is likely to continue. Figure 62 shows known locations capable of assembling IGBT modules necessary for power blocks.

Figure 62. Geographical positions of main manufacturing power block locations (non-exhaustive list).

Source: (NREL 2021)

Passive component manufacturing is geographically diverse but is heavily focused in China and the rest of Asia (Figure 63). In a database of 542 unique passive components (e.g., cathode, wire, die, terminals), 35 manufacturers built parts in 31 different countries. While the quantity of products built is not well known, 43% of the individual products were manufactured in China, 5% in Japan, and another 33% in the rest of Asia. Only 1% of the products were manufactured in the United States.

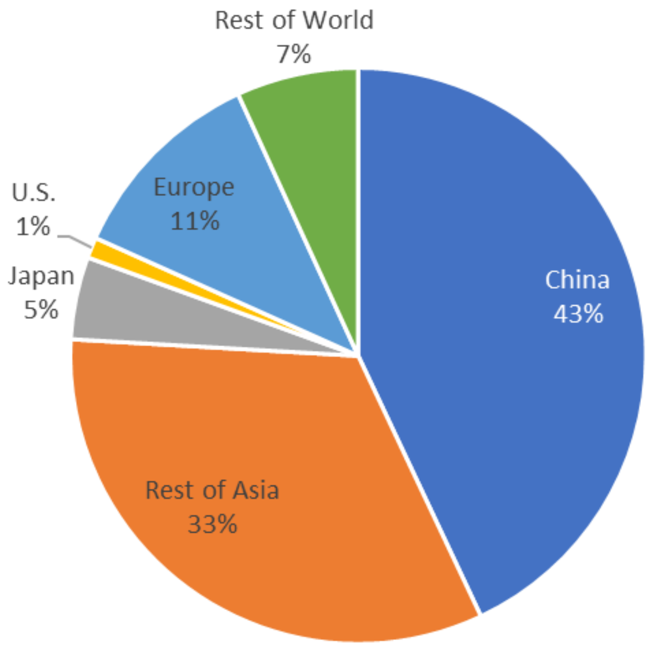

Figure 63. Percent of individual passive components manufactured by region.

Source: (SiliconExpert 2019)

While a small number of companies have some vertical integration starting at the device level all the way through to an inverter (e.g., ABB, Infineon), most inverter components are bought and then assembled. In 2020, 185 GW_{ac} of PV inverters were manufactured globally, with 121 GW_{ac}, or 66%, from companies headquartered in China.

Most of the European and Chinese companies manufacture domestically, but many inverter manufacturers produce products abroad – particularly those that produce module-level-power-electronics (MLPE). For example, the leading MLPE producer, SolarEdge, headquartered in Israel, has production facilities in Hungary, China, and Vietnam. The second leading MLPE producer, Enphase, headquartered in the United States, has production facilities in China and Mexico. The U.S. domestic market relies more heavily on inverters from companies headquartered in Europe and Japan (Figure 64).

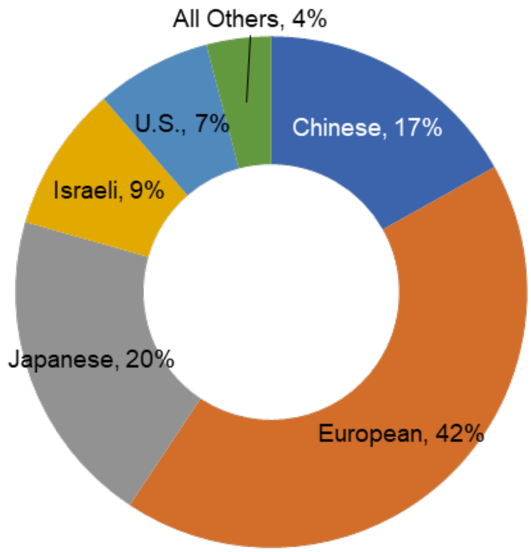

Figure 64. Percent of U.S. inverter shipments, by manufacturing headquarters, 2020.

Source: (Wood Mackenzie Power & Renewables 2021b)

However, the inverter supply chain varies by inverter type, with U.S. utility-scale applications dominated by European and Japanese companies, and residential applications dominated by U.S. and Israeli companies manufacturing in China and other foreign countries (Figure 65).

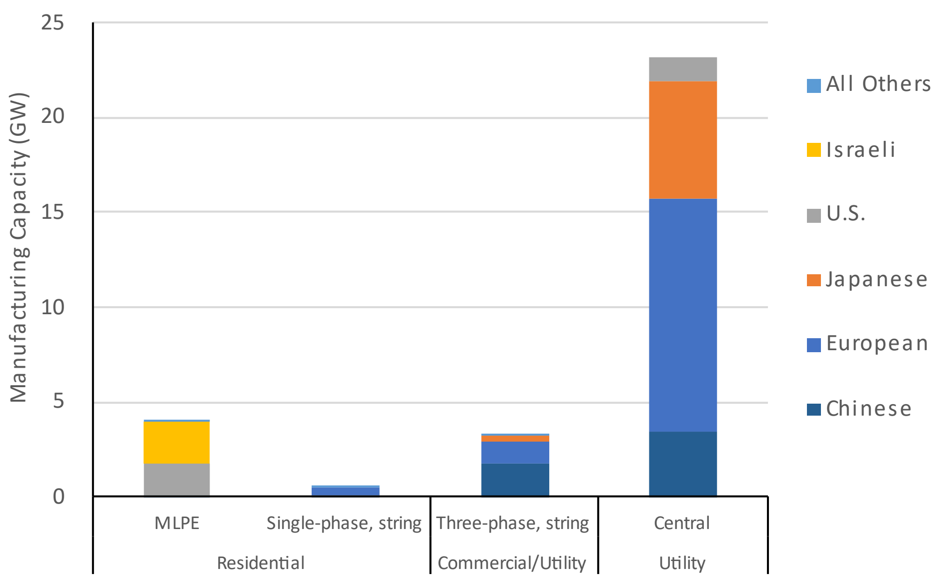

Figure 65. Global inverter manufacturing capacity by company location and application, 2020.

Source: (Wood Mackenzie Power & Renewables 2021b)

Through 2015, the U.S. manufactured approximately the same capacity of inverters domestically as what was installed each year, as demonstrated in Figure 66.

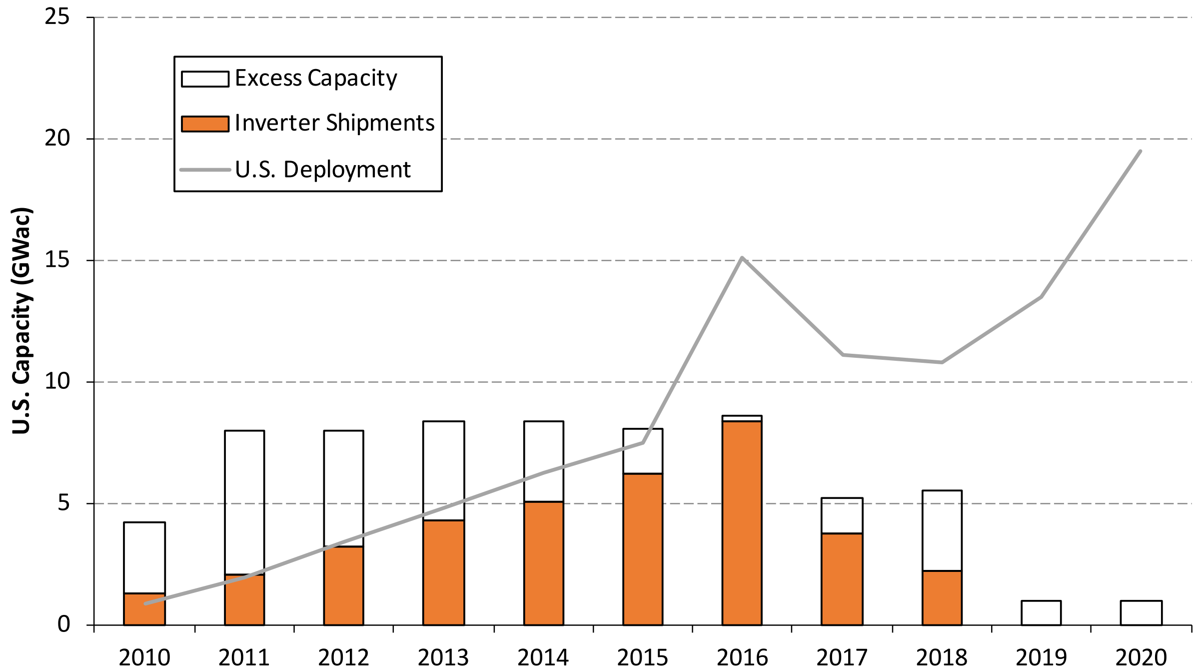

Figure 66. U.S. inverter production, manufacturing capacity, and system deployment.[4]

Source: (Wood Mackenzie & SEIA 2021)

U.S. inverter manufacturing capacity began to fall in the second half of 2016, largely due to continued price declines for utility-scale inverters, as shown in Figure 67.

[4] Inverter shipments and capacity are converted from ac to dc assuming a ratio of 1.2. Wood Mackenzie stopped reporting inverter production and capacity at the end of 2018. Q4 2018 shipment and capacity values represent Q1-Q3 2018 averages.

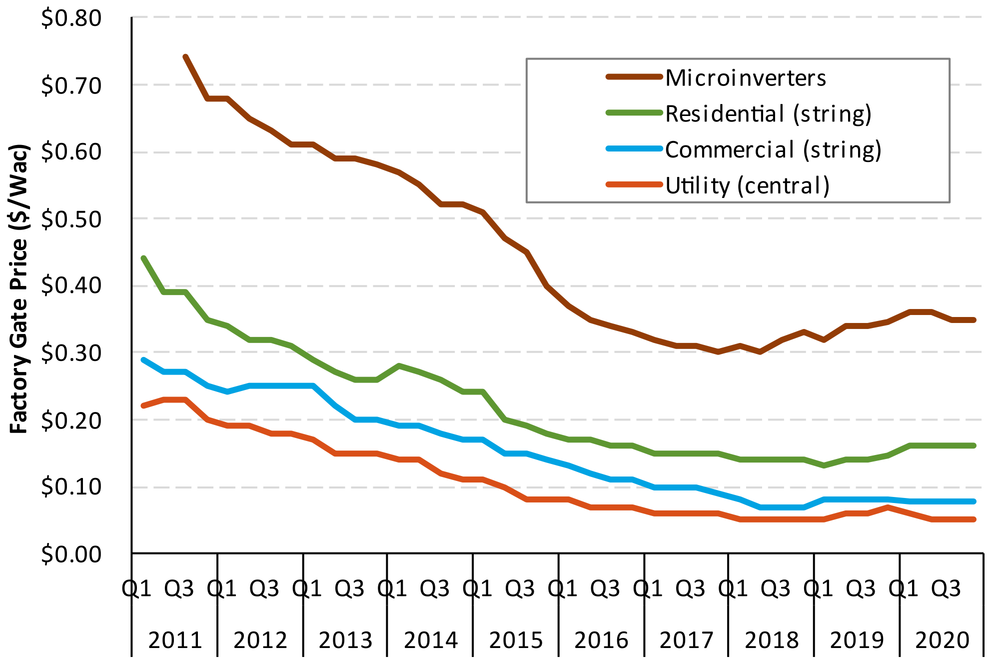

Figure 67. U.S. inverter pricing by sector.

Source: (Wood Mackenzie & SEIA 2021)

Two of the leading U.S. inverter manufacturers at the time (with headquarters in Europe), ABB and SMA, closed their U.S. facilities to consolidate manufacturing in their European plants (Wood Mackenzie & SEIA 2017). Inverters continue to be produced in the United States, mainly from foreign-owned firms, but at a much lower level compared with previous years. At the same time, U.S. demand for inverters has continued to grow, thus reducing the percentage of installed content from domestic producers.

2.8 Cadmium Telluride Technology

2.8.1 Cadmium and Tellurium Refining

2.8.1.1 Technology Overview

Cadmium (Cd) and tellurium (Te) are the primary elements used to make thin-film CdTe absorber material, which is the second most deployed PV technology, behind c-Si. Neither Cd nor Te are found isolated in mineral ores, and both are byproducts (considered as minor metals) of smelting of other prime metals such as copper (Cu), zinc (Zn), lead (Pb), and gold (Au) ("Assessment of Critical Thin Film Resources," n.d.).

The availability of Cd and Te depend predominantly on the demand for Zn and Cu, respectively. Around 80% of Cd is generated as a product of smelting Zn ores, with 20% from Pb ores. Te is produced as a byproduct of Cu refining and is considered a rare element (V. Fthenakis 2007). Cd and Te are used in a variety of products, although PV is the largest single usage of Te (Figure 68).

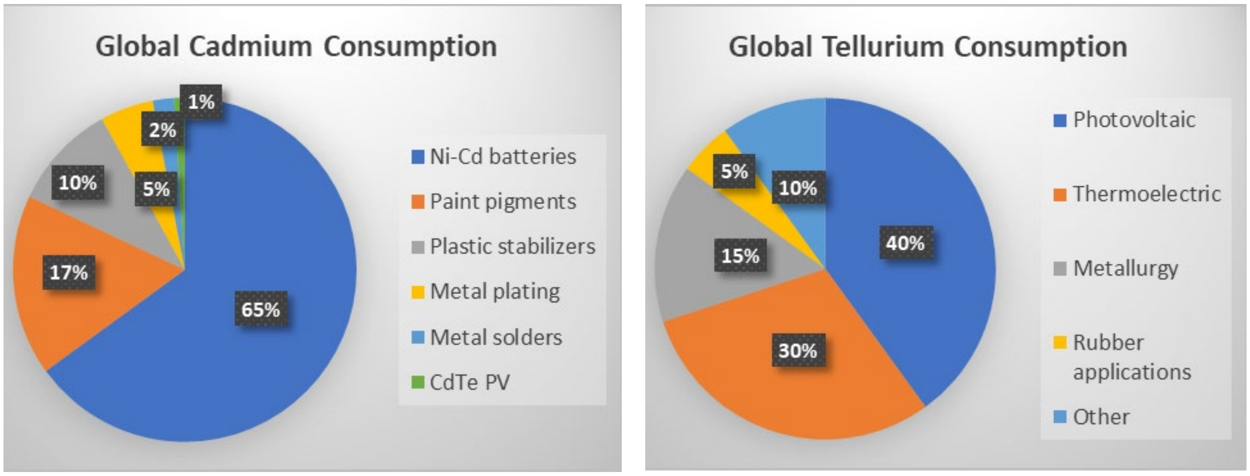

Figure 68. The primary products that use Cd (2004) and Te (2019).

Sources: (V. Fthenakis 2007; Anderson 2020)

Zinc concentrates are made by a process known as beneficiating, where the steps include crushing, grinding, and a flotation process (Figure 69). An estimated 90-98% of Cd present in Zn ores is recovered through this beneficiating process (including the original mining step) (Llewellyn 1994). Subsequently, the Zn concentrates are transferred to smelters/refiners to isolate and produce the primary metals. The smelting process is shown on the right side of Figure 69, where metallic precipitates from the three-step purification step (Cd, germanium (Ge), indium (In), and gallium (Ga)) go through electrowinning stations. The extracted Cd is formed into briquettes and further melted, and this refined metallurgical-grade Cd is 99.95% pure.

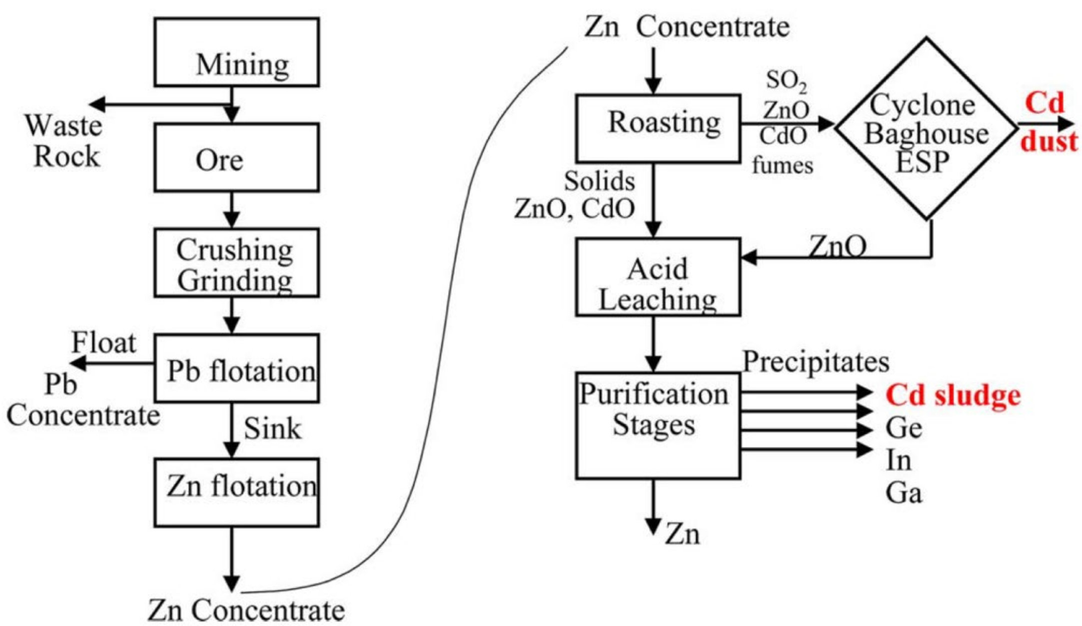

Figure 69. Cd flows in Zn mining and refining.

Source: (V. Fthenakis 2007)

While the production of Cd may not depend on the PV market, using Cd in PV modules provides a safe product to encapsulate (i.e., store) and utilize this hazardous element. If the Cd produced in Zn refineries is not used, the material needs to be disposed of safely. Much consideration must be given to disposal via landfills because Cd is a toxic element.

Currently more than 90% of Te is recovered from what are known as slimes, which are formed in the process of electrolytic refining of Cu. The extraction process of Te has been reported as a challenging and complicated process involving a variety of possible techniques depending on the Cu source including oxidizing roasting followed by leaching with water and electrowinning or sulfation followed by roasting, caustic leaching, and electrolysis (Makuei and Senanayake 2018).

However, using Cd and Te in CdTe modules requires purity beyond the standard commercial-grade ingots. Typical ingots are 3.5N (99.95% pure), while 5N (99.999% pure) to 6N (99.9999% pure) is needed for both Cd and Te in modules. Once both high purity Cd and Te are produced, high purity powders are produced by electrolytic purification followed by atomization or via vacuum distillation (Figure 70).

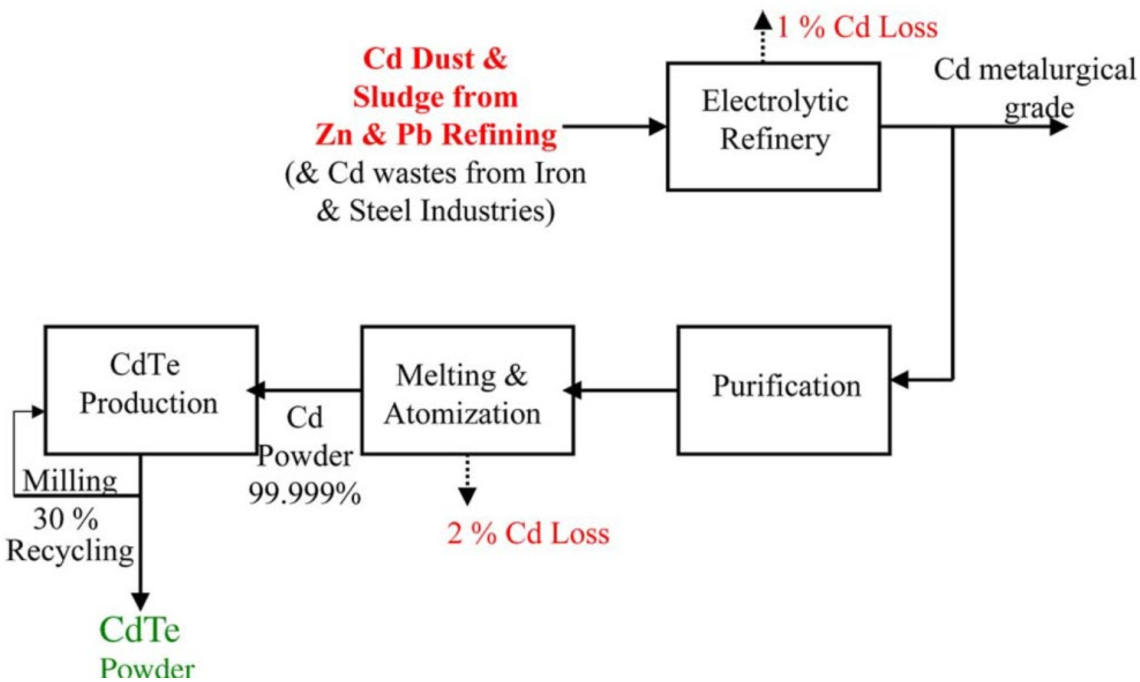

Figure 70. High purity CdTe production flow.

Source: (V. Fthenakis 2007)

2.8.1.2 Industry Overview

The United States imported the required Cd needed for domestic production predominantly from China, South Korea, Japan, and Canada (USGS, 2021a). Two U.S. companies also refined Cd in 2020 (Callaghan 2020). One company located in Tennessee refined Cd using Zn ores, while the second company (located in Ohio) recovered Cd from spent nickel-cadmium (Ni-Cd) batteries. First Solar claims to be capable of recovering 90% of its materials through recycling of its modules, with scalable capacity to accommodate the anticipated high volume as modules reach their end of life after 25 or more years. However, few modules have been recycled to date, so the ultimate recycling capacity and recovery fraction have yet to be demonstrated.

Because Cd is mined as a byproduct of other ores with a highly variable concentration, it is not possible to accurately estimate Cd global reserves (Table 5). However, the United States refined and produced 750,000 MT of Zn ores in 2019, with an expected Cd content over 200 MT (USGS, 2021a). Given that the estimated Cd material needed per GW_{dc} of CdTe PV modules is 50 MT (50 milligrams per watt), the 11,000,000 MT of Zn reserves in the United States is enough to supply Cd for about 50 GW_{dc} of CdTe modules. The 250,000,000 MT of global Zn reserves are enough to supply Cd for about 1000 GW_{dc} of CdTe modules (Figure 71).

Table 5. Cd content in various mineral feedstocks.

Material	Cd concentration range (ppm)
Zn ores	0.1 - 2000
Zn ore concentrate	3000 - 5000
Copper ore concentrate	30 - 1200
Iron ore	0.12 – 0.30

Source: (V. Fthenakis 2007)

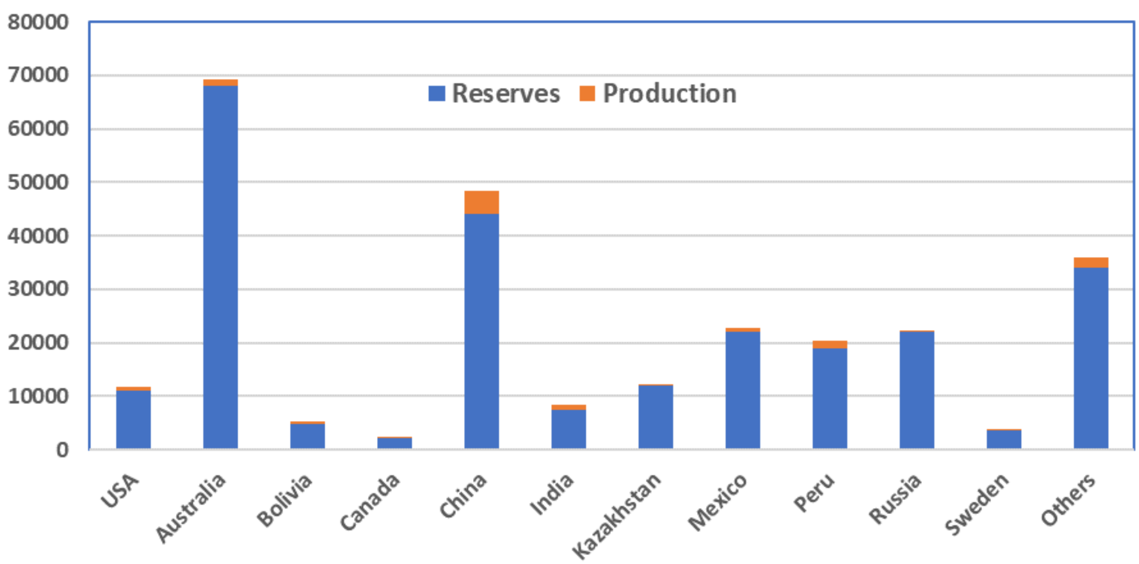

Figure 71. Global Zn reserves and production (kilotonnes).

Source: (A. Tolcin 2020)

The availability of rare Te is a more acute concern. Estimated global production and reserves are shown in Figure 72. The main countries that produce Te are Sweden, Japan, Russia, China, the United States, and Peru. Two mining districts, one in Southwest China and one in Skellefte VMS district, Sweden, account for 15% of annual global production. Tellurium reserves in the United States represent approximately 15% of the global total ("Tellurium: The Bright Future of Solar Energy," n.d.). Based on publicly available information, the U.S. reserves of 3500 MT of Te are located in Montana, Alaska, and Colorado (Karl 2019).

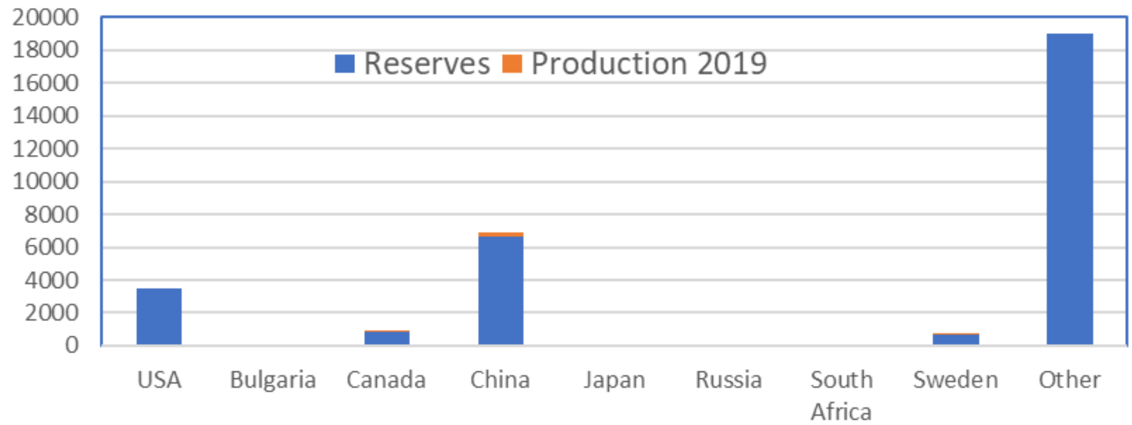

Figure 72. Global tellurium reserves and annual production (MT). "Other" is from nine countries.

Source: (Anderson 2020)

The estimated Te material needed per GW_{dc} of CdTe PV modules is 50 MT (50 milligrams per watt). The 30,000 MT of global reserves of Te are enough for 600 GW_{dc} of CdTe modules. However, the rate at which these reserves can be extracted cost-effectively is limited by their production as a byproduct of Cu refining. The world production of Te was estimated to be about 520 MT in 2019 and 490 MT in 2020 (USGS, 2021a). While the future global production of Te is somewhat uncertain, it appears to be sufficient to support the annual production of not more than 20 GW_{dc} of CdTe modules for thirty years.

The United States imported the required Te needed for domestic CdTe module production predominantly from Canada, China, and Germany (Karl 2019). There was no refining or production of Te in the United States from 2015 – 2019, but in 2020 one company in Texas was thought to export Cu anode slimes to Mexico for recovery of commercial-grade Te (USGS, 2021a). In March 2021, First Solar said it was in talks with the mining group Rio Tinto, which plans to spend $3 million on a facility in Utah to recover Te (Wagman 2021). However, the purity of Te needed for CdTe modules is higher than the commercial-grade Te ingots, so the ingots are further refined in an additional step, for which the main supplier to U.S. companies is 5NPlus, a Canadian company.

Given the limited availability of Te as raw material, recovering and recycling it from modules at their end of life has been proposed (Marwede and Reller 2012). However, due to the long service life of PV panels, it would take several decades before recycled Te could supply a significant fraction of the Te required, and if the annual demand for CdTe modules grows with time, it will take even longer. As noted above in the discussion of Cd, First Solar claims to be capable of recovering 90% of its materials through recycling of its modules, but few modules have been recycled to date, so the ultimate recycling capacity and recovery fraction have yet to be demonstrated.

2.8.2 Module Fabrication

2.8.2.1 Technology Overview

The substantial majority of thin-film manufacturing capacity uses CdTe technology. The fabrication process can be done in various ways, but typically these materials are deposited directly onto the glass of the solar module, making the manufacturing process (Figure 73) far more integrated than the various steps of c-Si module production.

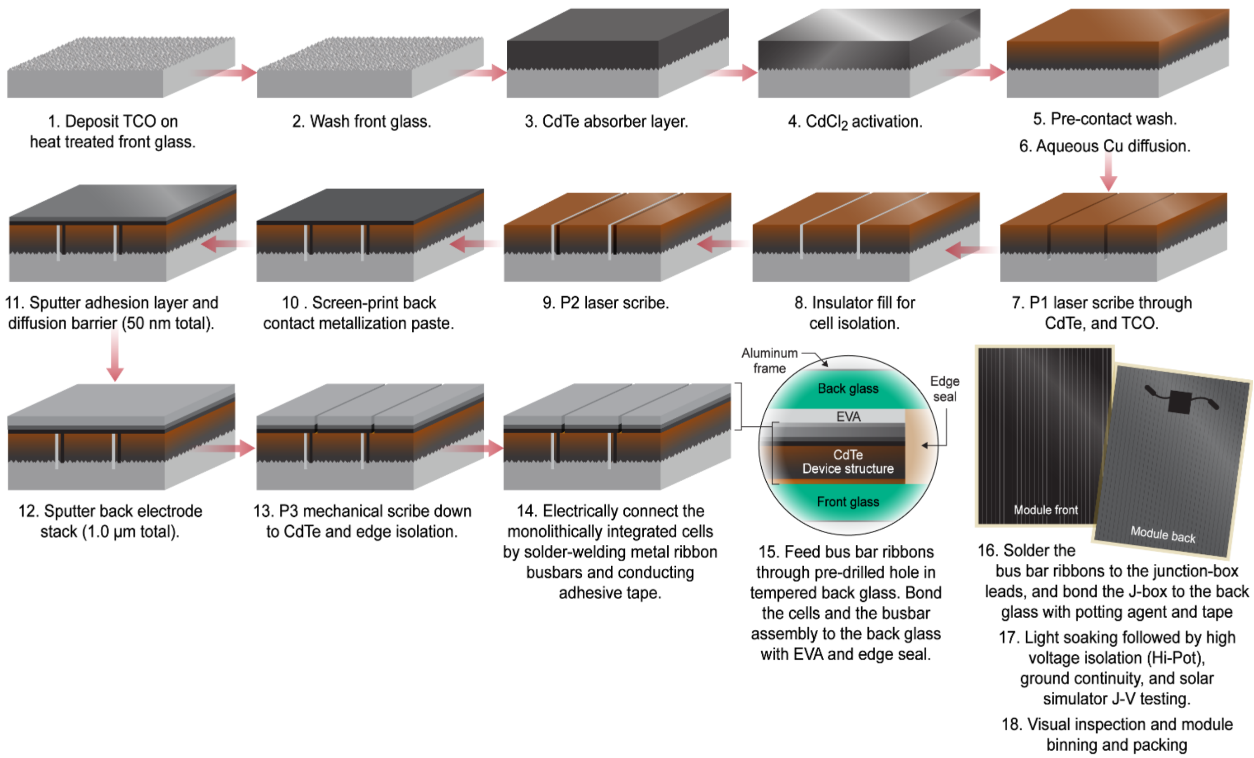

Figure 73. Process flow for making CdTe modules.

Source: NREL

2.8.2.2 Industry Overview

When global polysilicon prices rose dramatically in the late 2000s owing to supply constraints, PV modules that did not require polysilicon, including CdTe, gained significant market share. As shown in Figure 74, First Solar had a significant manufacturing cost advantage over its c-Si module competitors prior to 2012.

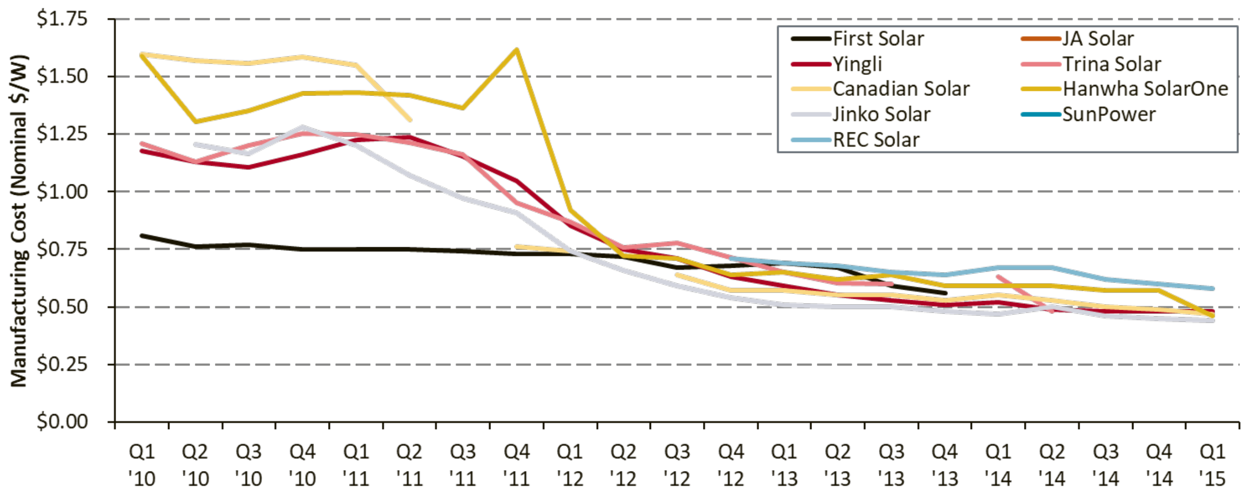

Figure 74. Manufacturing cost of modules from First Solar (CdTe PV) and various c-Si PV manufacturers.

Source: (Feldman, Boff, and Margolis 2015)

However, as polysilicon production capacity increased and its price fell, the thin-film market share began to drop. In 2020, CdTe accounted for approximately 4% of global shipments.

Despite having lower efficiency than competing c-Si technology (Figure 75), CdTe has captured a significant share of the market for utility-scale PV systems in the United States due to its ability to deliver electricity to the grid at a lower cost. CdTe accounted for approximately 29% of U.S. utility-scale capacity, representing 16% of all U.S. PV capacity through 2020 (Figure 76). The high concentration of global CdTe deployment in U.S. utility-scale systems is largely due to the market focus of First Solar, which is the leader in CdTe module manufacturing (Feldman and Margolis 2021). First Solar previously had a utility-scale development arm, and its module format is now designed specifically for large-scale applications.

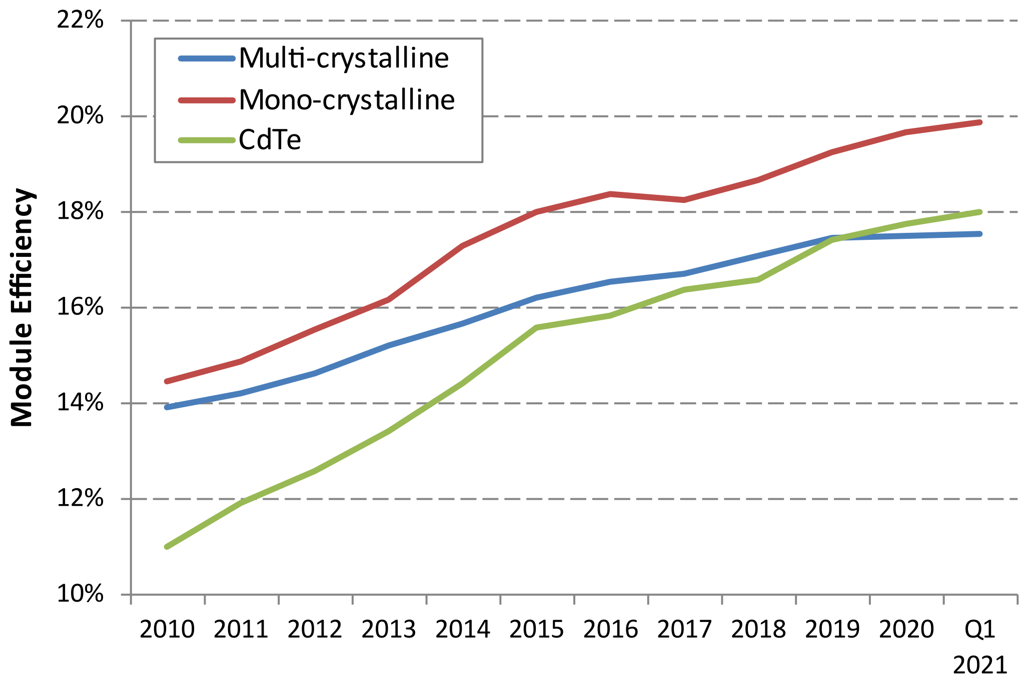

Figure 75. Efficiencies of c-Si and CdTe modules.

Source: (Feldman and Margolis 2021)

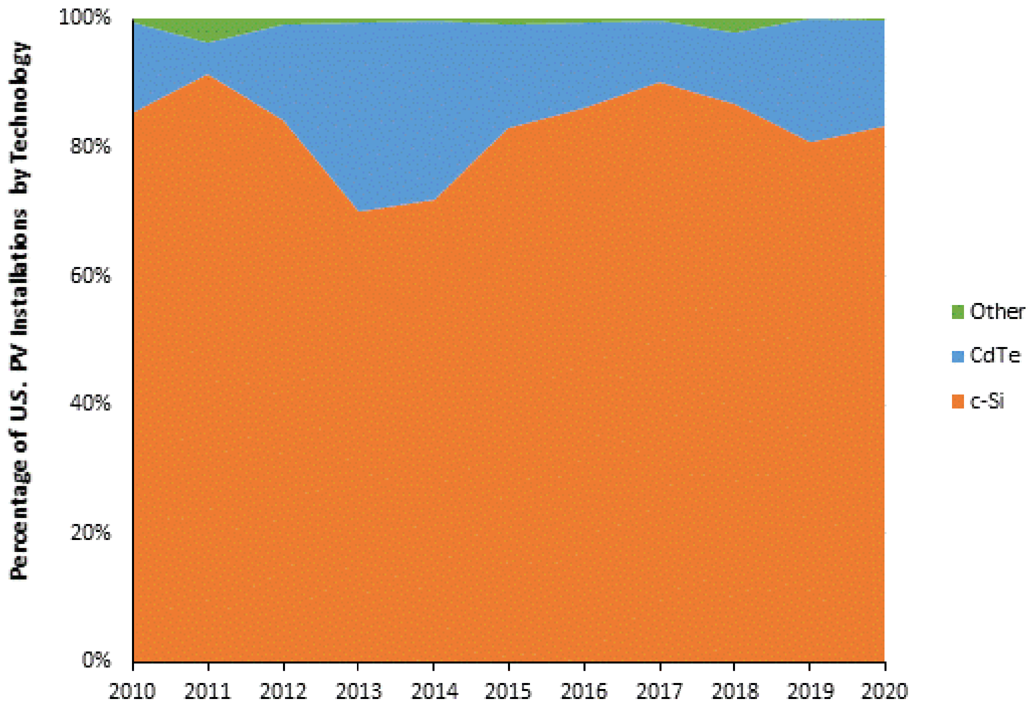

Figure 76. Percentage of U.S. PV installations by technology.

Source: (Mints 2021)

First Solar has manufacturing operations in Malaysia, the United States, and Vietnam. In June 2021, First Solar announced that it would be expanding its American solar manufacturing capacity by 3.3 GW_{dc} as well as adding a facility in India. The new U.S. facility will be built in Ohio with an investment of $680 million and is expected to employ more than 700 people when production starts in 2023. When these new sites come online, the company will have a total U.S. annual manufacturing capacity of 6 GW_{dc} and a global manufacturing capacity of around 16 GW_{dc} (First Solar 2021a). Additionally, First Solar reports that the new U.S. facility will become the largest vertically integrated solar manufacturing complex outside of China (First Solar 2021b).

In addition to CdTe, about 900 MW_{dc} per year of thin-film modules based on copper indium gallium diselenide (CIGS) have been produced by Solar Frontier in Japan. However, Solar Frontier recently announced it would close its CIGS production and switch to making c-Si panels (Bellini 2021c). There have been some announcements of thin-film manufacturing capacity additions in China, but no evidence of them moving beyond the pilot-line stage of development (Figure 77).

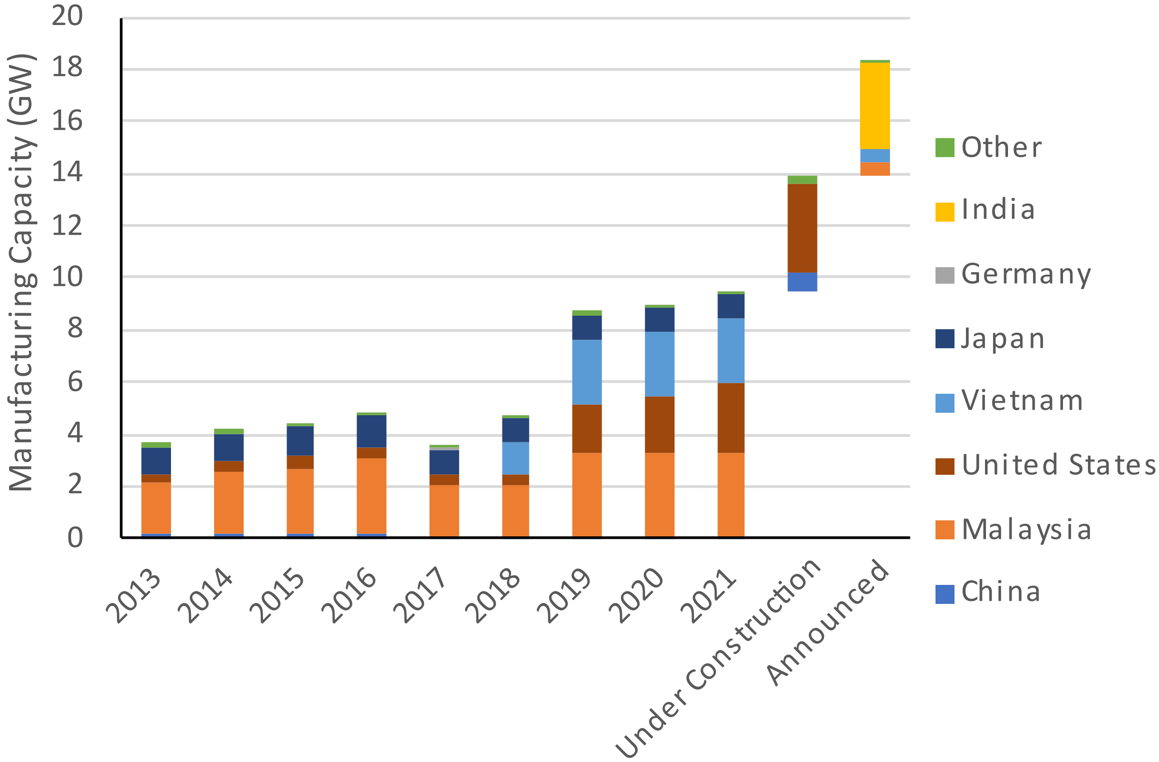

Figure 77. Thin film PV manufacturing capacity by country.

Sources: (First Solar 2021a; BloombergNEF 2021f)

3 Policy Considerations

3.1 Opportunities and Challenges

The United States has abundant natural resources, a resilient and innovative workforce, highly developed infrastructure, and a strong culture of intellectual property protection. The key opportunities identified in this section leverage these U.S. strengths to help overcome associated challenges. The opportunities are presented here in rank order of their potential to contribute to securing the solar supply chain in the timeframe necessary to help decarbonize the U.S. power sector by 2035.

3.1.1 Polysilicon Refining

Polysilicon refining is energy intensive compared to the other steps in the solar supply chain, with electricity representing the biggest production cost after capital asset depreciation. The United States has some of the least-expensive power in the world in the form of hydroelectric power in the Northwest, Upper Midwest, and Tennessee Valley. Hydropower is an emissions-free source of power, consistent with the intent to use solar modules to reduce dependence on fossil fuels. Furthermore, the amount of electricity required to produce the polysilicon used to make solar cells (30 to 80 kWh of electricity per kg of polysilicon) is recovered by operating the solar power plant for just two to six weeks (3 kg of polysilicon required per kW_{dc} of solar modules divided by the 2000 kWh of ac power delivered each year per kW_{dc} of deployed solar modules).

China currently produces a significant portion of its polysilicon using electricity from coal-fired power plants. As carbon removal from all supply chains becomes a larger priority for countries and companies, this may help the competitive position of U.S. polysilicon producers.

The United States has about 60 kilotonnes per year of polysilicon refining capacity, enough to support the production of 20 GW_{dc} of c-Si modules annually, equivalent to the current domestic demand. The U.S. capacity includes one of the world's largest installations of fluidized bed reactors (FBRs). The FBR process differs from the more commonly used Siemens process developed in the 1950s in that it uses about half as much electricity.

The sunk cost in existing polysilicon facilities in the United States is several billion dollars. These facilities are mostly, if not fully, depreciated, so they can be operated profitably even at the low selling price necessary to compete with Chinese polysilicon producers. These facilities are now either idle or have been repurposed to supply polysilicon to the semiconductor industry.

Re-establishing polysilicon refining in the United States is technically straightforward, but before that process could start, the polysilicon producers would need to have reliable customers. For the silicon solar supply chain, those customers would be ingot growers, but at present they are all in China and unwilling to purchase U.S. polysilicon because China has imposed hefty import duties (see Section 3.3). Unless ongoing trade negotiations with China alleviate this conflict, it would be necessary to build a new supply chain elsewhere. That could be in countries aligned with U.S. priorities, or within the United States itself. Either approach requires substantial investment.

3.1.2 Thin-Film Modules

The United States is the world leader in the commercialization of thin-film module technology, in the form of CdTe. These modules are assembled directly from commodity materials in a single factory, avoiding the complexity of multiple production sites that is inherent in c-Si technology. The near monopoly of the United

States in CdTe technology presents an opportunity to expand production up to the limit that CdTe material availability allows, with little risk of being overtaken by low-cost foreign competition.

Whereas CdTe technology faces a low risk of geopolitical disruption, CdTe technology does come with its own challenges. Among these is the concentration of capacity for this technology in a single company, First Solar. Not only does this near monopoly on CdTe production introduce business risk; it also introduces technology risk. All of First Solar's production plants are purposefully designed to be as similar as possible for maximum operational and cost efficiency. If there is a flaw in the production process that does not reveal itself until after product has been in the field for many years, it will affect essentially every CdTe module deployed.

CdTe also has issues related to its core materials, namely cadmium and tellurium. Cadmium can be toxic, and tellurium is rare. Attempts to substitute other elements have not been successful. Public concerns about Cd, reflected in environmental regulations, already limit the market for CdTe technology almost exclusively to utility-scale solar farms. Tellurium is currently obtained inexpensively as a by-product of copper mining, but production from that source is nearing saturation in every country other than China. For CdTe to increase its market share, it would likely need to start sourcing Te from China or using more-expensive methods, either of which would limit the benefit of relying on this approach.

3.1.3 Module-Assembly Clusters

Efficient module assembly relies on just-in-time logistics for component parts. Having suppliers of the key components nearby reduces the cost of maintaining inventory while ensuring reliable sourcing. This is especially important for bulky module components like glass, encapsulant, junction boxes, and aluminum frames. The United States currently has a cluster of module manufacturers in the contiguous southeastern states of Alabama, Florida, and Georgia. Concentrating future expansion of module assembly in this region of the country presents an opportunity to grow a competitive, robust local supply chain for module components available to all module assemblers in that region.

A potential issue that could arise with a heavy concentration of module assembly in the United States is how PV hardware is dealt with at its end-of-life. This could become an issue for module assemblers because most likely they will be held responsible for any recycling necessary to achieve long-term sustainability.

3.1.4 Mounting Structures

Mounting structures are composed mostly of heavy, low-cost steel components. International shipping of these components represents a significant fraction of their cost. All else being equal, this provides an inherent preference for domestic production relative to imports. Trackers are currently used in about half of all large, open-field PV plants installed globally. Tracking is most beneficial in locations with a relatively clear sky, because there is no benefit in tracking the sun across an overcast sky. The United States has an inherent advantage for the production and further refinement of trackers relative to most regions of the world due to having unusually clear skies located near large population centers over a large portion of the country.

Whereas the United States has a lead and inherent advantages in the continuing development of trackers, the tracking mechanism is only one component in the overall mounting structure, most of which is made of steel. Almost all the low-cost steel for PV mounting structures comes from China. Displacing Chinese steel with domestic steel presents a substantial national challenge across numerous industries, not just solar power.

3.1.5 Silicon Solar Cells

Although there is no current production of c-Si solar cells in the United States, the United States was once the world leader in terrestrial silicon solar cell technology. Remnants of that expertise are still available that could be leveraged to help start domestic cell production. Georgia Institute of Technology has been a focus of advanced c-Si research and development (R&D) since the 1990s and Arizona State University operates a silicon-cell pilot line for research and training purposes. A challenge is that the United States has lagged in c-Si R&D over the past two decades, as evidenced by papers published at international PV conferences in the United States (IEEE PVSC) and Europe (EUPVSEC and SiliconPV). For advanced cell technology, most of the relevant intellectual property is held by organizations in China, Southeast Asia, and Europe. Even Australia funds more advanced R&D for c-Si cells than the United States.

Despite the global competition, c-Si cell technology is attractive to pursue domestically because the materials used are available in very large quantity, are mostly benign, and have demonstrated long-term durability. In a high-deployment scenario where multiple terawatts of PV are deployed globally, c-Si technology could face limited availability of silver, but only if the downward trend in Ag consumption per wafer that has been demonstrated over the past decade were to stagnate.

3.1.6 Inverter Design

The U.S. has always been the leader in developing global standards for communications, from Morse code to Wi-Fi. Inverters for PV require communication protocols to respond to emergencies, identify component failures, and optimize the performance of the grid. The country and companies that establish the new international standards for communication protocols will have a first-mover advantage, providing a window of opportunity to restore U.S. competitiveness in PV inverter design and manufacturing. Closely related to communications protocols is the opportunity to lead in cybersecurity. Domestic inverter manufacturers would have a market advantage by offering inverters having a reduced risk of containing embedded malware and other vulnerabilities to cyberattack.

Although inverters can be designed and assembled in the United States, the application-specific integrated circuits and semiconductor power-handling components are almost entirely produced in Asia. It will be challenging to significantly reduce the risk of foreign interference in inverters unless the embedded electronic components are also produced in the United States. Efforts by several large industry sectors to onshore application-specific chip production would reduce the supply risk for solar inverters, as well.

Recent advances have resulted in the more widespread adoption of SiC based power electronics, which have many advantages, including a higher power conversion efficiency and the ability to handle more power (Thangavel 2021). As of 2016, the United States (along with Europe and Japan) manufactured a significant portion of SiC components. The United States does not currently have manufacturing capacity for mounting the bare SiC devices into a saleable product, but the U.S. could become an exporter of SiC wafers and devices to Asian countries that currently perform this packaging.

3.1.7 Perovskite Modules

Perovskites are a class of crystalline structures with three components, two of which are typically single atoms and the third can be either an atom or a small molecule. The set of perovskite materials in which the small molecule is organic and the other two atoms are a metal and a halide have shown remarkable progress in solar energy conversion efficiency for small-area devices in laboratory settings, climbing from 15% in 2012 to over 25% in 2020, and tandem cells pairing a perovskite top cell with a silicon bottom cell have achieved nearly 30% (NREL n.d.). Perovskites have not been commercialized because the cell efficiency decreases rapidly with increasing cell size (presumably due to spatial nonuniformity) and, more importantly, the devices degrade when exposed to simultaneous combinations of heat, light, and water vapor. To date, there has been no publicly reported result of a perovskite minimodule efficiency over 15% after one month of outdoor operation.

The key to enabling domestic production of perovskite cells is to be the first to discover a way to make full-size modules that are inherently durable outdoors without sacrificing either cost or performance.

The United States would benefit from being the first to commercialize perovskite technology, but the challenges are four-fold: (1) It would be unprecedented to develop PV technology in such a short period of time as to have a significant market impact in the timeframe required for decarbonization by 2035. The development timeline for all commercially successful PV technologies to date has been measured in decades, not years. (2) Maintaining support for technology development over decades requires evidence of commercial success along the way. Perovskites have not yet found a niche market to support early commercialization. (3) The perovskite devices that have shown the highest levels of performance contain water-soluble lead. Either an adequate replacement for lead must be identified or a highly reliable means of preventing the lead from leaching into the environment must be developed. (4) The United States faces intense competition from China, Europe, and Japan in the commercialization of perovskites. Europe was an early leader in perovskite research and one company based in the United Kingdom claims it will start operating a 100 MW_{dc} production line in Germany in 2022 (Oxford PV 2021). GCL in China has been operating a 10 MW_{dc} perovskite production line since 2019 with announced plans for 100 MW_{dc} (GCL 2019), though with no sales reported to date.

3.1.8 Kerfless Wafers

Sawing wafers wastes about one-third of the silicon ingot as sawdust (“kerf”). Since the 1980s, this has motivated a search for alternatives that avoid the sawing step altogether. The approaches tried to date fall into four groups: (1) Pull ribbons out of a molten bath of silicon, using various techniques to maintain the shape of the ribbon. (2) Grow silicon films from molten silicon on dissimilar substrates. (3) Deposit silicon from the gas phase onto substrate silicon wafers and subsequently removing the substrate for reuse. (4) Cleave the silicon ingot instead of sawing it. To date, none of these methods have been commercially successful relative to of conventional ingot growth and wire sawing. However, researchers continue to explore variations on each of the above themes because the cost advantage if successful is substantial and market acceptance is almost certain for any wafer that meets the specifications of cell producers.

3.1.9 Concentrating Solar Thermal Power

One way to avoid the supply-chain risks in the solar PV supply chain is to use a technology other than photovoltaics to convert sunlight into electricity. Concentrating solar thermal power uses tracking structures to support mirrors instead of PV modules. The mirrors, which can be readily produced domestically, focus sunlight onto a receiver, where it heats a material that drives a turbine-generator. The hot material can be stored inexpensively to drive the generator after the sun sets. Approaches using focused sunlight only work well when the sky is essentially free of haze or clouds, so they are limited to arid regions like the southwestern United States. First-generation approaches used linear parabolic mirrors to heat oil or water. Second-generation approaches used a field of mirrors focused on a central receiver tower to heat molten salt. These early attempts had technical success but have not been economically competitive. A third generation of the central-receiver approach could supplement PV to help achieve decarbonization goals if the turbine generator can be operated at a higher temperature to increase its energy conversion efficiency.

3.2 Current Policies in the United States

3.2.1 Incentives

At the federal level, the United States has implemented many measures to encourage domestic PV manufacturing. The American Recovery and Reinvestment Act of 2009 (ARRA) included a tax credit for investments in manufacturing facilities for clean energy technologies. The Section 48C Advanced

Manufacturing Tax Credit originally provided a 30% investment tax credit to 183 domestic clean energy manufacturing facilities valued at $2.3 billion (DOE 2012). However, many of the tax credits awarded were not claimed, either because rapidly changing market conditions led the awardee not to proceed or because they were unable to generate a taxable profit.

ARRA also included the Section 1705 Loan Program, which expanded the authority of the DOE Loan Programs Office (LPO). The LPO received 42 applications for solar manufacturing projects, performed due diligence on 16, provided a conditional commitment to 5, and closed 4 transactions for $1.3 billion. Due in large part to the significant time it took to close these transactions and the rapid reduction in PV module prices over the same period, the 4 transactions were not successful, with two of the recipients going bankrupt and the other two not moving forward with the loan.

The United States has also encouraged U.S. PV manufacturing using federal procurement. Part of this is simply increasing domestic solar demand, helped by GW-level commitments by each of the armed forces. The United States Agency for International Development (USAID) requires that at least 50% of renewable energy technology procured be manufactured in the United States (CRS 2021).

At state and municipal levels, policies intended to support domestic PV manufacturing have included grants, tax exemptions, land provision, and consumer incentives for purchasing domestic PV products (B. L. Smith et al. 2021; Feldman, Smith, and Margolis 2020). Consumer incentives for locally-made or domestic products have consistently been ruled to be in violation of international trade law (Trachtman 2019).

3.2.2 Tariffs

The United States has attempted to support domestic PV manufacturing through the implementation of several tariffs over the past 10 years. Its first two sets of tariffs, in 2012 and 2014, were Antidumping and Countervailing Duties (AD/CVD) placed on Chinese (and to a lesser extent Taiwanese) PV modules and cells. This resulted in Chinese companies shifting manufacturing to Southeast Asian countries, while U.S. PV manufacturing continued to contract, with many businesses closing or filing for bankruptcy.

The United States has also instituted AD/CVD on imported MGS. In 2018, the United States Department of Commerce (DOC) instituted AD/CVD, ranging from 2% to 100%, on MGS coming from Australia, Brazil, Kazakhstan, and Norway (Reuters 2018). In 2021, DOC determined that dumping was occurring in the United States from Malaysia, Bosnia and Herzegovina, Iceland, and Kazakhstan. The United States International Trade Commission affirmed that U.S. industry was injured as a result, leading DOC to institute tariffs up to 160% (U.S. International Trade Commission 2021; International Trade Administration 2021).

In 2018, the U.S. government put in place a 4-year safeguard tariff (Section 201 tariff) on nearly all imported PV cells and modules, exempting the first 2.5 GW_{dc} of PV cells to support domestic module assembly, plus additional tariffs (Section 301 tariff) on Chinese products, including solar products. The Section 201 tariff, which started at 30% and reduced to 15% in its final year, is credited with an increase in domestic PV module assembly, though it has not resulted in expanded U.S. PV cell manufacturing. The tariffs are also credited as a major factor in the recent scale-up of U.S. PV thin-film CdTe module manufacturer, First Solar, which benefits from the increased market price of competing c-Si PV modules.

From October 2020 until November 2021, modules that generated power when illuminated from either the front or back surface (bifacial) were excluded from the Section 201 tariff. Bifacial modules are primarily used in utility-scale PV systems. The bifacial exemption was retained when the tariff was extended for an additional four years in February 2022, and the exempted cell quota was increased from 2.5 GW_{dc} to 5 GW_{dc}.

The cumulative effects of the AD/CVD, Section 301, and Section 201 tariffs on different imports are shown in Figure 78.

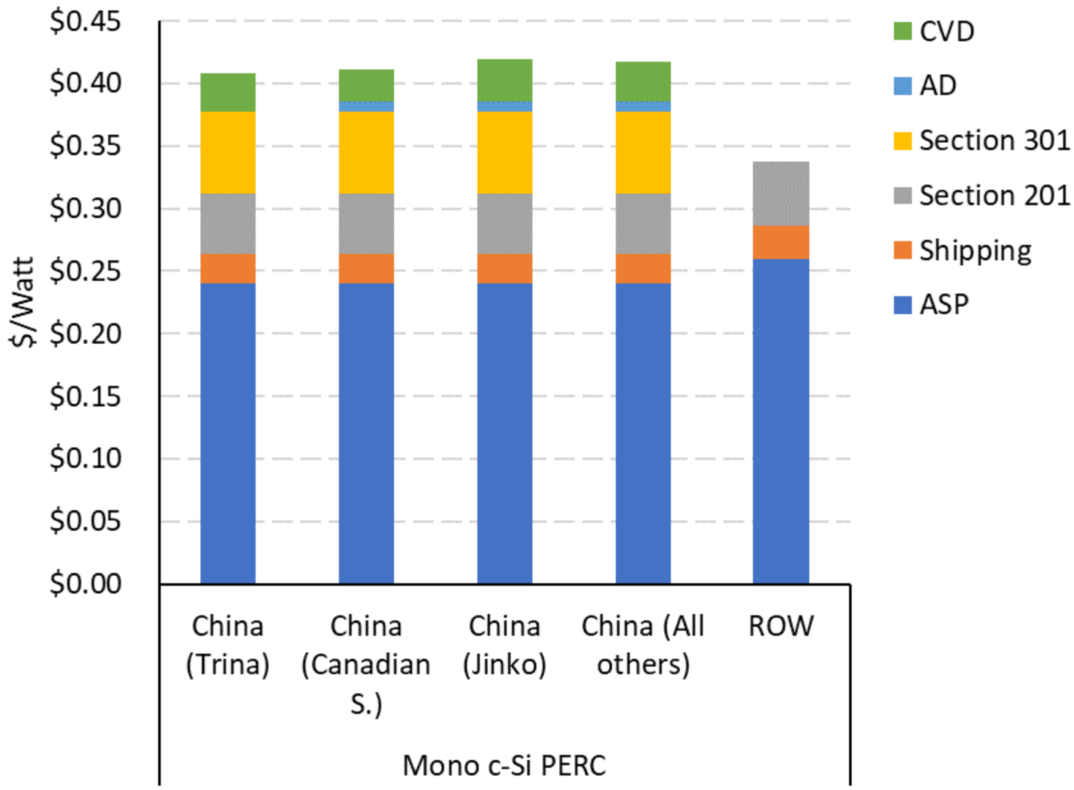

Figure 78. Impacts of U.S. tariffs on imported module prices.

Source: NREL

Though many U.S. PV manufacturing facilities have cited PV tariffs as a strong motivator for establishing U.S. capacity, this was offset to some degree by Section 301 and Section 232 tariffs on ancillary components upstream in the PV supply chain (B. L. Smith et al. 2021). An example of these tradeoffs is shown in Figure 79, illustrating that Section 301 and Section 232 tariffs add about 17% to the cost of domestic module assembly, which is similar to the Section 201 tariff on imported modules. Similarly, Section 301 and Section 232 tariffs were reported to make the commissioning of new manufacturing capacity less financially viable due to reliance on imported equipment and raw metal. Extruding PV racking domestically was also reported to become unprofitable due to Section 232 tariffs on raw metal. As a result, fully extruded products were imported instead (B. L. Smith et al. 2021).

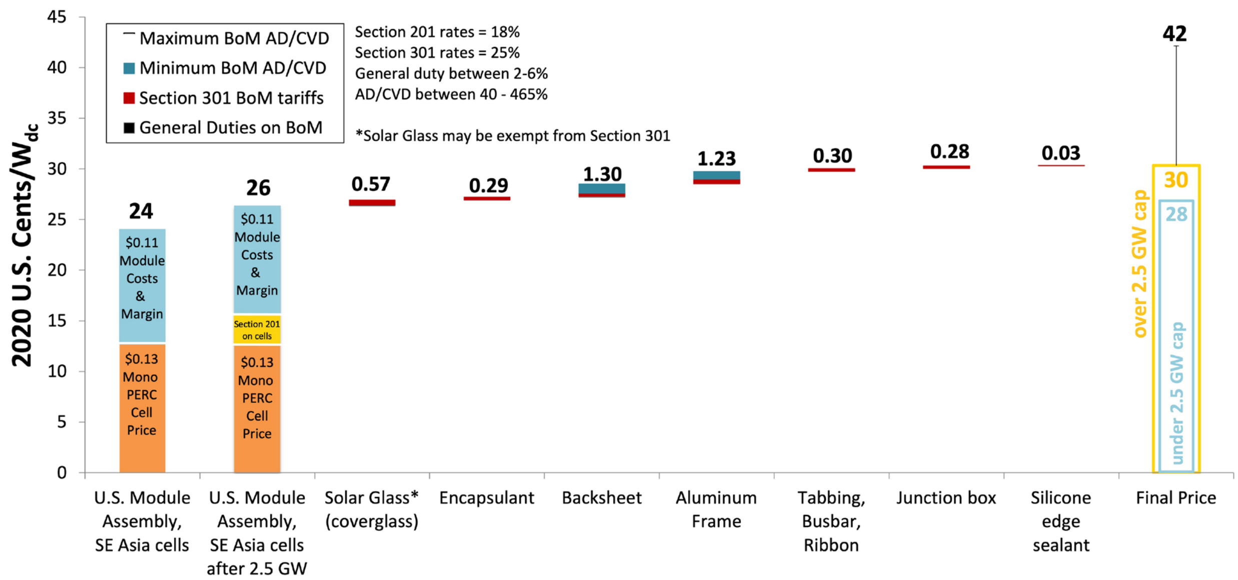

Figure 79. Tariff effects on U.S. module assembly.

Source: NREL

3.2.3 Withhold Release Order

A Withhold Release Order (WRO) requires U.S. Customs and Border Protection (CBP) to detain shipments upon arrival into the United States that CBP considers at risk of containing material from a prohibited source until the importer provides evidence that the detained shipment does not contain material from that source. In June 2021, CBP issued a WRO against shipments containing material produced from silica-based products made by the Chinese company Hoshine Silicon Industry Co. Ltd and its subsidiaries (CBP 2021). The WRO was issued following reports by Horizon Advisory and then Sheffield Hallam University that linked Hoshine to forced labor in the Chinese province of Xinjiang. The Hoshine WRO is part of a larger U.S. government effort addressing forced labor in Xinjiang. In January 2021, the CBP also issued a WRO on cotton and tomatoes from Xinjiang.

Hoshine is the world’s largest producer of metallurgical-grade silicon (MGS), also known as silicon metal. MGS is the primary feedstock for making refined polysilicon that, in turn, is the primary feedstock for producing c-Si PV cells and modules. Hoshine’s silica-based products are also used in a wide variety of other industries, including the production of aluminum alloys, stainless steel, silicone adhesives, and cosmetics. In 2017, 12% of MGS globally went to the solar industry (Chalamala 2018), but the fraction of Hoshine’s production used in the silicon solar supply chain has not been reported.

PV companies have reported that it has been difficult for c-Si producers to prove that their cells and modules contain no Hoshine MGS. The American Clean Power Association, a solar trade organization, polled major module suppliers that import from Southeast Asia in December 2021 and reported to DOE that c-Si module imports in 2021 were reduced by 7 GW$_{dc}$ from the expected 25 GW$_{dc}$ as a direct result of the Hoshine WRO. This 7 GW$_{dc}$ is comprised of 1.5 GW$_{dc}$ that was held at ports of entry (and could eventually be released or diverted to other countries), 1 GW$_{dc}$ that was already diverted to other countries, and 4.5 GW$_{dc}$ that was never produced because of the uncertainty of suppliers’ ability to import manufactured goods to meet demand. The impact of the Hoshine WRO on imported solar products could be even greater in 2022 if efficient MGS traceability is not established.

3.2.4 Uyghur Forced Labor Prevention Act

The Uyghur Forced Labor Prevention Act (UFLPA) is a bipartisan bill that passed without opposition in both the House and Senate and was signed into law in December 2021. It prescribes a period of public comment, followed by a public hearing, and then the development of a strategy for "how best to ensure that goods mined, produced, manufactured wholly or in part with forced labor in the People's Republic of China, including by Uyghurs, Kazakhs, Kyrgyz, Tibetans, and members of other persecuted groups in the People's Republic of China, and especially in the Xinjiang Uyghur Autonomous Region, are not imported into the United States." The UFLPA assigns the Forced Labor Enforcement Task Force (FLETF), which was created under the United States-Mexico-Canada Agreement, to create an enforcement plan that includes (but is not limited to) the use of WROs by CBP. Polysilicon, tomatoes, and cotton are listed as high-priority sectors for enforcement.

The law presumptively prohibits all products either originating in Xinjiang or produced by companies that participate in Chinese government poverty-alleviation or pairing-assistance programs. FLETF is tasked with creating a list of these entities, developing an enforcement plan, and prescribing a process for exemption based on effective supply-chain tracing to prove with "clear and convincing evidence" that an entity's goods are not produced using forced labor. The impact of UFLPA on the solar supply chain is not yet known but could be profound over the years that UFLPA is in effect (2022 – 2029) if the Chinese government prevents solar companies from providing the documentation required by FLETF to prove their goods are compliant.

3.3 Current Policies in Other Countries

In 2014, China finalized duties on imported polysilicon from the United States and South Korea for 5 years, made adjustments in 2017, and then extended the tariffs for another 5 years in 2019 (Bellini 2020). The duties against the U.S. were related to the Internal Revenue Service (IRS) 48C tax credit. Duties were also imposed on South Korea to further protect China's emerging polysilicon industry.

As shown in Table 6, the average Chinese tariff on U.S. polysilicon is ~55%, which would add $0.015 – $0.05/watt. As a result, most U.S. polysilicon capacity has been idled or is significantly underutilized. The tariff on South Korean polysilicon ranges from 4.4% to 113.8%. As a result, most South Korean polysilicon manufacturers shuttered their solar-grade silicon facilities. China did not impose duties on European polysilicon (namely Germany's Wacker) due to a trade agreement signed in 2013.

Before 2014, "processing trade" rules had allowed Chinese manufacturers to avoid Chinese import tariffs if the finished product was exported, but China's Ministry of Commerce closed the duty-free loophole.

Table 6. Chinese duties on U.S. and South Korean polysilicon.

	AD Duties	CVD	Total Duties
U.S. Companies			
REC Solar	57.0%	0.0%	57.0%
Hemlock	53.3%	2.1%	55.4%
MEMC/SunEdison	53.6%	0.0%	53.6%
AE Polysilicon	57.0%	2.1%	59.1%
Remaining companies	57.0%	2.1%	59.1%
South Korean Companies			
Woongjin Polysilicon	12.3%		
OCI	4.4%		
Hanwha	8.9%		
SKSS	9.5%		
KCC / Korean Advanced Materials/Innovation Silicon	113.8%		
Remaining companies	88.7%		

Source: USTR

Both France and South Korea have implemented regulations regarding the carbon emissions associated with the manufacture of PV modules. South Korea requires a determination of carbon footprint to determine which modules qualify for government subsidies (Stoker 2020), while France uses carbon footprints as a cutoff for bids to qualify for public tenders.

The European Union imposed duties on Chinese wafers, cells, and modules starting in 2013, but it allowed manufacturers to avoid such duties if they capped imports and sold products at a minimum price. The EU let this measure lapse after five years to support Europe's desire to increase renewable energy deployment (Blenkinsop 2018).

In 2021, India announced it would place a duty of 40% on all imported modules and a 25% duty on all imported cells, starting in April 2022. These duties are scheduled to replace the 15% safeguard duties currently in place on PV imports from China and Malaysia (Bhaskar 2021).

In 2015, Canada placed duties on Chinese crystalline and thin-film modules to protect its domestic module manufacturing lines (Beetz 2015). These duties were extended in 2021 for 5 years.

3.4 Policy Actions

Significant financial support and incentives from the U.S. government as well as strategic actions focused on workforce, manufacturing, human rights, and trade will facilitate a global solar industry aligned with U.S. interests and the reestablishment of robust U.S. domestic solar manufacturing leadership –thus leading to tremendous benefits for the climate as well as for U.S. workers, employers, and the economy. Below include vital policy strategies for the executive branch as well as recommendations for Congress to level the playing field for U.S. manufacturers. These include recommendations for Congress to consider that would directly address the biggest barrier to manufacturing growth – the higher costs of manufacturing in the U.S. Also included below are important policy actions that the U.S. government is either already engaging in or planning to launch. Several other policy actions and more detail will be included in the full DOE Energy Supply Chain Policy Strategy Report being released February 24, 2022.

3.4.1 Policy Recommendations for the Legislative Branch

Enact legislation to provide tax incentives to support domestic clean energy manufacturing, including incentives for building new facilities, for the ongoing operation of those facilities, and for domestic content

Tax incentives are needed to provide a clear demand signal and help U.S. manufacturers build and maintain a competitive edge in clean energy technologies such as solar photovoltaics. To reestablish domestic solar manufacturing in the U.S., companies that produce and sell solar components will require financial support to offset the 30 – 40% higher cost of domestic solar production. Expansion of ingot and wafer production should receive the highest incentive because nearly all the world's capacity exists inside China, and expansion in these sectors would have the compounding effect of creating demand for existing U.S. polysilicon producers to run at full capacity. These tax credits should be enacted for at least a decade to provide the long-term signal for companies to establish new production facilities. Renewal for some time thereafter, perhaps at a reduced level, could be required to maintain domestic competitiveness. Specific actions recommended to Congress for solar power and other clean energy technologies include:

- To directly address the higher costs of domestic production, establish investment-based and production-based manufacturing tax incentives specifically targeting critical aspects of the domestic supply chain, inclusive of materials, components, and logistics. Prioritize silicon ingot and wafer production. The levels for these incentives should be chosen to fully offset the higher costs of domestic production. For silicon ingot and wafer production, which is most difficult to locate outside of China, incentives should be significantly greater than the cost differential to give the best chance of establishing domestic production.

- To accelerate the establishment of new manufacturing capacity, extend, expand, and revise eligibility for advanced energy manufacturing tax credits (e.g., IRS 48C) to include material processing facilities such as those for equipment manufacturing facilities such as solar polysilicon, wafers, cells, modules, and other components.

- As proposed in the Build Back Better Act passed by the House of Representatives in 2021, the federal government could offer bonuses for sufficiently high domestic content on government-supported energy projects (e.g., those projects receiving investment or production tax credits) and penalties if domestic content requirements are not met by the end of 2025.

- #### Enact legislation to encourage domestic demand and deployment

Extend and revise credits for clean energy deployment, such as the Production Tax Credit (PTC) and Investment Tax Credit (ITC) to provide stronger incentives for clean energy projects that support domestic manufacturing and a major increase in family-sustaining jobs. Though policies in support of domestic manufacturing facilities exist or have been proposed,[5] such demand-side incentives may be necessary to stimulate deployment of components manufactured domestically. To provide demand certainty in support of domestic manufacturing investment, these tax credits should be in place for at least 10 years and should not phase out until significant progress has been made toward domestic competitiveness and decarbonization goals.

3.4.2 Policy Strategies Planned for the Executive Branch

Promote adoption & implementation of traceability standards to improve global supply chain mapping capabilities, instill integrity of product custody, and promote social responsibility of energy supply chains (DOS, DOE, DOC, DOL, EPA, CBP, NASA, DOD)

In June 2021, Customs and Border Patrol (CBP) issued a withhold release order (WRO) against shipments containing silica-based products made by Hoshine Silicon in Xinjiang, a supplier to polysilicon suppliers, in response to evidence of forced labor practices. In December 2021, President Biden signed the Uyghur Forced Labor Prevention Act (UFLPA) into law, which imposes importation limits on goods produced using forced labor in China, especially the Xinjiang Uyghur Autonomous Region. Building on existing interagency efforts and to implement UFLPA requirements, the U.S. government will work with the solar industry to promote implementation of supply chain traceability that provides information about the materials and companies composing the supply chain for solar products.

Enhance coordination of trade policy across the U.S. government to create fair conditions for the U.S. solar industry and its workers (DOC, USTR, DOE)

U.S. solar manufacturers have too often faced unfair – and illegal – competition from firms that benefit from foreign, non-market practices such as dumping. The United States has responded with trade remedies designed to protect domestic manufacturing. Transparent, effective coordination and implementation of these policies is critical to supporting domestic manufacturing as well as clean energy deployment. The U.S. government will continue to conduct expert analysis and engage with relevant stakeholders to refine implementation of trade policies to optimize their effectiveness in leveling the playing field across the supply chain, while removing barriers to solar deployment.

Leverage federal purchasing power to provide a sustained demand signal for both domestic clean energy products and the capability to manufacture them domestically (DOE, DOD, GSA, SBA, EPA)

Specific actions include: 1) Whenever possible, require domestic content standards for federal procurement of solar PV systems – including extending Buy American provisions to support domestic content in solar facilities from which electricity is procured, and 2) Leverage the authorities of federal agencies to provide a strong demand signal for domestic clean energy manufacturing of solar components.

Convene multiple workforce stakeholders to advance energy workforce development (DOL, ED)

U.S. government will develop targeted sector-based plans (including solar power) that will include convening federal agencies, regional employers, state and city governments, labor unions, training partners, and NGOs to advance skill-adjacent training and registered apprenticeships that will support the large-scale training needs of energy workers and employers in the solar industry and other clean energy arenas.

[5] For example, §20302 of the proposed America COMPETES Act of 2022 authorizes $3 billion for DOE to provide grants and direct loans for new and existing facilities that manufacture solar components.

Raise awareness, coordinate, and expand manufacturing programs (SBA, DOE, DOC, DOD, DOL) For example:

- The U.S. Small Business Administration (SBA) will expand support to Small and Medium Enterprises (SMEs) and will expand the 504-loan program to include supply chain financing for small businesses with the working capital and longer repayment terms they need to pay suppliers upfront, access discounts, and command more attention from suppliers to fulfill orders.

- DOE Loan Programs Office (LPO) will provide federal loan guarantees to solar manufacturers to incentivize them to build their supply chains in the United States. LPO will further leverage flexibility provided by the Infrastructure Investment & Jobs Act to co-finance or guarantee state-backed projects that have been previously too small to apply to LPO directly.

- DOE and other agencies will expand, within their authorities, competitive grants that support domestic manufacturing capabilities for solar components and job creation potential. Grants will focus on key areas that build on U.S. capabilities and developing markets for solar power.

Establish and fund an initiative for expanding clean technology manufacturing capacity globally to achieve the dramatic scale-up in manufacturing of key climate and clean energy equipment associated with meeting net-zero commitments (DOE, DOS, DFC, EXIM, USTDA, DOC)

The global market for clean technologies including solar photovoltaics—if we are to meet global climate goals—is simply much larger than the U.S. can fulfill alone. Supporting global development of solar capacity needed with key partners and allies and in accordance with principles and standards supported by the Build Back Better World initiative can help secure more resilient, diversified, and sustainable supply chain sourcing to meet global climate goals. Specific actions will include:

- Leverage bilateral and multilateral energy dialogues to promote: the expansion of like-minded manufacturing capacity; the creation of research partnerships between labs and foreign academic institutions in support of a net zero manufacturing accelerator network; and development of relevant workforce capacity.

- Examine gaps in domestic manufacturing and align with global locations conducive to the development of clean energy technology manufacturing. Additionally, expand technical assistance in partner countries to facilitate development of clean technology supply chain and manufacturing capacity.

- Convene financial institutions to assess available resources and develop uniform criteria for supporting clean energy manufacturing projects.

Engage government and private sector to continue to support solar technology innovation from research to commercialization to recycling (DOE)

To ensure secure, resilient supply chains for decades to come, it is critical that the United States lead in innovating, commercializing, and scaling the next generation of solar technologies while continuing to advance existing technologies. It takes decades from invention and initial demonstration to successful commercialization and scaling of a technology or a process. In addition, investments are needed to support innovation across the full life cycle, including recycling. DOE will continue to invest through financial assistance for research, development, and demonstration, LPO direct loan and loan guarantees, as well as partnering with other agencies to facilitate successful development and transfer of technology to the solar industry.

Appendix

Stakeholder Outreach

The following stakeholders outside DOE provided input to senior leadership in DOE's Solar Energy Technologies Office related to the challenges presented in this report and to express their interest in participating in the solutions proposed. The dates shown are for teleconferences in 2021 that influenced this document. Several of these organizations also responded to DOE's Request for Information (RFI).

Organization	Teleconference Date(s) in 2021
Private Sector	
American Clean Power Association	7/27, 8/27, 12/8
Canadian Solar	RFI
Center for Strategic and International Studies	4/15
Clean Energy Associates	11/19
Clearway	5/27, 9/2
Coalition for a Prosperous America	3/11
EnPhase	8/24
First Solar	3/17, RFI
Hanwha Q-Cells America	3/17, 3/18, 7/15, 8/30, 12/3, RFI
Heliene	RFI
Hemlock Silicon	3/17, 11/17, RFI
LG Electronics	3/17
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List of Acronyms

ac	alternating current
AD	antidumping
Al-BSF	aluminum back surface field (c-Si PV cell structure)
ASP	average selling price
ARRA	American Recovery and Reinvestment Act
CBP	United States Customs and Border Protection
CdTe	cadmium telluride (PV module technology)
c-Si	crystalline silicon (PV module technology)
CVD	countervailing duties
Cz	Czochralski (silicon ingot growth method)
dc	direct current
DFC	United States International Development Finance Corporation
DOC	United States Department of Commerce
DOD	United States Department of Defense
DOE	United States Department of Energy
DOL	United States Department of Labor
DOS	United States Department of State
DS	directional solidification (silicon ingot growth method)
ED	United States Department of Education
EPA	United States Environmental Protection Agency
EVA	ethylene vinyl acetate (PV module encapsulation material)
EXIM	Export-Import Bank of the United States
FBR	fluidized bed reactor (polysilicon refining method)
GSA	United States General Services Administration
GW_{dc}	gigawatts (dc power rating under standard test conditions)
IGBT	insulated-gate bipolar transistor

IRS	United States Internal Revenue Service
ITC	Investment Tax Credit
ITRPV	International Technology Roadmap for Photovoltaics
LPO	DOE Loan Programs Office
kW_{dc}	kilowatts (dc power rating under standard test conditions)
kWh	kilowatt-hour (units for electrical energy)
MGS	metallurgical-grade silicon (silicon metal)
MT	metric tonne (1000 kg)
MW_{dc}	megawatts (dc power rating under standard test conditions)
NASA	National Aeronautics and Space Administration
NREL	National Renewable Energy Laboratory
PERC	passivated emitter and rear cell (c-Si PV cell structure)
PET	polyethylene terephthalate (a form of polyester)
POE	polyolefin elastomers (PV module encapsulation material)
PTC	Production Tax Credit
PV	photovoltaic (adjective) or photovoltaics (noun)
PVDF	polyvinylidene fluoride (PV module backsheet material)
PVF	polyvinyl fluoride (PV module backsheet material)
ROW	rest of world
SBA	United States Small Business Administration
SiC	silicon carbide (power electronics device material)
USAID	United States Agency for International Development
USGS	United States Geological Survey
USTDA	United States Trade and Development Agency
USTR	United States Trade Representative
WRO	withhold release order

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