Special Report on Solar PV Global Supply Chains

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Abstract

Solar PV is a crucial pillar of clean energy transitions worldwide, underpinning efforts to reach international energy and climate goals. Over the last decade, the amount of solar PV deployed around the world has increased massively while its costs have declined drastically. Putting the world on a path to reaching net zero emissions requires solar PV to expand globally on an even greater scale, raising concerns about security of manufacturing supply for achieving such rapid growth rates – but also offering new opportunities for diversification.

This special report examines solar PV supply chains from raw materials all the way to the finished product, spanning the five main segments of the manufacturing process: polysilicon, ingots, wafers, cells and modules. The analysis covers supply, demand, production, energy consumption, emissions, employment, production costs, investment, trade and financial performance, highlighting key vulnerabilities and risks at each stage. Because diversification is one of the key strategies for reducing supply chain risks, the report assesses the opportunities and challenges of developing solar PV supply chains in terms of job creation, investment requirements, manufacturing costs, emissions and recycling. Finally, the report summarises policy approaches that governments have taken to support domestic solar PV manufacturing and provides recommendations based on those.

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Questions or comments?

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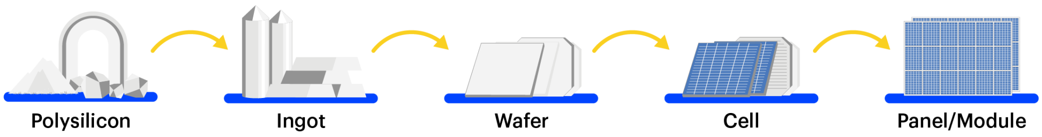
Executive Summary

China currently dominates global solar PV supply chains

Global solar PV manufacturing capacity has increasingly moved from Europe, Japan and the United States to China over the last decade. China has invested over USD 50 billion in new PV supply capacity – ten times more than Europe − and created more than 300 000 manufacturing jobs across the solar PV value chain since 2011. Today, China's share in all the manufacturing stages of solar panels (such as polysilicon, ingots, wafers, cells and modules) exceeds 80%. This is more than double China's share of global PV demand. In addition, the country is home to the world's 10 top suppliers of solar PV manufacturing equipment. China has been instrumental in bringing down costs worldwide for solar PV, with multiple benefits for clean energy transitions. At the same time, the level of geographical concentration in global supply chains also creates potential challenges that governments need to address.

Key stages in the main manufacturing process for solar PV



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Government policies in China have shaped the global supply, demand and price of solar PV over the last decade. Chinese industrial policies focusing on solar PV as a strategic sector and on growing domestic demand have enabled economies of scale and supported continuous innovation throughout the supply chain. These policies have contributed to a cost decline more than 80%, helping solar PV to become the most affordable electricity generation technology in many parts of the world. However, they have also led to supply-demand imbalances in the PV supply chain. Global capacity for manufacturing wafers and cells, which are key solar PV elements, and for assembling them into solar panels (also known as modules), exceeded demand by at least 100% at the end of 2021. By contrast, production of polysilicon, the key material for solar PV, is currently a bottleneck in an otherwise oversupplied supply chain. This has led to tight global supplies and a quadrupling of polysilicon prices over the last year.

Solar PV products are a significant export for China. In 2021, the value of China's solar PV exports was over USD 30 billion, almost 7% of China's trade surplus over the last five years. In addition, Chinese investments in Malaysia and Viet Nam also made these countries major exporters of PV products, accounting for around 10% and 5% respectively of their trade surpluses since 2017. The total value of global PV-related trade – including polysilicon, wafers, cells and modules – exceeded USD 40 billion in 2021, an increase of over 70% from 2020.

Today, electricity-intensive solar PV manufacturing is mostly powered by fossil fuels, but solar panels only need to operate for 4-8 months to offset their manufacturing emissions. This payback period compares with the average solar panel lifetime of around 25-30 years. Electricity provides 80% of the total energy used in solar PV manufacturing, with the majority consumed by production of polysilicon, ingots and wafers because they require heat at high and precise temperatures. Today, coal generates over 60% of the electricity used for global solar PV manufacturing, significantly more than its share in global power generation (36%). This is largely because PV production is concentrated in China – mainly in the provinces of Xinjiang and Jiangsu where coal accounts for more than 75% of the annual power supply and benefits from favourable government tariffs.

Continuous innovation led by China has halved the emissions intensity of solar PV manufacturing since 2011. This is the result of more efficient use of materials and energy – and greater low-carbon electricity production. Despite these improvements, absolute carbon dioxide (CO_2) emissions from solar PV manufacturing have almost quadrupled worldwide since 2011 as production in China has expanded. Nonetheless, solar PV manufacturing represented only 0.15% of energy-related global CO_2 emissions in 2021. As power systems across the world decarbonise, the carbon footprint of PV manufacturing should shrink accordingly. Transporting PV products accounts for only 3% of total PV emissions.

Concentration of PV supply chains brings vulnerabilities, posing potential challenges for the energy transition

Meeting international energy and climate goals requires the global deployment of solar PV to grow on an unprecedented scale. This in turn demands a major additional expansion in manufacturing capacity, raising concerns about the world's ability to rapidly develop resilient supply chains. Annual solar PV capacity additions need to more than quadruple to 630 gigawatts (GW) by 2030 to be on track with the IEA's Roadmap to Net Zero Emissions by 2050. Global production capacity for polysilicon, ingots, wafers, cells and modules would need to more than double by 2030 from today's levels. As countries accelerate their efforts to reduce emissions, they need to ensure that their transition towards a sustainable energy system is built on secure foundations. For solar PV supply chains to be able to accommodate the requirements of a net zero pathway, they will need to be scaled up in a way that ensures they are resilient, affordable and sustainable.

The world will almost completely rely on China for the supply of key building blocks for solar panel production through 2025. Based on manufacturing capacity under construction, China's share of global polysilicon, ingot and wafer production will soon reach almost 95%. Today, China's Xinjiang province accounts for 40% global polysilicon manufacturing. Moreover, one out of every seven panels produced worldwide is manufactured by a single facility. This level of concentration in *any* global supply chain would represent a considerable vulnerability; solar PV is no exception.

Solar PV's demand for critical minerals will increase rapidly in a pathway to net zero emissions. The production of many key minerals used in PV is highly concentrated, with China playing a dominant role. Despite improvements in using materials more efficiently, the PV industry's demand for minerals is set to expand significantly. In the IEA's Roadmap to Net Zero Emissions by 2050, for instance, demand for silver for solar PV manufacturing in 2030 could exceed 30% of total global silver production in 2020 – up from about 10% today. This rapid growth, combined with long lead times for mining projects, increases the risk of supply and demand mismatches, which can lead to cost increases and supply shortages.

The long-term financial sustainability of the solar PV manufacturing sector is critical for rapid and cost-effective clean energy transitions. The net profitability of the solar PV sector for all supply chain segments has been volatile, resulting in several bankruptcies despite policy support. Bankruptcy risk and low profitability could slow the pace of clean energy transitions if companies are unwilling to invest because of low returns or are unable to withstand sudden changes in market conditions.

Trade restrictions are expanding, risking slower deployment of solar PV. As trade is critical to provide the diverse materials needed to make solar panels and deliver them to final markets, supply chains are vulnerable to trade policy risks. Since 2011, the number of antidumping, countervailing and import duties levied against parts of the solar PV supply chain has increased from just 1 import tax to 16 duties and import taxes, with 8 additional policies under consideration. Altogether, these measures cover 15% of global demand outside of China.

Diversification can reduce supply chain vulnerabilities and offer economic and environmental opportunities

Recent disruptions have raised important supply chain questions. The Covid-19 crisis, record commodity prices and Russia's invasion of Ukraine have all focused attention on the high reliance of many countries on imports of energy, raw materials and manufacturing goods that are key to their supply security. Countries can improve resilience by investing to diversify their manufacturing and imports.

New solar PV manufacturing facilities along the supply chain could attract USD 120 billion investment by 2030. Annual investment levels need to double throughout the supply chain. Critical sectors such as polysilicon, ingots and wafers would attract the majority of investment to support growing demand.

The solar PV industry could create 1 300 manufacturing jobs for each gigawatt of production capacity. The solar PV sector has the potential to double its number of direct manufacturing jobs to 1 million by 2030. The most job-intensive segments along the PV supply chain are module and cell manufacturing. Over the last decade, however, the use of automation and automated guided vehicles has increased labour productivity, thereby reducing labour intensity.

Diversification of supply chains and the decarbonisation of the power sector could rapidly reduce solar PV manufacturing emissions. Domestic manufacturing can reduce manufacturing CO_2 emissions if the local electricity mix is less carbon-intensive than in the exporting country. Europe holds the highest potential, given the considerable shares of renewables and nuclear in its power mixes, followed by countries in Latin America and sub-Saharan Africa that have strong hydropower output.

Diversifying solar PV supply chains will require addressing key challenges

Currently, the cost competitiveness of existing solar PV manufacturing is a key challenge to diversifying supply chains. China is the most cost-competitive location to manufacture all components of the solar PV supply chain. Costs in China are 10% lower than in India, 20% lower than in the United States, and 35% lower than in Europe. Large variations in energy, labour, investment and overhead costs explain these differences. Still, in the absence of financial incentives and manufacturing support, the bankability of manufacturing projects outside of panel assembly remains limited outside of China and few countries in Southeast Asia.

Low-cost electricity is key for the competitiveness of the main pillars of the solar PV supply chain. The diversification of highly concentrated polysilicon, ingot and wafer manufacturing would provide security-of-supply benefits. Electricity accounts for over 40% of production costs for polysilicon and nearly 20% for ingots and wafers. Around 80% of the electricity involved in polysilicon production today is consumed in Chinese provinces at an average electricity price of around USD 75 per megawatt-hour (MWh). This is almost 30% below the global industrial price average. Maintaining competitiveness in these segments requires that manufacturers have access to comparable or lower electricity costs.

Building solar PV manufacturing around low-carbon industrial clusters can unlock the benefits of economies of scale. Solar panel manufacturers can also use their products to generate their own renewable electricity on site, thereby reducing both electricity bills and emissions. Electricity-intensive solar manufacturing could be located near emerging industrial clusters (e.g renewable-based hydrogen), enabling them to benefit from cost-competitive renewable electricity. Meanwhile, economies of scale and vertical integration of manufacturing can reduce variable costs and further increase competitiveness.

Recycling of solar PV panels offers environmental, social and economic benefits while enhancing security of supply in the long term. If panels were systematically collected at the end of their lifetime, supplies from recycling them could meet over 20% of the solar PV industry’s demand for aluminium, copper, glass, silicon and almost 70% for silver between 2040 and 2050 in the IEA’s Roadmap to Net Zero Emissions by 2050. However, existing PV recycling processes struggle to generate enough revenue from the recovered materials to cover the cost of the recycling process.

Government policies are vital to build a more secure solar PV supply chain

High commodity prices and supply chain bottlenecks led to an increase of around 20% in solar panel prices over the last year. These challenges have resulted in delays in solar panel deliveries across the globe. Globally, policies to support solar PV to date have focused mostly on increasing demand and lowering costs. However, resilient and sustainable supply chains are also needed to ensure the timely and cost-effective delivery of solar panels worldwide. Governments therefore need to turn their attention to ensuring the security of solar PV supplies as an integral part of clean energy transitions. Countries should consider assessing their domestic solar PV supply chain vulnerabilities and risks – and developing strategies and actions to address them.

The IEA's five key policy action areas to ensure solar PV security of supply:

Diversify manufacturing and raw material supplies

- Move solar PV supply chain diversification up the policy agenda as an integral part of advancing clean energy transitions.
- Consider crafting an industrial policy while maintaining a commitment to principles of open and transparent markets and avoiding barriers to trade.
- Consider integrating solar PV manufacturing facilities in industrial clusters, near traditional energy-intensive plants or other larger renewable electricity consumers (green hydrogen or green steel consortia) to help aggregate demand.
- Diversify raw material and PV import routes to reduce supply chain vulnerabilities.

De-risk investment

- Facilitate investment in manufacturing, e.g. through finance and tax policies, and other measures to de-risk PV manufacturing investment.
- Tailor demand support policies (e.g. auctions) in order to take into account long-term financial sustainability across solar PV supply chain segments.
- Encourage public-private collaborations, e.g. involving research institutions and labs, and public clean energy funding to catalyse private investment.

Ensure environmental and social sustainability

- Strengthen international cooperation on creating clear and transparent standards, taking into account environmental and social sustainability criteria.
- Focus on skills development, worker protection and social inclusion across the solar PV supply chain. Adopt policies promoting employment standards and transparency in order to help improve working conditions.
- Ensure PV manufacturing facilities adopt low-carbon and material-efficient manufacturing practices.

Continue to foster innovation

- Expand research and development funds with the aim of further improving solar cell conversion efficiency and reducing raw material use and costs.
- Promote technology innovation in manufacturing processes that reduce material intensity, especially for critical minerals such as silver and copper.

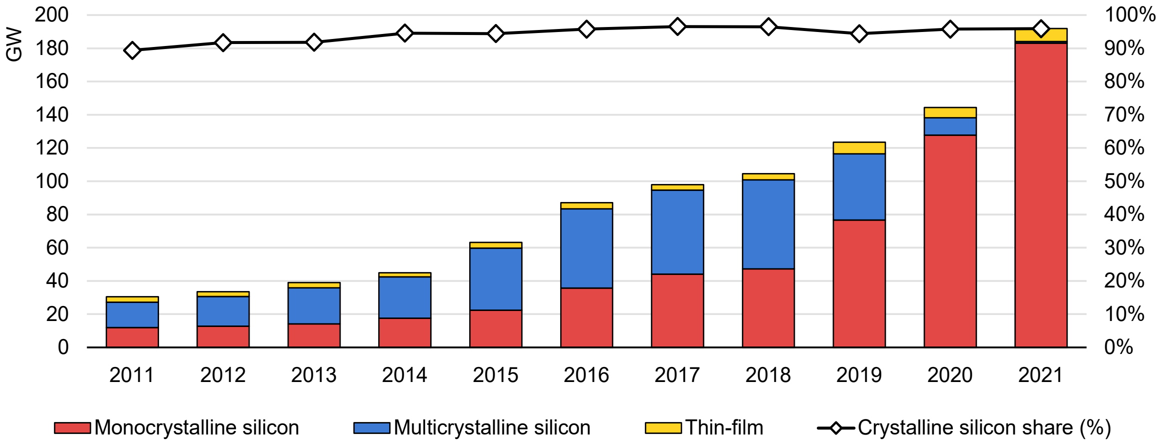
Develop and strengthen recycling capabilities

- Implement comprehensive regulatory frameworks to define stakeholder responsibilities and establish minimum requirements for collection and recycling.
- Support technology development efforts that improve recycling processes as well as solar PV panel design for recycling, reusability and greater durability.

Background and coverage

Two main technologies currently dominate global solar PV markets and supply chains: crystalline silicon (c-Si) modules account for over 95% of global production while cadmium telluride (CdTe) thin-film PV technology makes up the remaining.[1]

Solar PV module production by technology, 2011-2021



Source: IEA analysis based on BNEF (2022a), IEA PVPS, SPV Market Research, RTS Corporation and PV InfoLink.

For c-Si modules, high-purity silicon is manufactured by purifying metallurgical-grade (MG) silicon from quartzite and quartz pebble at high temperatures. High-purity or solar-grade silicon is then further purified, most often through the Siemens chlorination (i.e. gasification and chemical vapour deposition) process, or alternatively by a fluidised bed reactor (FBR) or an upgraded metallurgical-grade (UMG) silicon process. Next, purified solar-grade silicon is crystallised into monocrystalline silicon ingots through the Czochralski process or are cast into multicrystalline ingots, which are then sliced very thinly and cleaned to form wafers.

Silicon wafers are then transformed into solar cells using multiple methods, depending on the exact cell technology (at least 8 steps are involved for heterojunction cells, and 11 for TopCON cells). Steps include texturing, cleaning, doping, etching, and printing silver paste metal connections. The solar cells are then arranged on a backsheet, connected, and laminated with an encapsulating plastic

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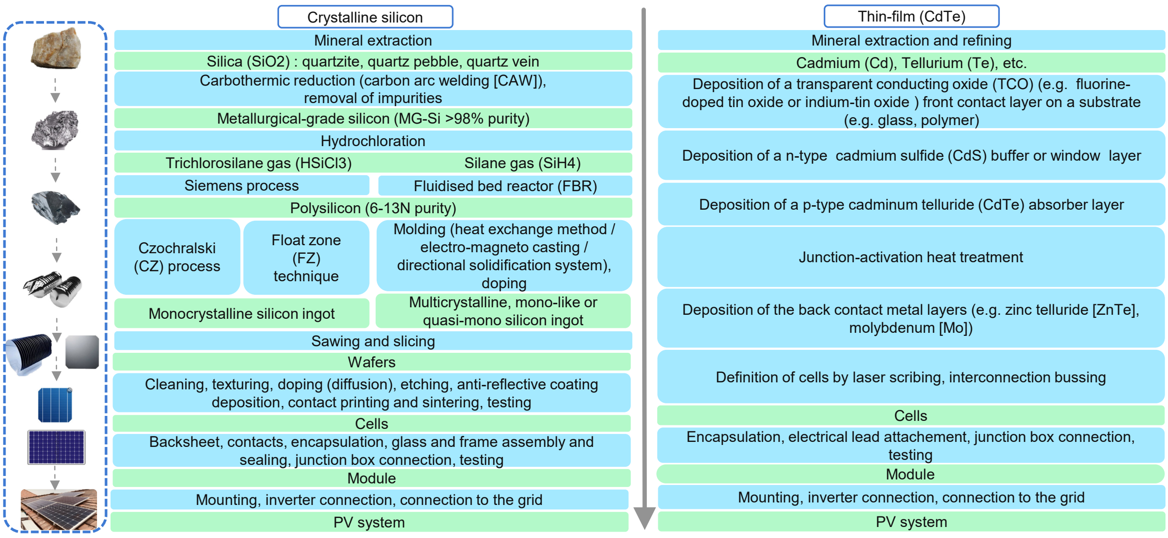
[1] A few other thin-film technologies exist, such as CIGS, a-Si and GaAs cells, but they do not currently represent a significant or growing market share globally, and some have only very specific applications (e.g. spatial for GaAs).

material (mainly ethylene vinyl acetate [EVA] or polyolefin elastomers [POE]). Modules are usually completed with the addition of front glass (as well as back and side glass, depending on the model), a junction box and an aluminium frame.

CdTe thin-film PV technology does not use polysilicon as its main material. Instead, the process starts by extracting and refining specific minerals, in particular cadmium and tellurium as by-products of zinc and copper mining and refining, and then proceeds to deposit a series of thin layers (transparent conductive oxide, an absorber layer, back contact, etc.), each a few micrometres thick, on a substrate, usually glass. Cells are then delimited by laser scribing or etching before being encapsulated, framed and covered. Both silicon and thin-film modules require a mounting structure, cables and inverters to be connected to the grid to start producing electricity.

Simplified manufacturing from raw materials for c-Si and CdTe solar PV systems



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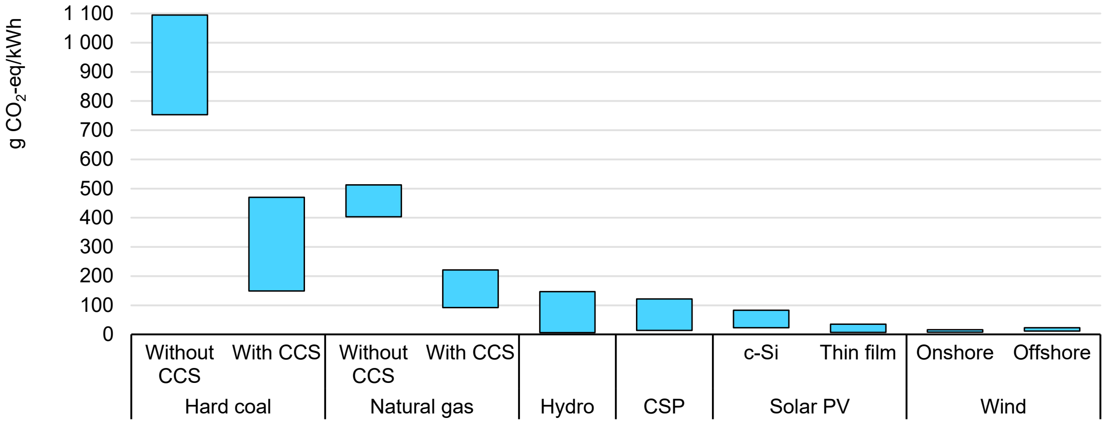
This report covers primarily supply, demand, production, energy consumption, CO_2 emissions, jobs, manufacturing costs, equipment, investment, trade and financial performance for the five main segments of solar PV manufacturing: polysilicon, ingots, wafers, cells and modules. The key focus is on c-Si technologies because of their currently high market share and expected dominance through 2030.

Lifecycle GHG emissions ranges for selected sources of electricity, 2020



Notes: CCS = carbon capture and storage. CSP = concentrated solar power. Ranges reflect regional variations.

Source: UNECE (2021) calculations based on data from Hertwich et al. (2016), Gibon et al. (2017) and Wernet et al. (2016). UNECE (2021) adapted these datasets based on recent scientific literature, technical reports and expert consultation.

Our analyses of energy consumption and CO_2 emissions do not aim to repeat or challenge lifecycle assessments (LCAs) of the solar PV sector. Many academic studies have already conducted in-depth LCA analyses and established that solar PV achieves some of the lowest lifecycle GHG emissions of all electricity-generating technologies, especially compared with fossil fuel-based ones. Instead, our report focuses more specifically on energy consumption and CO_2 emissions within the manufacturing process (for polysilicon, ingots, wafers, cells and modules), but only for the production stages that involve the semiconductor material. This report therefore does not analyse upstream energy consumption or emissions from raw material mining, or from manufacturing non-semiconductor intermediate products involved in PV module assembly (glass, cables, etc.). We do, however, offer additional analysis of cross-country transport of polysilicon, wafers, cells and modules as part of our comparative assessment of trade and manufacturing emissions. We also cover raw materials, including critical minerals, from the perspective of energy security.

Chapter 1 – Solar PV manufacturing today

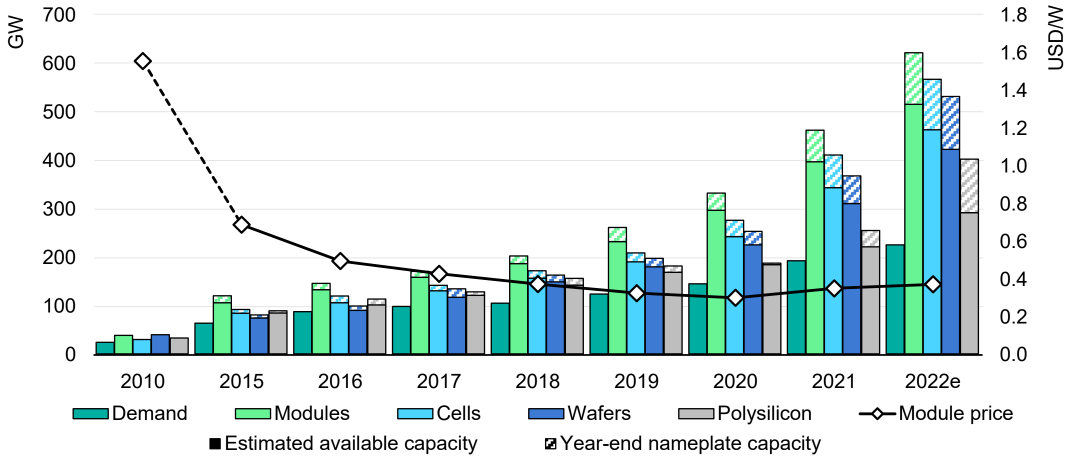
Capacity and production

Polysilicon production is currently a bottleneck in an otherwise oversupplied PV value chain

Solar PV supply chain expansion has outpaced rapid demand growth in the last decade, with crystalline silicon technology dominating the market at over 95% of installed capacity in the last five years. At the end of 2021, global capacity for manufacturing wafers and cells and for assembling modules exceeded demand by at least 100%. Even though 30-40% of current manufacturing capacity was commissioned before 2018 and may therefore require modernisation to produce components compatible with the latest module technology standards, markets for wafers, cells and modules will still be significantly oversupplied.

In contrast, the polysilicon supply glut that began in 2015 has ended, with the supply-demand balance becoming tight once again in 2021. Based on the manufacturing projects currently under construction, name plate polysilicon production capacity is expected to reach around 400 GW by the end of this year. However, considering production ramp-up times and maintenance schedules, only a portion of this new capacity will be available throughout 2022 and as a result, polysilicon supply could remain tight.

Global PV manufacturing capacity, demand and average module selling price, 2010-2022



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Note: Module price reflects all-in global average price for all solar PV technologies. Values for 2022 are estimates.

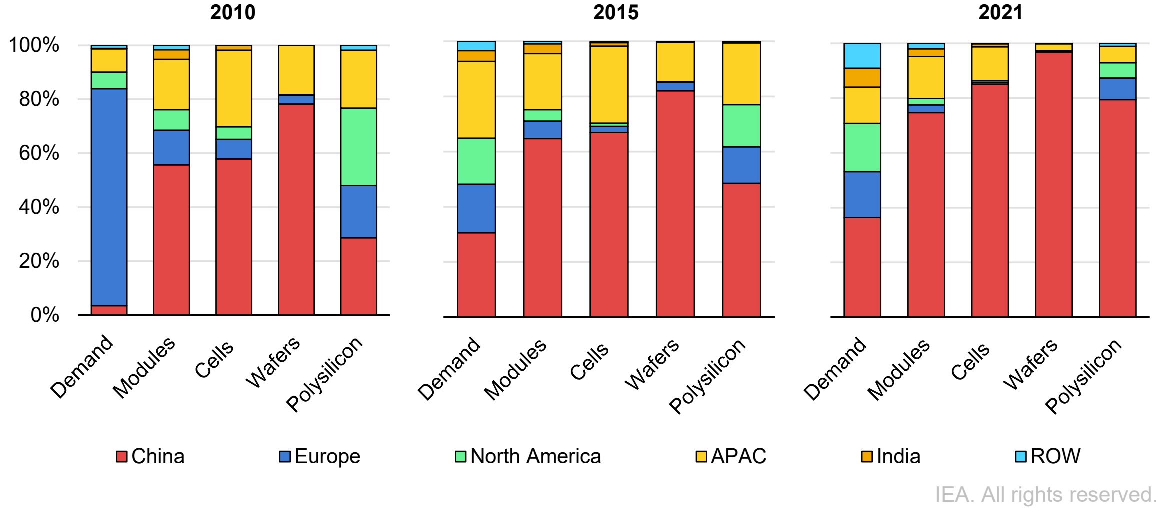
Source: IEA analysis based on BNEF (2022a), IEA PVPS, SPV Market Research, RTS Corporation and PV InfoLink.

Economies of scale and continuous innovation throughout the supply chain have enabled steep drops in manufacturing costs at every step of the production process. As a result, module prices fell more than 80% in the last decade and solar PV has become the most affordable electricity generation technology in many parts of the world. In 2021, the average selling price of modules increased for the first time – by around 20% compared with 2020 – due to higher commodity and freight prices. While module prices remained elevated in the first half of 2022, continuous innovation to further improve material and energy efficiency are expected to drive cost reductions. Nevertheless, price drops in the short term will depend upon the easing of commodity, polysilicon and freight prices.

China significantly dominates every single solar PV supply chain segment

A major geographical shift has occurred in solar PV manufacturing capacity and production over the last decade. The People's Republic of China (hereafter, "China") further strengthened its leading position as a manufacturer of wafers, cells and modules between 2010 and 2021, while its share of global polysilicon production capacity almost tripled. Today, the country's share in all manufacturing stages exceeds 80%, more than double its 36% share in global PV deployment.

Solar PV manufacturing capacity by country and region, 2010-2021



Notes: APAC = Asia-Pacific region excluding India. ROW = rest of world.

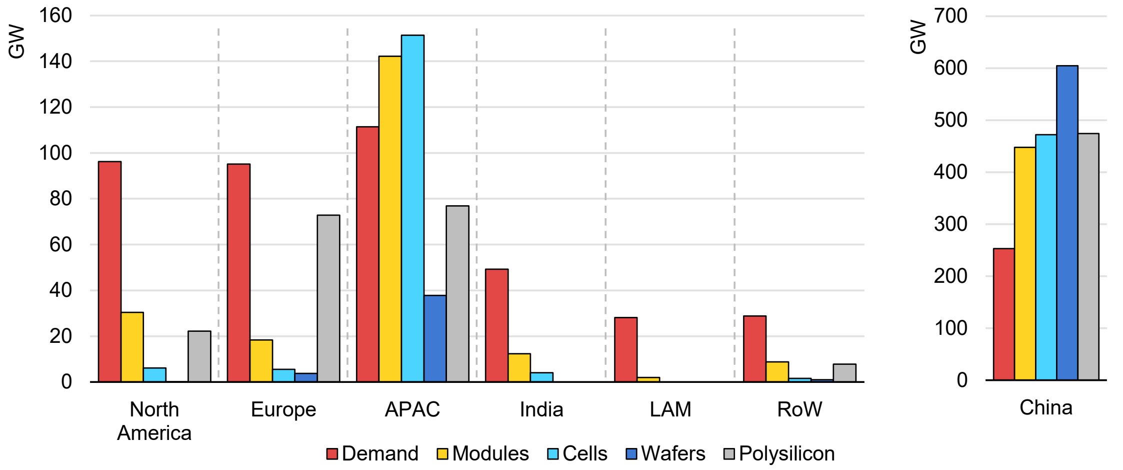
Source: IEA analysis based on BNEF (2022a), IEA PVPS, SPV Market Research, RTS Corporation and PV InfoLink.

For wafers, China has very little competition, while for cells and modules Southeast Asia has considerable manufacturing capacity, mostly in Viet Nam, Malaysia and Thailand. For polysilicon, Germany continues to be a major supplier for the c-Si PV modules industry, while the United States and Japan possess significant capacity but focus their production on semiconductor-grade products. Considering manufacturing plants under construction and planned, China's dominance in solar PV manufacturing is expected to persist or even expand in the short term.

Module assembly is more geographically diversified but almost all inputs are manufactured in China

In all countries except China, demand for solar PV exceeds manufacturing capacity, from polysilicon to modules. In the last five years, only the Asia-Pacific region outside of China has become capable of covering any meaningful share of its needs, with production located mostly in ASEAN countries. Although countries in North America and Europe have significant module-manufacturing capability, they depend almost entirely on China and Southeast Asia for solar cells, except for manufacturing capacity linked to thin-film technology, which relies less on the Chinese supply chain. In addition, China is also the main manufacturer of module components including glass, EVA, backsheet and junction box.

Cumulative solar PV production and demand, 2017-2021



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Note: APAC = Asia-Pacific region excluding India.

Source: IEA analysis based on BNEF (2022a), IEA PVPS, SPV Market Research, RTS Corporation and PV InfoLink.

Raw and processed materials: Just a few minerals account for the bulk of solar PV material costs

Material requirements for renewable electricity technologies differ significantly from those of fossil fuel and nuclear power plants. Global acceleration in renewable electricity deployment in the past two decades has elicited concern about rising new material requirements for the energy sector, including for solar PV.

Our estimates suggest that raw materials make up 35-50% of the total cost of a solar PV module at 2021 prices. Solar PV manufacturing requires metals, metalloids, non-metallic minerals and polymers, with material needs differing across technologies and segments. Solar-grade glass (for covering), aluminium (for the frame and structure) and polymers (particularly EVA and polyolefin for encapsulation, barrier films such as PVDF, PVF or PET for backsheets, and PET for junction boxes) constitute most of the weight of a solar PV module.

In contrast, semiconductors and conductors are used in relatively small quantities, but they can nonetheless account for a disproportionately high share of total raw material costs in PV module production. For instance, in c-Si modules, silver and polysilicon together make up less than 5% of a module's weight, but at 2021 prices the monocrystalline silicon wafer and silver paste represent nearly two-thirds of material costs. Similarly, the tellurium in CdTe modules accounts for less than 0.07% of the weight but more than 3% of raw material content costs. Reducing the material intensity of these expensive minerals is therefore critical to keep production costs down and soften the impact of volatile commodity prices.

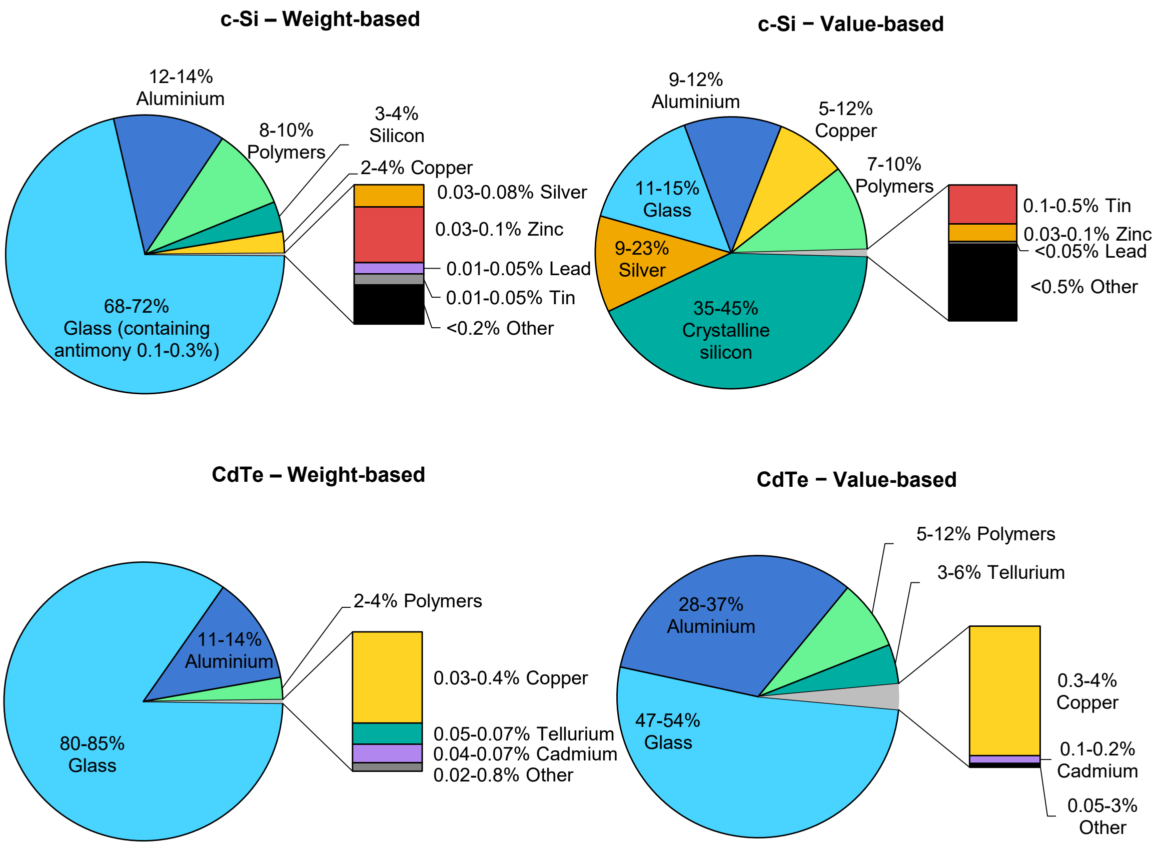
The use of selected materials in c-Si and CdTe solar PV manufacturing

Technology	Material	Main uses
c-Si	Aluminium	Module frame; mounting structure; connectors; back contact; inverters
	Antimony	Solar-grade glass (used to reduce the long-term impact of ultraviolet radiation on the solar performance of glass) and encapsulant (used as a polymerisation catalyst)
	Copper	Cables, wires, ribbons, inverters
	Glass	Module cover
	Indium	Transparent conducting layer (indium tin oxide [ITO]) in silicon heterojunction (SHJ)
	Lead	Soldering paste and ribbon coating in c-Si modules
	Silicon	c-Si wafers; in the form of high-purity quartz (HPQ), for crucibles to grow monocrystalline silicone ingots via the Czochralski process
	Silver	Electronic contacts: silver paste, busbars and soldering
	Tin	Solder, ribbon coating in c-Si modules
	Zinc	Galvanized steel in mounting structures
Thin-film CdTe	Aluminium	Module frame; mounting structure; connectors; inverters
	Antimony	Solar-grade glass (used to reduce the long-term impact of ultraviolet radiation on the solar performance of glass) and encapsulant (used as a polymerisation catalyst)
	Cadmium	Absorber layer
	Copper	Cables, wires, ribbons, inverters
	Glass	Module cover
	Indium	Transparent conducting layer (indium tin oxide [ITO])
	Molybdenum	Back contact layer
	Selenium	Absorber layer in some CdTe cells
	Silver	Electronic contacts: silver paste and soldering
	Tellurium	Absorber layer (CdTe) and back contact (ZnTe)
	Tin	Solder; transparent conducting oxide (indium tin oxide)
	Zinc	Galvanized steel in mounting structures; back contact (ZnTe)

Note: Beyond CdTe and c-Si technologies, CIGS, GaAs and a-Si thin-film technologies have their own specific material requirements, including gallium and arsenic in addition to aluminium, copper, indium, etc. These technologies are niche markets, however, and currently account for a negligible share of global demand for these materials.

In addition to the constitutive materials that make up solar PV modules, other raw materials that do not appear in the final composition of a module are also used during the manufacturing process. For instance, carbonated feedstock materials (coal, woodchips and charcoal) are used in the carbothermic reduction of quartz into metallurgical-grade silicon, and the quartz crucibles used in the Czochralski process to make monocrystalline silicon ingots are made from high-purity quartz (HPQ) and need to be replaced every six to eight ingot cycles. As the production of solar PV modules scales up, so will demand for these materials.

Material composition shares of crystalline silicon and CdTe thin-film solar PV modules by weight and average value, 2021



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Notes: Calculations of value-based composition are based on average 2021 market prices of materials, i.e. aluminium: USD 2 500/Mt; copper: USD 9 408/Mt; silver: USD 803/kg; crystalline silicon: USD 34/kg; and solar-grade glass: USD 590/Mt. Value-based assessments are sensitive to currently high commodity price volatility.

Sources: Estimates of material composition based on Soren (2022), Frischknecht et al. (2020), Carrara et al. (2020), Giurco et al. (2019), IRENA (2017), World Bank (2017), IRENA and IEA-PVPS (2016), Latunussa et al. (2016), Fizaine and Court (2015), Elshkaki and Graedel (2013), and Candelise et al. (2011). Material prices are derived from USGS (2022) and Bloomberg (2022a).

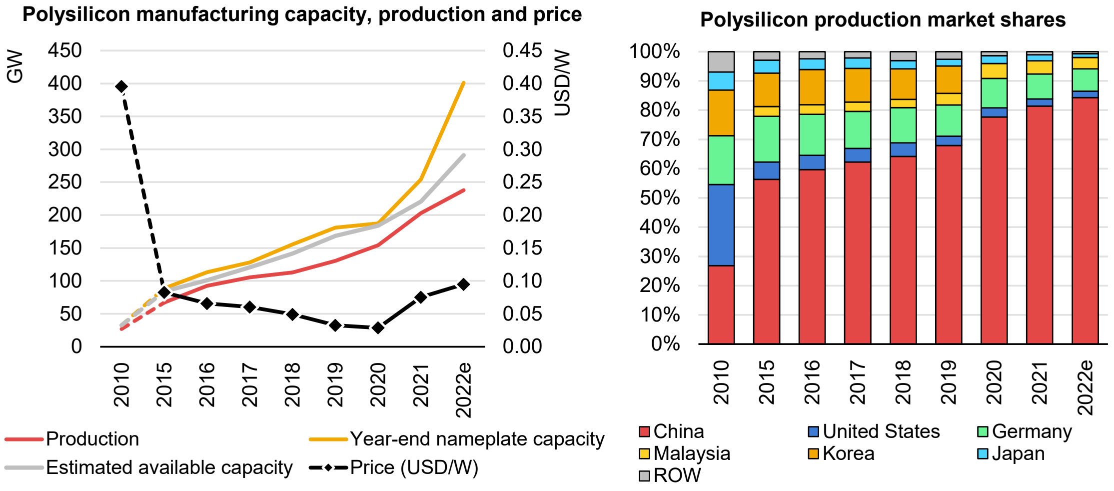
Fortunately, significant improvements in material intensity have been achieved in the past two decades for key materials. For instance, the polysilicon intensity of c-Si cells (in g/W) dropped by more than six times between 2004 and 2020 thanks to cell efficiency improvements, thinner diamond wire sawing and wafers, and larger ingots (Fraunhofer, 2022). Similarly, the silver intensity of c-Si cells (in g/cell) was cut by about three during 2009-2018, owing partly to improvements in screen printing processes (CRU, 2018). Material intensity for these relatively expensive minerals is expected to continue to fall over the next decade, albeit at a slower pace.

Polysilicon: Cycles of supply glut and market tightness

At the end of 2021, annual PV-grade polysilicon manufacturing capacity reached 750 000 metric tonnes, which should be enough to manufacture around 250 GW of crystalline silicon modules. China produced about 80% of the polysilicon used for solar PV modules globally in 2021, with the remaining market share split among Germany, Malaysia and the United States.

In 2010, at the beginning of the solar PV demand boom in the European Union, producers from the United States, Germany, Korea, Japan and China were competing for market shares, with each holding 15-30%. During 2010-2015, China expanded its manufacturing capacity twice as quickly as the rest of the world, leading to a major global supply glut and causing polysilicon prices to plummet 70%, pushing many producers out of the market.

Global polysilicon manufacturing capacity, production, average price and market shares, 2010-2022



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Note: ROW = rest of world.

Source: IEA analysis based on BNEF (2022a), IEA PVPS, SPV Market Research, RTS Corporation and PV InfoLink.

Despite rapid demand growth through 2020, the overcapacity situation persisted as Chinese manufacturers further invested in new production facilities. Meanwhile, low prices have led producers in Japan, Korea and the United States to downsize or close their polysilicon plants. In the United States, low prices combined with import tariffs limiting exports to China have reduced PV-grade polysilicon production since 2015.

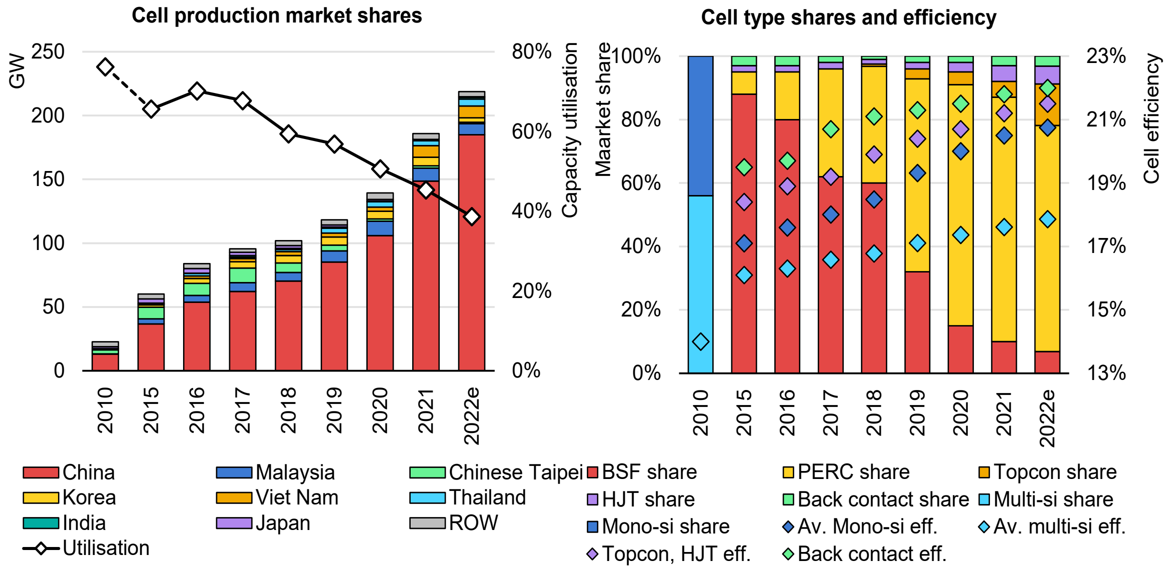
In the second half of 2020, supply chain disruptions due to the Covid-19 pandemic, fires in large manufacturing plants in China, shuttering of plants in Korea and a step increase in global PV installations transformed the previous supply glut into tightness with polysilicon prices quadrupling to around USD 35/kg in the last quarter of 2021. As of June 2022, polysilicon prices remained high (monthly average (USD 35/kg) even though 60 GW of additional polysilicon capacity was commissioned in China last year. While the commissioning of new plants is expected to increase global polysilicon capacity from around 220 GW in 2021 to almost 400 GW in 2022, rapidly growing global PV demand, fires and maintenance in existing plants in China, and slow ramp-up period for new plants, are all expected to keep the polysilicon market tight. In addition, 350 GW of manufacturing capacity is to be commissioned in upcoming years. Considering demand projections through 2025, another polysilicon supply glut cycle is possible if this additional capacity is completed in the coming years.

Wafers: Low capacity utilisation, highest geographical concentration and increasing sizes

In 2021, global PV-grade silicon wafer manufacturing capacity exceeded 360 GW, almost twice the estimated demand. Wafer market capacity utilisation was relatively low throughout the last decade, falling to 50% in 2021 from a peak of 85% in 2016. Although technological developments allowed wafer production costs to decline continuously and overcapacity contributed to price stability, wafer prices have increased drastically since the beginning of 2021 due to higher polysilicon prices.

Wide introduction of the diamond wire saw in 2018 enabled a significant reduction of silicon consumption in the ingot-cutting process as well as an increase in wafer size. The use of larger wafers accelerated in 2020, further improving the material and energy efficiency of production so that average polysilicon use per watt of finished cell decreased almost 60% between 2010 and 2021. Furthermore, switching to monocrystalline wafer production in 2019-2020 allowed for cost-effective large-scale manufacturing of high-efficiency cells, which further reduced the per-watt cost of solar PV modules.

Global PV wafer production and capacity utilisation (left), and wafer market shares by size and average polysilicon use per watt (right), 2010-2022



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Notes: ROW = rest of world. Values for 2022 are estimates.

Source: IEA analysis based on BNEF (2022a), IEA PVPS, SPV Market Research, RTS Corporation, PV InfoLink and VDMA.

China currently accounts for 97% of global manufacturing capacity, a rise from its already-high share of 80% in 2010. Thanks to economies of scale as well as supply chain integration, innovation and government support, Chinese companies were able to become cost-competitive in wafer production relatively quickly, preventing other market participants from attaining significant market shares. Almost all remaining capacity, although small, is in the Asia-Pacific region, making nearly the whole world entirely dependent on imports for cell production.

Even though overcapacity was at 80% in 2020, China added almost 115 GW of new manufacturing capability in 2021, and another 300 GW has already been announced. Should these plans be realised by 2023/2024, China will become even more dominant in global wafer production. However, the upgrades necessary for many existing plants to be able to produce the larger wafers now demanded by cell manufacturers (M10 and G12 wafers) might cause some factories to be put in idle mode and thereby reduce the oversupply.

Cells: Technology improvements raise efficiency

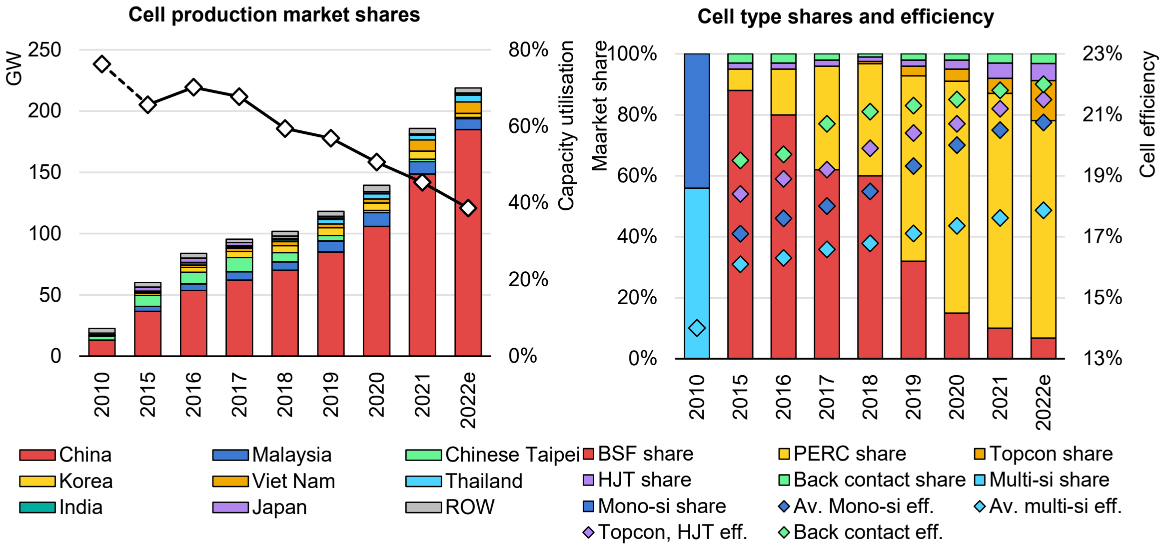
Global solar cell-manufacturing capacity reached almost 410 GW at the end of 2021, with average utilisation of the global fleet at around 45%. Meanwhile, cell capacity utilisation worldwide never exceeded 70% during the last decade. R&D

spending has resulted in consecutive annual improvements in the efficiency of energy conversion from solar irradiation to electricity as well as reductions in material use, reducing manufacturing costs significantly.

Multicrystalline silicon back surface field (BSF) technology has been gradually replaced by more efficient Passivated Emitter and Rear Cell (PERC) cells since 2015. Improvements in the manufacturing process and the shift to monocrystalline wafer production enabled rapid cost reductions, making the more efficient PERC cell the dominant technology. More efficient cells allow for a higher capacity while keeping module area the same, reducing overall solar PV generation costs.

In upcoming years, greater market shares are anticipated for more advanced cell designs, notably heterojunction (HJT), TOPCon and back contact, promising further efficiency gains. Modules using such cells currently reach 22% efficiency in real-life operating conditions, making them one-fifth more efficient than standard modules installed just 4-5 years ago. Furthermore, mass manufacturing of multilayer and tandem silicon-perovskite or silicon-CdTe hybrids is currently under consideration. These solutions could raise cell efficiency to more than 30%, at competitive production costs.

Global PV cell production and manufacturing capacity utilisation (left), and market shares and module efficiency by cell type (right), 2010-2022



Notes: ROW = rest of world. BSF = back surface field. HJT = heterojunction. PERC = Passivated Emitter and Rear Cell.

Source: IEA analysis based on BNEF (2022a), IEA PVPS, SPV Market Research, RTS Corporation, PV InfoLink and VDMA.

As the dominant cell manufacturer, China's share in production increased from 60% in 2010 to almost 80% in 2021. In 2010, the cell market was relatively diversified, with significant portions supplied by Chinese Taipei (14%), Japan (7%), Germany (6%) and the United States (5%). However, these markets did not install additional capacity during the last decade, while China added another 300 GW. In 2012-2016, cell manufacturing began to develop in Southeast Asia, first in Korea and Malaysia and later in Viet Nam and Thailand. Chinese integrated manufacturers established most of the manufacturing plants in the ASEAN region, partly because of cost advantages but mainly to circumvent US import tariffs on Chinese solar PV cells and modules. Today, Southeast Asia and Korea hold 18% of the global cell market, leaving only 2% of production to the rest of the world.

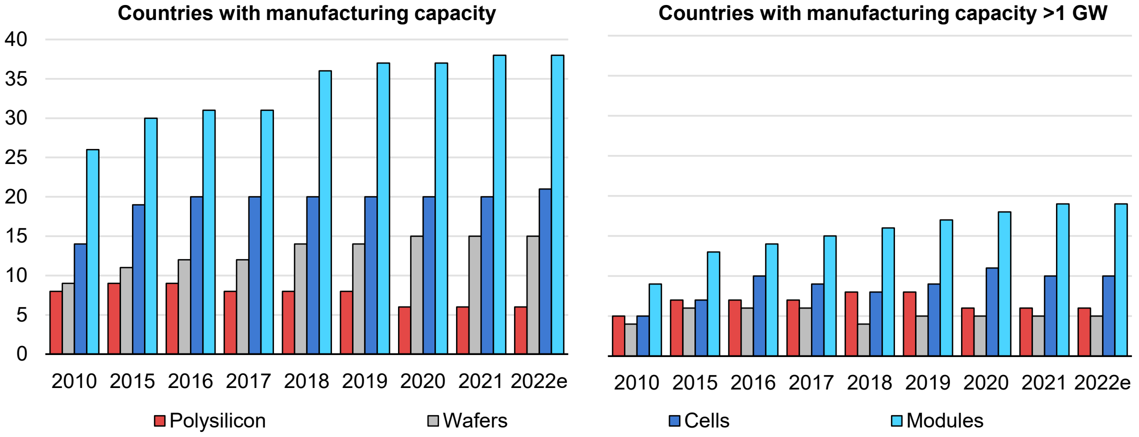
In 2021, Chinese manufacturers announced the addition of another 250 GW of cell production capacity. Realisation of these projects planned for 2022-2023 would further solidify geographic concentration of the solar cell market and inflate the oversupply situation. However, a significant number of existing plants will require modernisation to produce new cell types, possibly reducing the supply glut.

Modules: More geographically diversified producers still depend on Asia for all key inputs

Solar PV module production capacity reached 460 GW in 2021, with crystalline silicon technology assembly accounting for 98% and thin-film manufacturing making up the remainder. Module assembly has registered the highest manufacturing capacity and lowest plant utilisation levels of all supply chain segments because it requires only modest investment and relatively limited technological knowhow.

Low solar cell prices, the possibility of sourcing several panel components locally (frame, glass, wiring and packaging), trade restrictions and government support have encouraged many companies around the world to invest in module assembly lines. Accordingly, 38 countries had module assembly capabilities in 2021, by far the highest of all steps of the PV manufacturing process. In many cases, however, investments were relatively small or stopped at the pilot stage, with just 19 countries having assembly capacity of at least 1 GW.

Number of countries with manufacturing capacity across the PV value chain, 2010-2022



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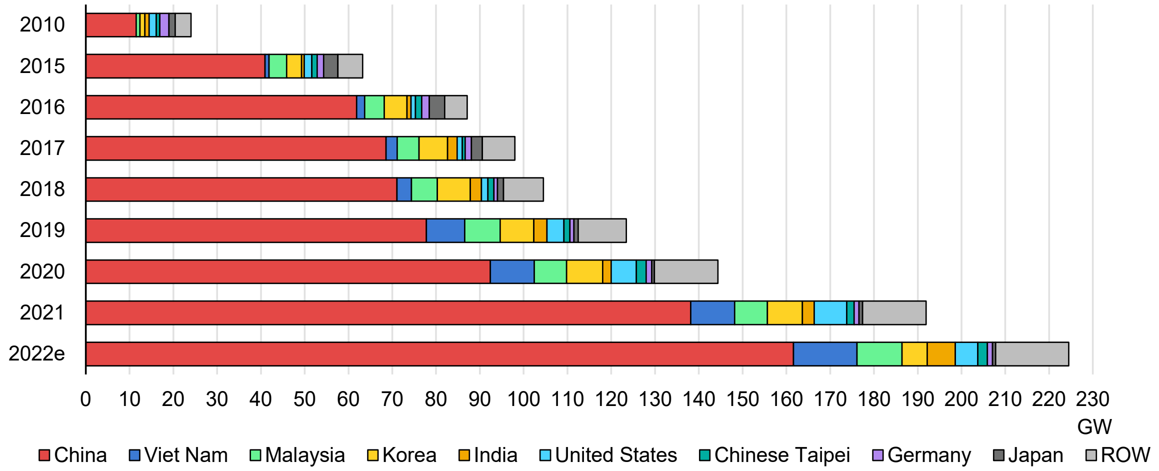
Source: IEA analysis based on BNEF (2022a), IEA PVPS, SPV Market Research, RTS Corporation and PV InfoLink.

Although 38 countries have module assembly facilities, China was still responsible for about 70% of production in 2021, up from 50% in 2010. Other important manufacturers include Viet Nam (5%), Malaysia (4%), Korea (4%) and Thailand (2%), but most manufacturing capacity in these countries was developed by Chinese companies focusing on exports to the United States. Other countries with high module assembly capacity, such as the United States (4%), Germany (1%) and India (1%), produce mainly for their domestic markets, although they often lack adequate manufacturing capacity for PV cells and wafers (except for thin-film technology, wherein facilities include the entire supply chain).

Because c-Si PV cell manufacturing is concentrated in the Asia-Pacific region, large solar PV demand centres in the United States, India and Europe depend strongly on imports for the main solar module components. Although countries in these markets often possess multi-GW module production capability, most of the plants simply assemble modules from parts shipped from manufacturers located primarily in mainland China. For thin-film technology, however, the United States, Malaysia and Viet Nam each have 2-3 GW of manufacturing capacity and are relatively less dependent on China for supply chain components.

With wafers increasing in size since 2019 and cell efficiency improving, the power output of individual PV modules has grown. The standard module design of 72 cells for utility-scale applications has been replaced by 144 more efficient half-cells, and 60 cells in rooftop applications by 120 half-cells. As a result, the power output of typical solar panels rose to 400-500 W for utility-scale applications in 2021. For rooftop applications using mostly 60 cells or 120 half-cells, output reached 350-400 W.

Global solar PV module production, 2010-2022



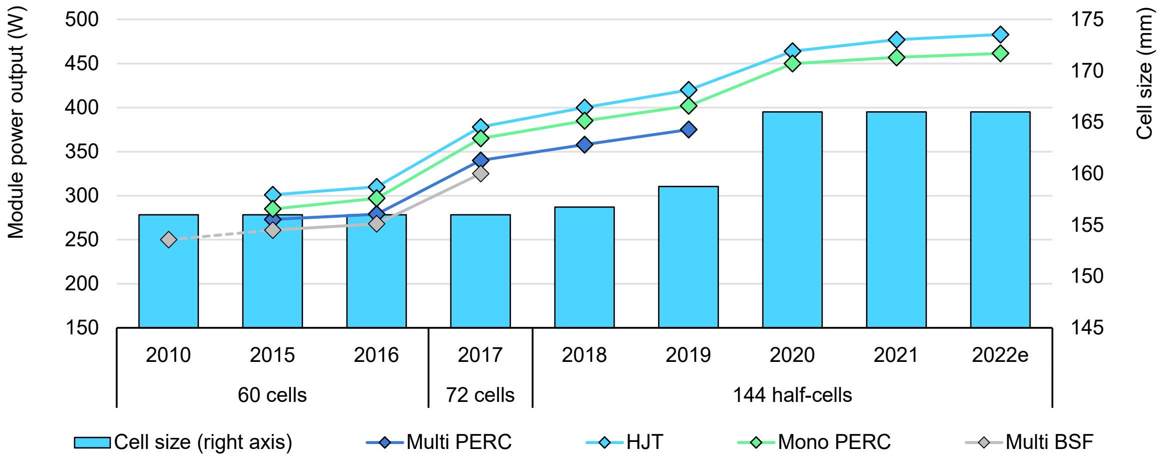
Notes: ROW = rest of world. Values for 2022 are estimates.

Source: IEA analysis based on BNEF (2022a), IEA PVPS, SPV Market Research, RTS Corporation and PV InfoLink.

The largest, most advanced modules on the market today offer up to almost 700 W under standard testing conditions, more than double the 250-300 W of panels used in 2010. Although continued increases in wafer size and cell technology advances are expected to drive power output even higher in the future, logistical and system installation limitations may delay further growth in module size, especially for rooftop applications. Today, the largest modules offered for utility-scale projects are 3 m^2 in size and weigh more than 30 kg.

Companies in several countries and regions are contemplating significant expansions to their manufacturing capacity in upcoming years, notably in India, Viet Nam, Thailand, the United States and the European Union. However, with over 300 GW of new assembly plants under consideration in China, its market share is expected to remain high in the medium term. Given ongoing and planned investments in manufacturing capacity, in addition to innovation and further potential for efficiency gains, crystalline silicon technology is expected to dominate the solar PV market for many years to come.

Standard PV module power output, cell number and size, 2010-2022



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Notes: PERC = Passivated Emitter and Rear Cell. HJT = heterojunction. BSF = back surface field.

Source: IEA analysis based on IEA PVPS, SPV Market Research, RTS Corporation, PV InfoLink and VDMA.

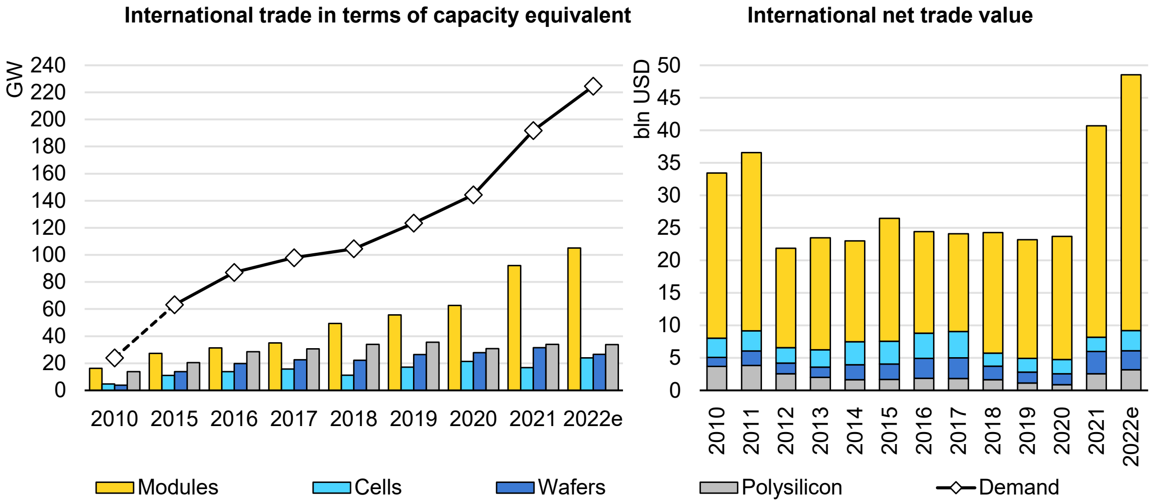
Trade

Almost half of all solar PV modules manufactured in 2021 were traded between countries, a more than quadruple increase since 2010

Taking together polysilicon, wafers, cells and modules, the total value of PV-related trade reached USD 40 billion in 2021 – an increase of over 70% from 2020. With solar PV manufacturing heavily concentrated in China and Southeast Asia, almost all other countries with high solar PV demand remain large importers. In the last five years, the European Union has imported 84% of its installed solar PV modules, the United States 77% and India 75%. Moreover, modules produced in these areas depend 60-80% on imported PV cells. Meanwhile, international polysilicon, wafer and cell trade remained significantly lower than for modules, reaching just 22-34 GW in 2021 due to the high concentration of integrated manufacturing in China.

Following the 2011-2013 PV installation boom in Europe prompted by generous FITs, the value of solar PV trade remained relatively stable at around USD 25 billion until 2021 due to a sharp decline in module prices, even though trade in PV products was growing. In 2021, higher polysilicon and module prices, together with rising demand, boosted PV trade to a record value of almost USD 40 billion.

Global exports/imports of PV-grade polysilicon, wafers, cells and modules, and total trade value, 2010-2021



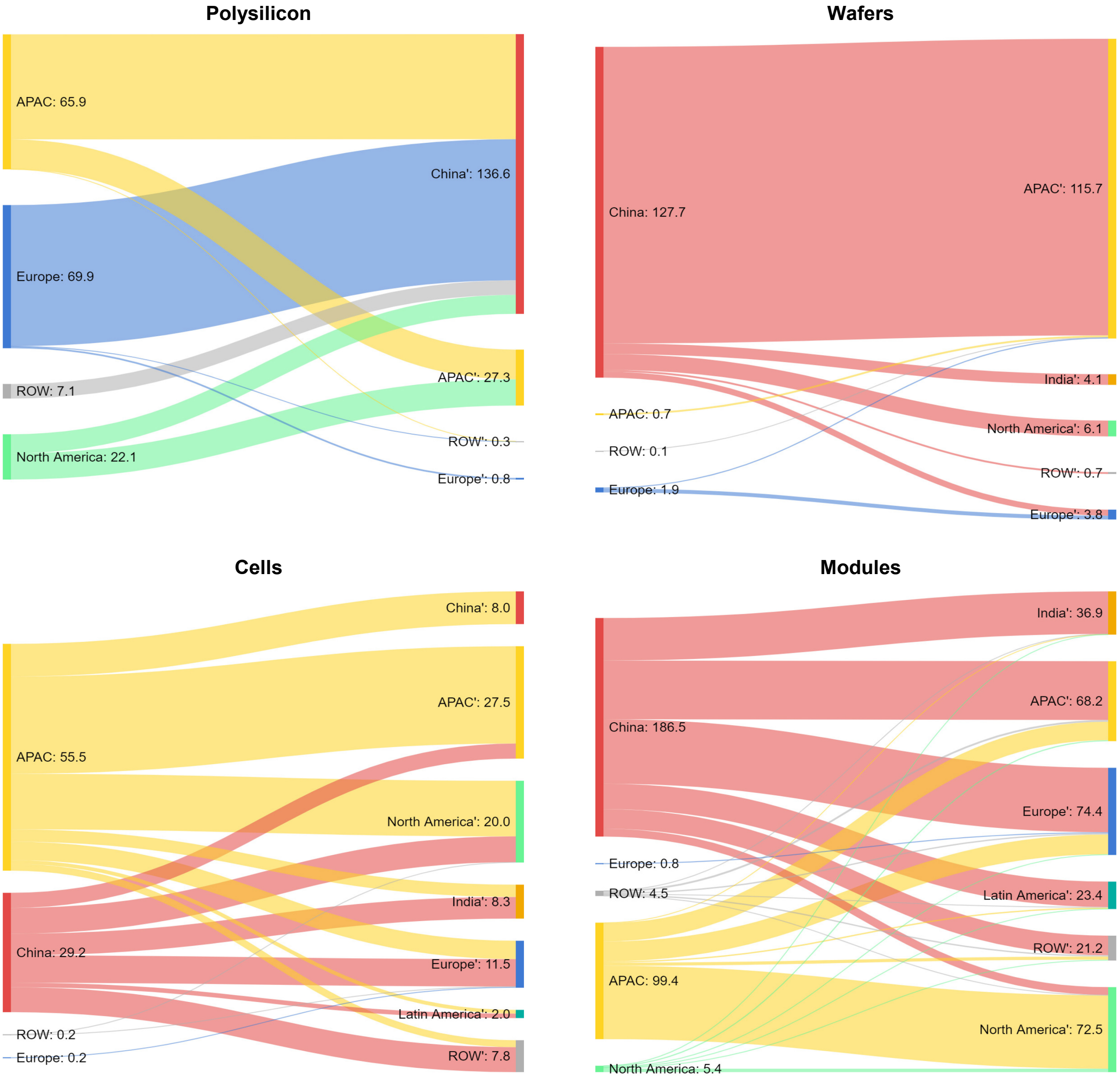
Source: IEA analysis based on BNEF (2022a), IEA PVPS, SPV Market Research, RTS Corporation and PV InfoLink.

International solar PV trade volumes depend strongly on China's domestic demand because the country is both the largest producer and consumer of polysilicon, wafers, cells and modules. Furthermore, in the last five years it has been the main importer of PV-grade polysilicon, mainly from Germany, Malaysia and Japan, as its domestic production has fallen short of local demand for wafer production.

Finished wafers were exported mostly to Asia-Pacific cell manufacturers, with the primary importers being Malaysia, Viet Nam, Thailand and Korea. These countries were in turn responsible for over 60% of cell exports, as China's production was used mostly domestically. The main importers of solar cells from Southeast Asia were major module assemblers in the same region, from Viet Nam, Singapore and Korea. US cell imports also came mainly from Southeast Asia, largely due to restrictions on imports from China. The rest of the large module assemblers in India, the Republic of Türkiye (hereafter, "Türkiye"), the European Union, Canada and Mexico were supplied by remaining Southeast Asian exports and China.

In 2017-2021, Southeast Asian module manufacturers were responsible for one-third of global PV module exports, directed mostly towards the United States and the European Union, where Chinese modules were subject to various trade restrictions. The rest of the market was dominated by China, with its shares in India and Brazil exceeding 90%.

Cumulative international shipments of PV-grade polysilicon, wafers, cells and modules in GW-equivalent by region, 2017-2021



Notes: APAC = Asia-Pacific. ROW = rest of world. The figure provides data for international shipments only. Diagrams were created using the SankeyMATIC system.

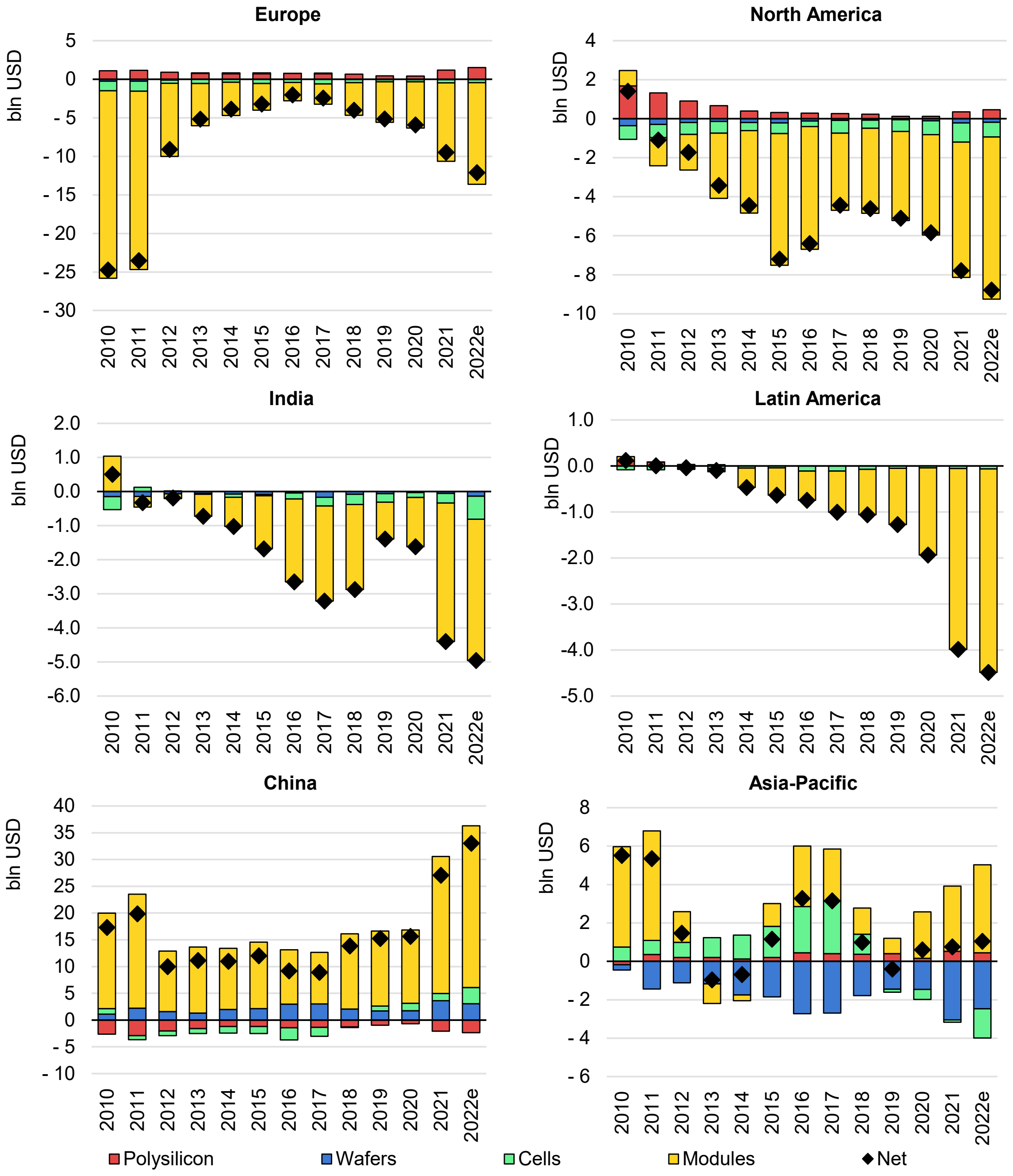
Source: IEA analysis based on BNEF (2022a), IEA PVPS, SPV Market Research, RTS Corporation, PV InfoLink and UN Comtrade.

European, US and Indian solar PV trade deficit reached more than USD 20 billion in 2021

Although Europe imported an unprecedented 26 GW of PV modules in 2021, the bill was just one-third the record cost of 2010, when it imported only 15 GW at very high prices. For instance, in 2009-2011, Germany and Italy were the first countries to adopt solar PV on a large scale and purchased modules at five times the average

2021 price, paying as much as USD 25 billion in 2010-2011. With demand increasing since 2018, however, Europe had the largest net trade deficit of all regions in 2021.

Net import value of PV-grade polysilicon, wafers, cells and modules by region, 2010-2021



Source: IEA analysis based on BNEF (2022a), IEA PVPS, SPV Market Research, RTS Corporation, PV InfoLink, and UN Comtrade.

In North America, the net trade deficit reached a record USD 8 billion in 2021 when it imported its highest-ever number of PV modules. At the same time, India's imports also reached a record-breaking USD 4 billion as installation levels rebounded in 2021-2022 and project developers rushed to stockpile modules before higher import duties came into force in April 2022. In Latin America, record installations expected in 2022 led to unparalleled module imports, which together with elevated prices in 2021 resulted in a more than doubling of its net import bill that year.

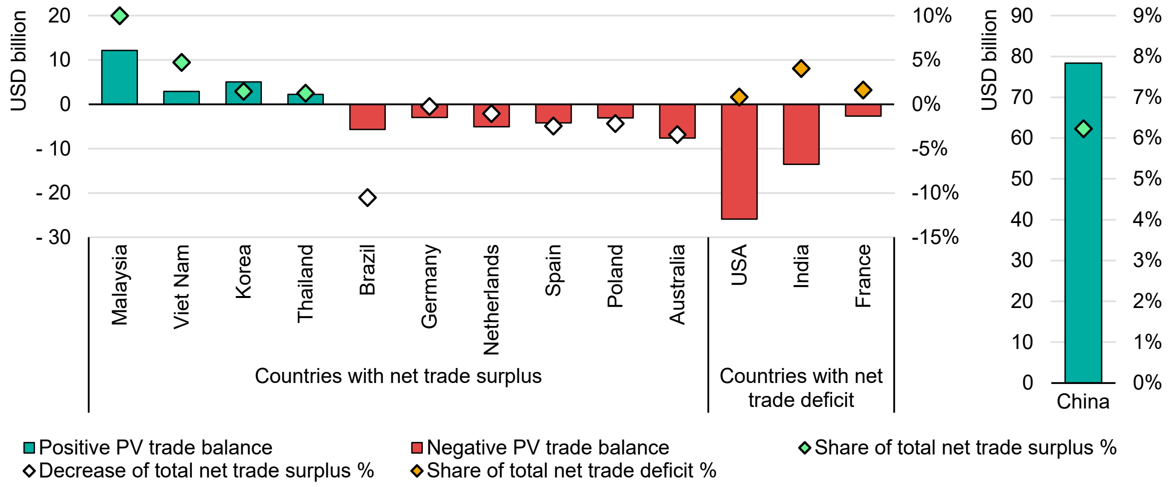
Unsurprisingly, China and Asia-Pacific countries benefited significantly from higher demand and prices, experiencing record or near-record incomes from PV equipment sales in 2021. In Asia-Pacific, however, the need to import large quantities of solar wafers for cell production reduced the region's net trade value considerably.

PV exports contribute to overall trade balances in China and Southeast Asia

Solar PV trade is responsible for a significant share of many countries' overall national trade balances. In China, exports of modules, wafers and cells made up an average over 6% of the country's trade surplus over the last five years. For the smaller exporting countries of Malaysia and Viet Nam, the PV sector is even more important for the economy, as it was responsible for 10% of Malaysia's trade surplus and 5% of Viet Nam's. For the largest PV component importers, impacts on trade balance have been significant in the last five years: Brazil's solar PV imports reduced the country's trade surplus by 12% and Australia's dropped 4%. In countries with negative net trade balance, massive PV component imports (mainly modules and cells) further increased their deficit. Shares of PV in trade deficits over 2017-2021 were 1% for the United States, 2% for France and as much as 4% for India.

These values are significant in terms of overall national trade balances, indicating that many countries are vulnerable to price and volume risks as solar PV becomes a critical element of power infrastructure owing to many countries' ambitious net zero pledges. In the current manufacturing market structure, PV-related trade flows are expected to continue expanding, which may enlarge solar PV's role in national trade balances.

Cumulative PV-grade polysilicon, wafer, cell and module trade balances, and national net trade balances in goods and services for major PV exporters and importers, 2017-2021



Notes: CAB = current account balance

Source: IEA analysis based on BNEF (2022a), IEA PVPS, SPV Market Research, RTS Corporation, PV InfoLink, UN Comtrade, OECD and World Bank.

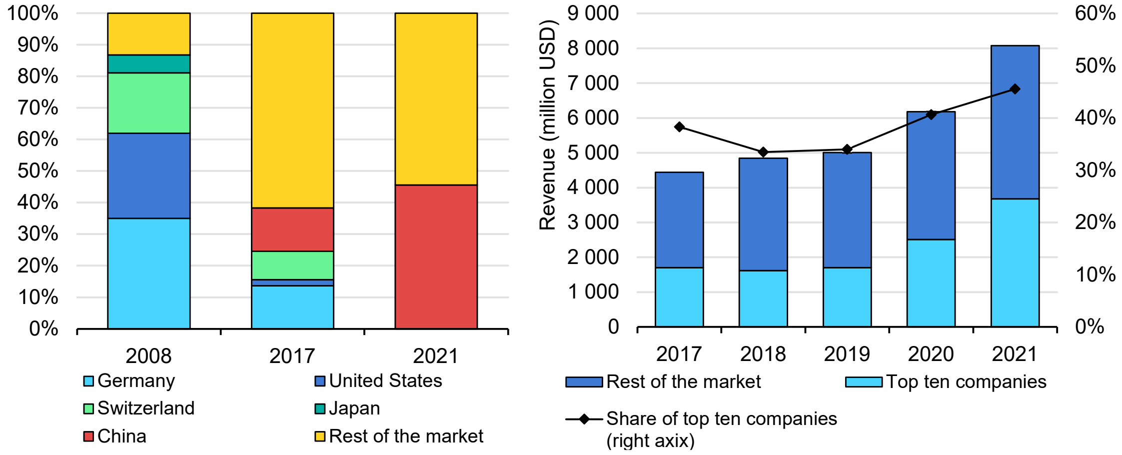
Equipment for solar PV manufacturing

China now leads the market once dominated by Europe, the United States and Japan

Both the scale and geographical dispersion of the PV equipment manufacturing market have changed dramatically over the past decade, with leadership shifting from Europe, the United States and Japan to China. Driven by the exponential expansion of global demand, the total number of firms entering the PV equipment manufacturing market surged 150% during 2007-2020 to almost 1 900, with the number of Chinese firms almost quadrupling during this period to more than 700 (RTS, 2021). The PV equipment market today is one of the most diversified markets within the solar PV supply chain but is becoming increasingly concentrated in China.

In 2008, the ten main solar PV equipment manufacturers accounted for almost 90% of global market shares, and they operated in just four countries (Germany, the United States, Switzerland and Japan) (KDB, 2010). In contrast, by 2021 the top ten manufacturers’ share had dropped by half, mainly because many new firms had entered the market, leading to considerable diversification. Today, all top ten equipment manufacturers are in China and claim over 45% of the global market share (QYResearch, 2022).

Top ten companies' shares of PV manufacturing equipment revenue



Source: IEA analysis based on KDB (2010) and QYResearch (2022).

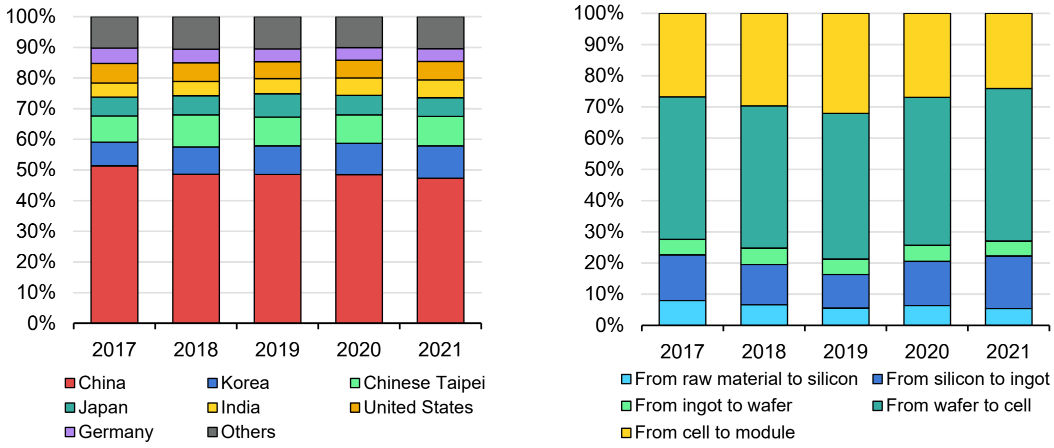
Global PV manufacturing equipment sales rose 80% during 2017-2021 to exceed USD 8 billion. Asian countries dominate sales: China accounts for almost 50%, followed by Korea, Chinese Taipei and Japan, which has expanded to cover another quarter in the last five years (QYResearch, 2022).

Key PV manufacturing processes by segment

Segment	Key processes
Polysilicon	Silicon purification
Ingots	Crystalline ingot growing; material property analysis; ingot cutting
Wafers	Wiring; pre-washing; wafer separation; main washing; wafer inspection and sorting
Cells	Wet station; diffusion; chemical vapour deposition (CVD)/sputtering; screen printing; baking; cell transfer; inspection
Modules	Cell wiring (string); layup (module assembly); laminating and sealing; curing; frame and terminal assembly; module transfer; inspection

Each segment of PV manufacturing requires various types of special equipment (e.g. for silicon purification, ingot-growing, wafer and cell production, and module assembly). Equipment for manufacturing cells from wafers accounts for almost half of global PV manufacturing equipment sales. The sophistication, precision and advanced automation entailed in manufacturing solar cells imply more expensive equipment. For instance, assembly lines to produce modules from cells usually require highly automated machinery and accurate quality-testing equipment at multiple stages.

PV manufacturing equipment revenue by country (left) and by segment (right), 2017-2021



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Source: IEA analysis based on QYResearch (2022).

Equipment prices depend on level of automation and module assembly plant capacity, which can range from 50 MW to 20 000 MW per year. Meanwhile, polysilicon and ingot production processes use simpler, more conventional equipment such as vacuum chambers and melting furnaces to produce high-purity materials: the annual polysilicon production capacity of each vacuum reactor varies from 150 to 700 tonnes depending on the manufacturer (TaiyangNews, 2017).

Energy consumption

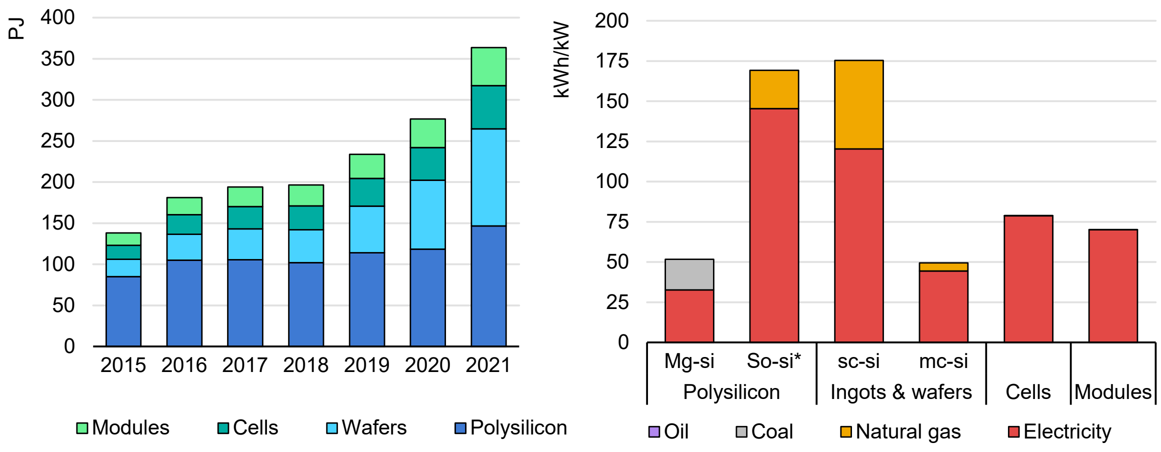
Electricity-intensive solar PV manufacturing is fuelled mostly by coal

Manufacturing crystalline silicon solar PV panels is an energy-intensive process. The amount of energy consumed globally to produce polysilicon, ingots and wafers, and cells and modules reached 364 PJ in 2021, roughly equivalent to Croatia's total primary energy demand. At current production levels, however, this consumption is low compared with other large industries and makes up less than 0.2% of global industry energy use.

Polysilicon production accounts for 40% of all energy consumed to manufacture solar PV modules, the largest portion of all supply chain segments. Polysilicon is the most energy-intensive segment due to the high temperature of the heat and lengthy time it needs to be applied to melt quartz, extract silicon and refine it to the level of purity required for solar cells. The first step is to produce metallurgical-grade silicon (Mg-si) by melting quartz silica in an arc furnace at around 1 700°C, and the second step is to remove impurities to produce solar-grade polysilicon (So-si).

Several different technologies can be used to produce So-si, but the Siemens process is employed for more than 90% of polysilicon produced today because it delivers the higher-purity polysilicon needed for monocrystalline high-efficiency cells at a lower cost per unit. The Siemens process is the most mature technology for silicon purification, but it is also highly electricity-intensive. The less-utilised FBR process uses less energy but also results in lower-purity silicon. Investment costs are also higher for the FBR method, and scaling up fluid dynamics at larger scales is challenging.

Energy consumption of solar PV manufacturing by segment, 2015-2021 (left), and energy intensity per segment (right)



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Notes: Mg-si = metallurgical-grade silicon. So-si* = solar-grade silicon using the Siemens process. sc-si = monocrystalline wafers. mc-si = multicrystalline wafers.

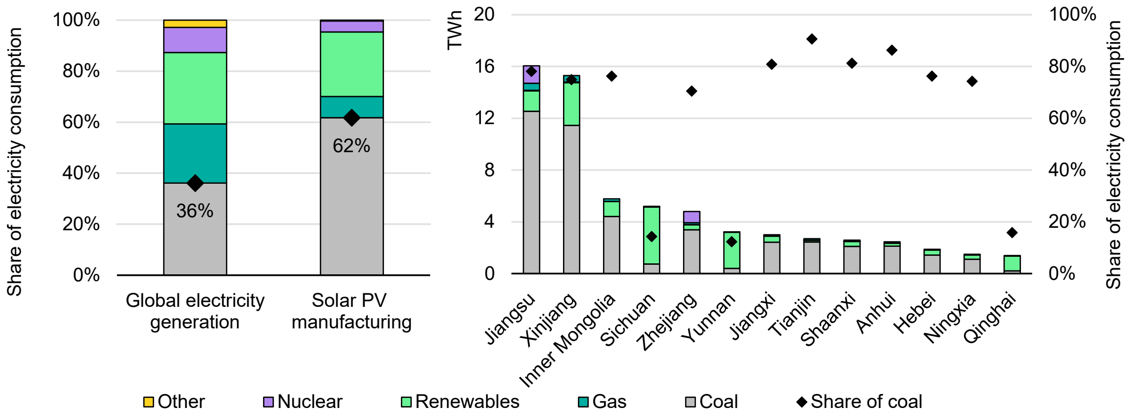
Source: Right graph: IEA-PVPS (2020).

Ingot and wafer production is also electricity-intensive because it requires high-temperature heat for long periods of time; in fact, it has the second-highest energy consumption after polysilicon production. Energy use for wafer manufacturing has been growing since 2015 because of rising demand for monocrystalline wafers, which are three times more energy-intensive to produce than multicrystalline cells but also have higher efficiencies. Finally, accounting for less than one-third of energy consumption are cells and modules. Their production processes require less heat and lower temperatures for drying and cooling, and most of the electricity is used for automated mechanical work.

Electricity supplies over 80% of total energy consumed in solar PV manufacturing. Polysilicon and ingot production together make up two-thirds of total electricity consumption due to their high heat requirements: heat must be applied continuously at a precise temperature over a period of 100-200 hours.

Coal fuels 62% of the electricity used for solar PV manufacturing, significantly more than its share in global power generation (36%), largely because production is concentrated in China – mainly in the provinces of Xinjiang and Jiangsu. In these provinces, coal often accounts for more than 75% of the power supply, partly because the government offers favourable tariffs. Reducing the carbon intensity of manufacturing could thus be a prime opportunity for the PV sector to further decrease its carbon footprint. Using renewables-based electricity in production processes could reduce emissions from PV manufacturing significantly.

Global electricity supply by source and for solar PV manufacturing (left) and in Chinese provinces by fuel (right), 2021



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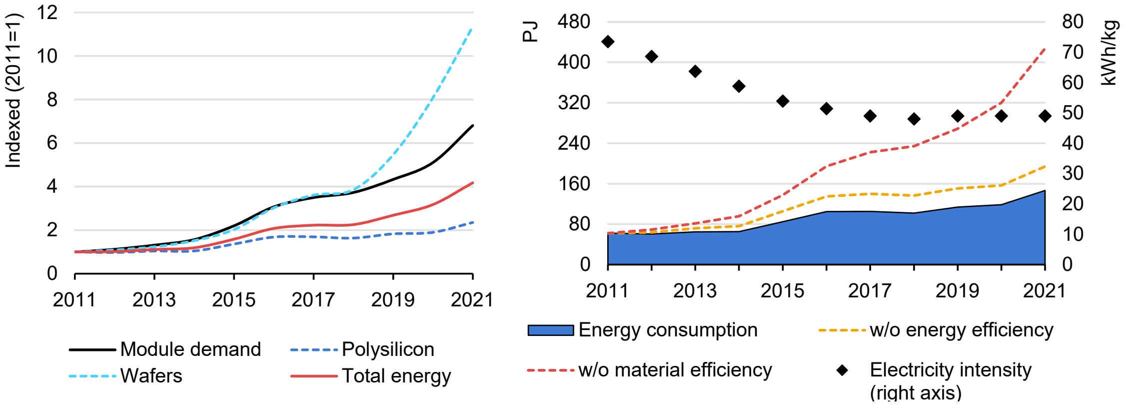
Sources: Left graph: IEA (2022b).

More efficient polysilicon production has achieved 50% energy savings since 2011, decoupling module demand from energy consumption

Energy consumption for manufacturing has increased more slowly than module production since 2011 thanks to greater energy efficiency in polysilicon production. In the last ten years, module production has expanded by more than six – from around 30 GW to 185 GW – but only four times as much energy was needed to meet increased demand thanks to energy savings in polysilicon production processes achieved in the past decade.

In fact, total savings would have been even higher had energy consumption for wafers remained stable instead of increasing by a factor of 11 due to higher demand for more energy-intensive monocrystalline wafers. Compared with the multicyrstalline wafers that dominated the market until 2018, monocrystalline ones require three times more energy to manufacture. Thus, with monocrystalline wafers in high demand since 2018, energy consumption for wafer production has grown exponentially.

Global energy consumption for solar PV manufacturing and module production (left) and polysilicon energy savings since 2011 (right)



Source: Frischknecht et al. (2020).

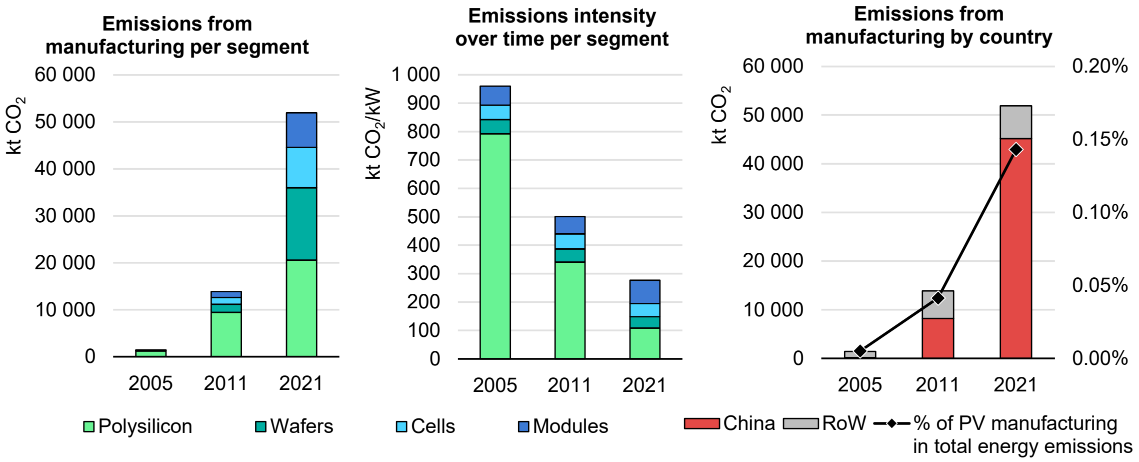
Despite being energy-intensive, the energy and material efficiency of the Siemens process has improved significantly over the last decade and achieved almost 50% energy savings over the last ten years. These savings result from the electricity intensity of the process declining from over 70 kWh/kg in 2011 to roughly 50 kWh/kg in 2021 thanks to larger furnaces, upgraded furnace wall materials, a greater number of silicon rods and adjustment of the gas mix used during silicon purification. These improvements saved an estimated 12% of energy consumption over the last ten years, and an additional savings of 39% came from material efficiency innovations to reduce and reuse waste. Without these improvements, energy consumption to meet polysilicon demand in 2021 could have reached 430 PJ – more than twice the actual 150 PJ consumed.

CO_2 emissions

CO_2 emissions from PV manufacturing almost quadrupled as demand expanded and production moved to China

Globally, CO_2 emissions from solar PV manufacturing almost quadrupled to more than 51 900 kilotonnes of carbon dioxide (kt CO_2) over the last decade,[2] accounting for almost 0.15% of total energy-related global emissions in 2021. This growth resulted from an almost sevenfold production increase in the last decade and from manufacturing capacity moving to China. Emissions increases have, however, been counterbalanced by energy and material efficiency improvements and declining electricity generation emissions intensity in many countries.

Absolute emissions and emission intensity of PV manufacturing globally



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Notes: RoW = rest of world. This report does not consider emissions derived from manufacturing intermediate products involved in PV module assembly (glass, cables, etc.). Total energy emissions refers to CO_2 emissions from energy combustion and industrial processes.

Sources: Right graph: IEA (2021a; 2022d). Left graph: IEA (2021a). IEA analysis also based on BNEF (2022a), PVPS, InfoLink and UN Comtrade.

Polysilicon production is the most CO_2-intensive segment of the solar PV supply chain, even though its share in overall PV manufacturing emissions has declined

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[2] CO_2 emissions from manufacturing across the entire PV supply chain are calculated by accounting for all electricity and other fuels used during the production process. For electricity, we used grid emission factors (CO_2/KWh) from the Energy Data Center. The numerator represents absolute CO_2 emissions from fossil fuels consumed for electricity generation, while the denominator represents total electricity generated. As a result, emissions per kWh vary across countries and from year to year, depending on the generation mix (IEA, 2021a). For primary energy emissions, we relied on IPCC CO_2 emission factors (IPCC, 2006).

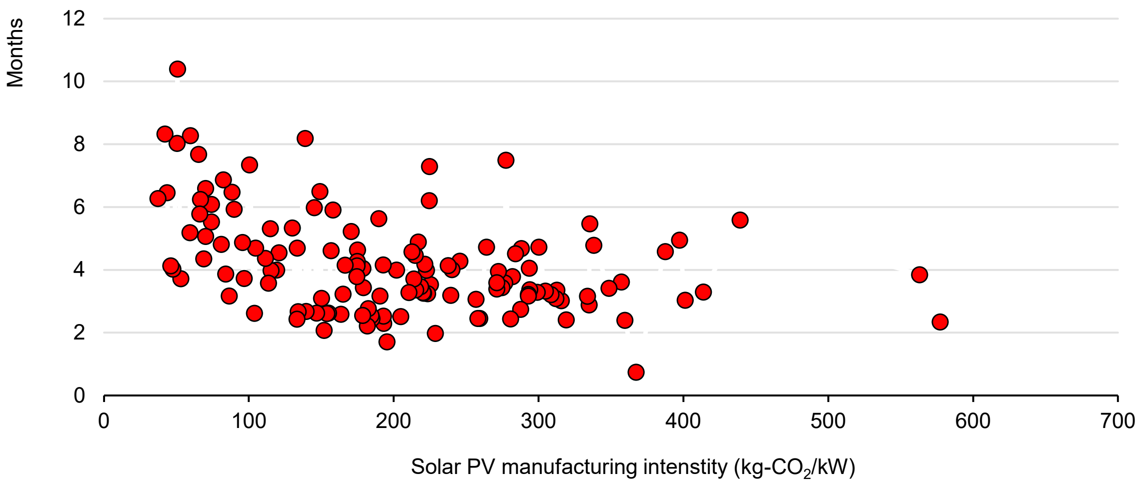
continuously from more than two-thirds in 2011 to just over 39% last year. Meanwhile, the technology shift from multicrystalline to more-energy intensive monocrystalline technology boosted the share of wafer production in overall solar PV manufacturing emissions by 17 percentage points.

Today, China is responsible for 87% of global emissions from solar PV manufacturing involving polysilicon, ingots, wafers, cells and modules, compared with only over 59% in 2011. In the last decade, China's increase in production capacity surpassed global growth in all segments. As a result, enlargement of its production and CO_2 emissions shares outpaced even global expansion.

Nevertheless, the amount of CO_2 emissions PV plants are able to displace during their operational lifetime far outweighs the volume emitted during module manufacturing. For instance, 1 GW of installed solar PV capacity could offset 1.5 million tonnes of carbon dioxide (Mt CO_2) annually from coal-fired generation (IEA, 2020a).

In most countries, domestically-produced solar PV modules (including polysilicon, ingots, wafers, cells and module assembly) need to operate only three to five months to make up for all their manufacturing-related emissions. This measurement is only indicative, however, as a comprehensive lifecycle assessment should also consider all upstream and downstream emissions, including from balance-of-system component manufacturing and PV power plant construction. Nevertheless, although the payback period could double or triple when lifecycle emissions are taken into account (depending on the type of system), it would still be very short considering a PV system's typical lifetime of 25-30 years.

Solar PV manufacturing emissions intensity and payback period



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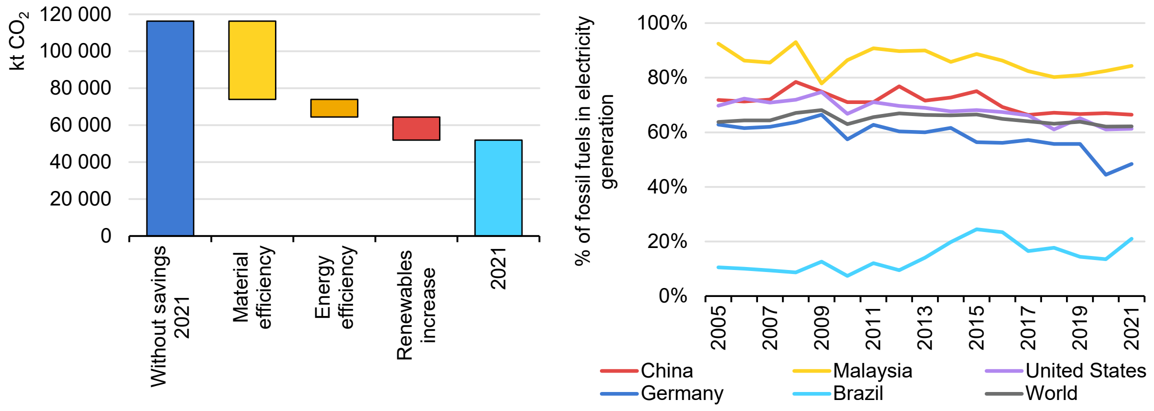
Notes: Each data point represents a country. The analysis assumes that renewable electricity generation from solar PV capacity displaces fossil fuels in the electricity mix, based on their current share.

The emissions intensity of PV manufacturing has fallen 45% since 2011 with process improvements and a switch to low-carbon electricity generation

Contrary to absolute emissions, the emissions intensity of solar PV manufacturing has decreased almost 45% in the last decade thanks to material and energy efficiency improvements as well as declining electricity generation from fossil fuels.[3] Without these improvements, total CO_2 emissions in 2021 would have more than doubled to over 116 000 kt CO_2, corresponding to 0.32% of total global energy-related emissions.

Three factors can be credited for this trend. First, material efficiency in polysilicon manufacturing contributed almost two-thirds of overall CO_2 emissions reductions. Second, energy efficiency improvements in producing polysilicon reduced emissions by 9 500 kt and, finally, a greater share of low-carbon electricity in China and other production centres was responsible for 20% of the reduction. In most key manufacturing hubs, including China, Germany and the United States, the share of fossil fuels in electricity generation has decreased by 5 to 14 percentage points since 2011.

Solar PV manufacturing CO_2 emissions savings in 2021 (left) and share of fossil fuels in electricity mix per country (right)



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Note: Left figure indicates possible emissions levels in 2021 without material and energy efficiency improvements, if electricity mixes had remained unchanged since 2011.

Sources: Right graph: IEA (2021a). Left graph: IEA (2022b; 2021e). IEA analysis also based on BNEF (2022a), PVPS, InfoLink, UN Comtrade.

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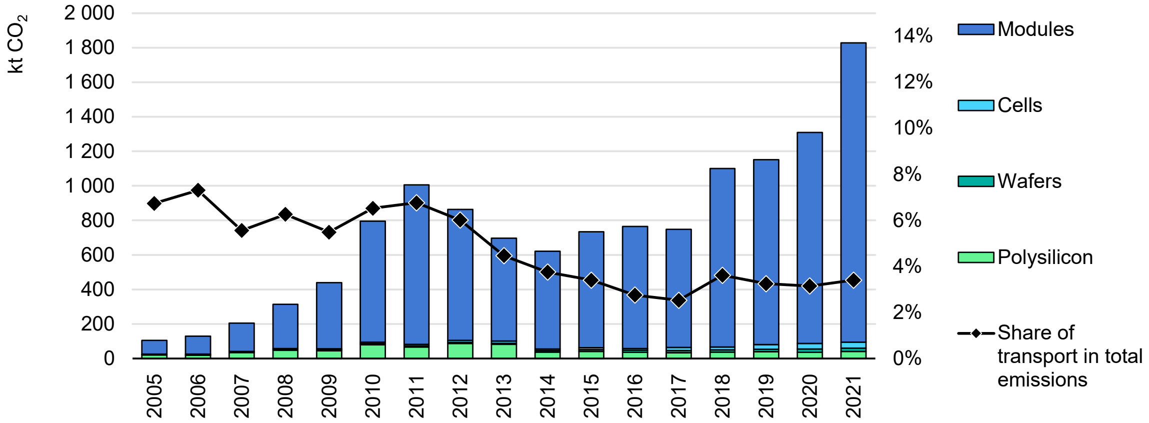
[3] Emissions intensity in kg CO_2/kW represents the number of kilogrammes of CO_2 emitted with production of one kW of polysilicon, wafers, cells or modules.

Transport accounts for only 3% of total CO_2 emissions from solar PV manufacturing

Transporting solar PV products produces far less emissions than manufacturing them does, especially because the transport share has been declining since 2011. Weight, distance and means of transport are the key variables that determine emissions associated with transporting PV goods.[4] Accounting for an estimated 95% of PV transport-related emissions in 2021, assembled modules are the heaviest of all PV components shipped, travelling primarily from China to various global markets.

Although CO_2 emissions from transporting modules fell 35% from 2011 to 2013, they climbed again in 2015 despite trade volume stability. First, China's domestic demand increased drastically with the country's share in global annual installations growing from 12% in 2012 to almost 45% in 2016. Meanwhile, trade routes for solar PV modules shifted away from Europe and towards Japan, India and Australia instead, meaning that Chinese exports travelled shorter distances, reducing overall transport-related emissions.

Absolute CO_2 emissions associated with transport of PV components



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Sources: IEA (2022a). IEA analysis also based on BNEF (2022a), PVPS, InfoLink and UN Comtrade.

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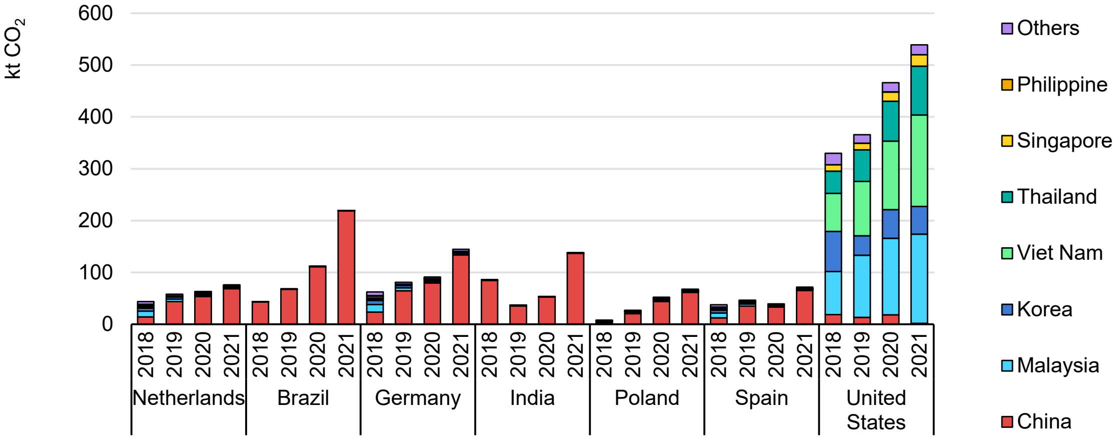
[4] For this report, calculations are based on emissions resulting from transportation within the various supply chain segments and from transporting finished modules from manufacturing country to installation destination. Transport emissions are calculated individually by segment and year, and from country of origin to destination. For each entry, the weight of goods transported and packaging material were calculated, then distributed into containers of forty-foot equivalent units and twenty-foot equivalent units. The IEA Global Energy and Climate Model (IEA, 2022a) provided data on distances between country of origin and destination and on emissions intensity for each transport mode. The main mode of transport was decided based on distance, switching and mixing among maritime shipping, rail freight and heavy-duty truck.

In 2021, however, long-distance exporting increased again – with distances doubling in most cases – as products moved from Viet Nam and Malaysia to the United States, and from China to India, Germany, Brazil, Spain and France.

The United States had the highest emissions from module imports, accounting for over 31% of total module trade-related emissions globally. Although the United States has domestic module production, it meets only 30% of the country's demand, which rose an average of 30% per year in the last three years.

Due to the high number of panels China transported and the distances they travelled before reaching destinations such as Europe, Brazil and India, transport-related emissions originating from Chinese exports accounted for over 62% of all module export-related emissions worldwide.

Absolute CO_2 emissions associated with module transport in high-import countries



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Sources: IEA (2022a). IEA analysis also based on BNEF (2022a), PVPS, InfoLink and UN Comtrade.

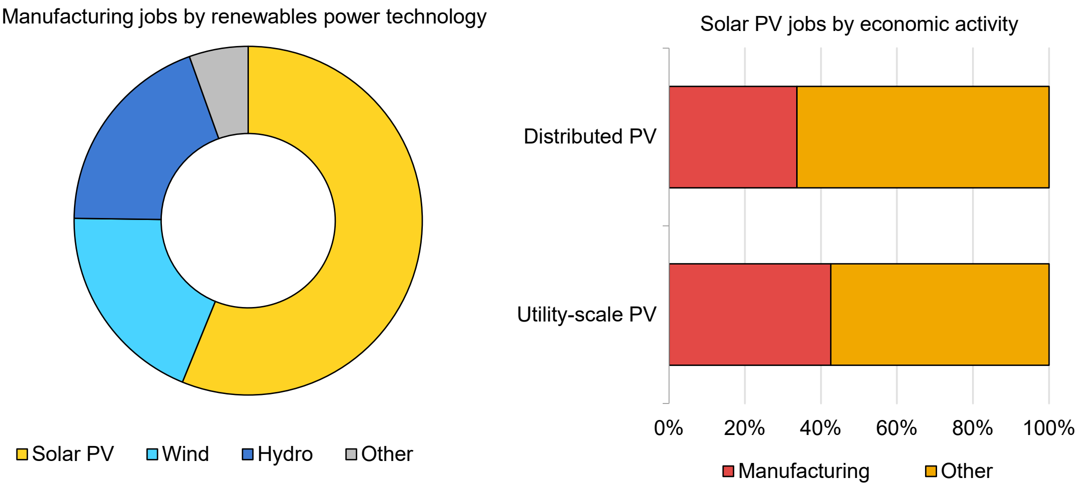
Job creation

China and ASEAN countries hold almost 90% of global PV manufacturing jobs

Solar PV is one of the most employment-intensive sectors of all renewable and fossil fuel energy technologies. Most solar PV jobs worldwide involve constructing plants and installing panels on residential and commercial rooftops – providing more employment than is associated with their manufacture. However, local downstream jobs that involve mostly electricians, engineers and sales professionals are highly dependent on local demand that can fluctuate annually due to policy changes and market developments. Meanwhile, manufacturing jobs, although smaller in number, contribute to local economic development and are perceived by many governments as sustainable long-term employment.

We estimate that the total number of jobs worldwide associated with manufacturing polysilicon, wafers/ingots, cells and modules more than doubled in the last decade to nearly 600 000 in 2021. In addition, manufacturing other equipment associated with solar PV systems (e.g. inverters, racking and mounting) also provided employment. For instance, inverter production accounts for nearly 50% of PV manufacturing jobs in Europe (Solar Power Europe, 2021), while racking and mounting make up nearly 20% of PV manufacturing jobs in the United States. However, a lack of country-level data prevents comprehensive analysis of jobs associated with solar PV manufacturing.

Renewable technology total manufacturing jobs by technology (left) and PV manufacturing by upstream and downstream segments (right)



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Notes: Employment estimates are based on IEA energy investment, capacity and production data, and are calibrated using amalgamated data from national statistics, international governmental organisation databases (including the International Labour Organisation), company reports and academic literature. Energy employment encompasses all direct jobs in energy facility construction and operation, and jobs related to manufacturing direct inputs specific to the energy industry. Indirect employment associated with general goods (e.g. cement production) is not counted as energy employment, and neither is induced employment included. As much as possible, these estimates also attempt to capture informal employment.

Source: IEA (2022c).

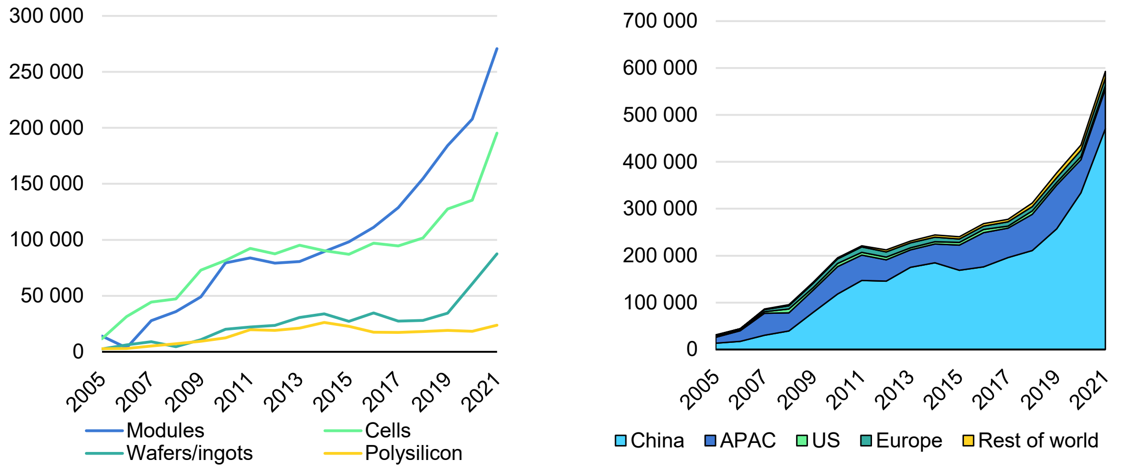
Of the main processes, module production creates the most PV manufacturing jobs (46%), followed by the making of cells (33%), wafers/ingots (15%) and polysilicon (just 4%). The manufacture of other materials such as glass, EVA and backsheet represents an additional 2% of employment in this domain.

In 2021, over three-quarters of all solar PV manufacturing jobs were in China, followed by the Asia-Pacific region (14%), Europe (3%) and the United States (1%).

The consolidation of manufacturing jobs in China and Southeast Asia accelerated in the past decade to take advantage of relatively low labour costs, subsidies for equipment and energy, cost efficiency gains offered by automation and company/plant integration, and bankruptcies in Europe and the United States. Furthermore, processes that were historically manual have become increasingly automatised, increasing output and reducing labour requirements.

During 2005-2011, global solar PV manufacturing jobs increased nearly eightfold to meet a 20-fold demand increase. While in 2005 the United States and Europe held nearly one-quarter of total global PV manufacturing jobs, incentives changed after the 2011 deployment boom in Europe and production moved rapidly to China and the ASEAN region to benefit from lower costs and to comply with trade restrictions. Thus, European countries and the United States lost over 20% of employment in this area from 2011 to 2014.

Total PV manufacturing jobs per segment (left) and by region (right)



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Notes: APAC = Asia-Pacific. Jobs per segment are calculated based on publicly available totals and plant-level government and company data for 2005-2021.

In 2021, nearly 85% of the world's polysilicon manufacturing jobs were in China. In addition to its industrial policy supporting domestic solar PV supply chain segments, the Chinese government imposed antidumping import duties on American and Korean polysilicon in 2010/11. These trade measures contributed to a nearly 35% increase in polysilicon jobs in China from 2013 to 2014. Greater automation and low labour costs have also helped move wafer, cell and module-manufacturing jobs to China and Southeast Asia, where the average hourly wage for these employees can be around 90% lower than in Europe and the United States. China has the most employment associated with wafers, cells and modules at nearly 80%, followed by Malaysia, Thailand and Viet Nam.

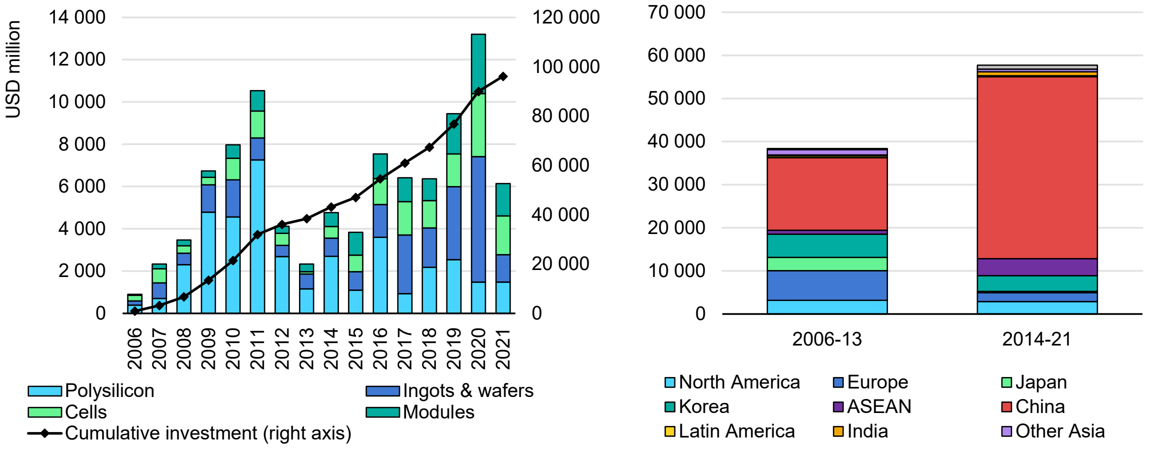
In 2021, nearly 85% of all PV-related manufacturing jobs were in just four countries. In part to help stimulate local labour markets, 16 countries have policies in place to reshore manufacturing, creating over 19 000 jobs in total in nascent markets such as Brazil, India, Türkiye and South Africa. However, countries with reshoring policies are home to less than 4% of total global solar PV manufacturing jobs.

Investment

Mismatched PV supply and demand leads to volatile annual investment in solar PV manufacturing plants

Global cumulative investment in solar PV manufacturing facilities more than doubled in the past decade to almost USD 100 billion in 2021. Overall, polysilicon and ingots/wafers together account for almost 70% of all investment in solar PV manufacturing due their high capital requirements. While annual solar PV installations have increased consistently since 2006, yearly investment volumes for manufacturing PV products have been volatile, ranging from less than USD 1 billion to as high as USD 15 billion. This inconsistency results mainly from periods of overinvestment being followed by years of underinvestment, widening the supply and demand balances of several products in the PV supply chain.

Solar PV manufacturing facility investment by segment (left) and by country/region (right), 2006-2021



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Notes: ASAEN = Association of Southeast Asian Nations. Investment numbers are associated with the manufacturing facilities' commissioning dates. The partial commissioning of large plants is taken into account.

For polysilicon, investments rose rapidly during 2008-2011 because escalating demand for solar PV installations resulted in polysilicon shortages as early as 2005, with the spot price reaching a record of almost USD 400/kg[5] – more than ten times today's price. Having peaked in 2011, investment in polysilicon production plants declined significantly due to 50% overcapacity, followed by the spot price falling below the historical low of around USD 10/kg. Investment levels from 2017 to 2021 were relatively modest, mainly because of the economies of scale achieved in China, where larger production facilities were installed at very low investment costs.

Annual investments accelerated again in 2016 to reach a new peak in 2021 as wafer, cell and module production expanded massively to meet growing demand in China following introduction of the government's generous FIT scheme. Over 2014-2021, global investment in solar PV manufacturing increased 50% from the previous seven-year period. It also shifted from Europe, Japan and Korea to China and ASEAN countries. During this period, China invested more than USD 50 billion cumulatively in solar PV manufacturing facilities, mostly for wafer and cell production, which has boosted investment volumes.

Financial performance

Integrated PV companies financially outperform pure-play companies, but still lag behind other similar industries

Solar PV industry profitability in the past decade has been volatile, showing lower average profit margins than the oil, coal, chemical and semiconductor industries. As profitability of companies in any sector is a key indicator to measure the financial health/performance of an industry, it is critical for the long-term sustainability of any sector, particularly those expected to expand rapidly such as solar PV.

Vertically integrated solar industry manufacturing companies have consistently been the most profitable business segment since 2014. They outpace pure-play companies active in only one specific solar PV supply chain segment because they are able to compensate for losses in one segment through profits in another. In

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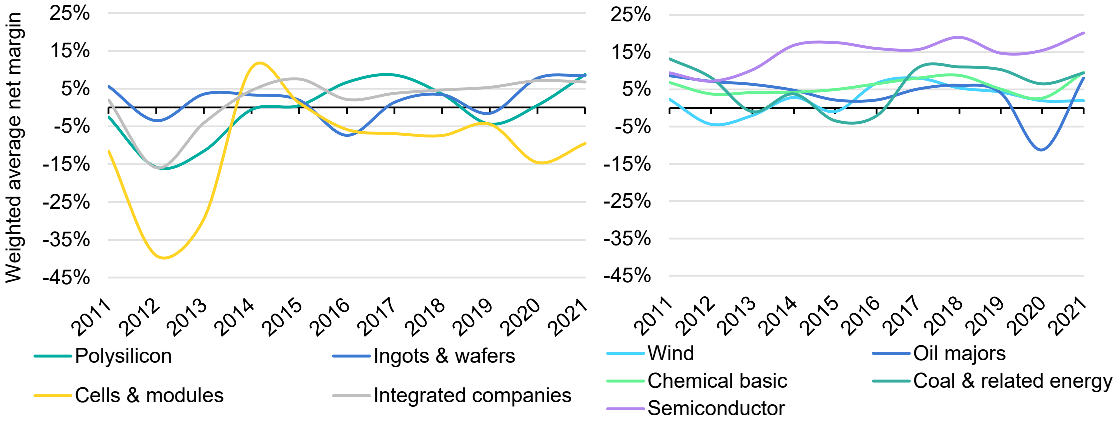
[5] Long-term purchase contracts well below the USD 400/kg spot price were also common, so not all manufacturers were exposed to high prices.

addition, 80% of medium-sized integrated companies[6] in China are also solar PV power plant developers receiving stable revenues through long-term contracts.

The polysilicon business, which is a subsector of the chemical industry, has been the second most financially underperforming part of the PV supply chain compared with the chemical industry, which had an average profit margin of 6% in the last decade. Similarly, wafer manufacturing has had profit margins ranging from -5% to a maximum of 10%, significantly lower than those of semiconductor production. Cells and modules have underperformed the most financially, as they account for the largest share of manufacturing costs, and competition among suppliers is fierce.

Profit margins of solar PV supply chain segments (left) and of other industries (right)



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Notes: Companies covered for each segment:

Polysilicon: Wacker Chemie AG, OCI Co Ltd, GCL-Poly Energy Holdings Ltd, REC Silicon ASA, LDK Solar Co Ltd, Tokuyama Corp, Daqo New Energy Corp, Tongwei Co Ltd, Xinte Energy Co Ltd and Osaka Titanium.

Ingots & wafers: Sino-American Silicon Products Inc, Comtec Solar Systems Group Ltd, Beijing Jingyuntong Technology Co Ltd, Shuangliang Eco-Energy Systems Co Ltd, Golden Solar New Energy Technology Holdings Ltd and Woongjin Energy Co Ltd.

Cells & modules: Motech Industries Inc, Gintech Energy Corp, China Sunergy Co Ltd (CSUN), United Renewable Energy Co Ltd, Shanghai Aiko Solar Energy Co Ltd, GCL System Integration Technology Co Ltd, TSEC Corp, Tainergy and Vikram Solar Pvt Ltd.

Integrated companies: JA Solar Technology Co Ltd, JinkoSolar Holding Co Ltd, Longi Green Energy Technology Co Ltd, Tianjin Zhonghuan Semiconductor Co Ltd, Risen Energy Co Ltd, Canadian Solar Inc, Trina Solar Co Ltd, Solargiga Energy Holdings Ltd and First Solar. (First Solar is a thin-film-based company with integrated manufacturing that covers the processing of raw materials to module assembly.)

Wind: Siemens Gamesa RE, Vestas Wind Systms, Suzlon Energy Ltd, China Longyuan Power Group Corp Ltd, Boralex, Dongfang Electric Corp Ltd, Xinjiang Goldwind Science & Technology, Sinovel Wind Group Co Ltd and Guodian Technology & Environment.

Oil majors: BP, Chevron, Exxon Mobil, Shell and Total.

Sources: Based on Bloomberg (2022b). Damodaran (2022) for historical to present global averages for “chemical basic”, “coal & related energy” and “semiconductor” categories.

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[6] An integrated company manufactures in at least three segments of the PV value chain. Medium-integrated companies produce a minimum of 5 000 MW in one segment.

Supply gluts in the solar PV sector have created considerable profit margin volatility since the late 2000s when China began to strengthen and expand its domestic solar PV industry through financial support, innovation and R&D spending. Naturally, China’s policies spurred many manufacturers in the country to expand their production.

Between 2011 and 2013, erratic global demand impacted the profitability and investment cycles of solar PV manufacturers. Declining demand in Europe, the largest market at the time, led to global overcapacity in all supply chain segments. Polysilicon, cell and module prices dropped drastically, resulting in lower-than-expected revenues and bankruptcy for many solar PV manufacturers with high exposure to debt.

A similar trend affected the wind industry in 2012, but lower losses were incurred because wind turbine manufacturers were regionally diversified compared with solar PV companies, which are concentrated mainly in China. By the end of 2013, local solar demand in China had recovered with sustained financial support from the Chinese government, leading to a profitability increase for all solar industry segments.

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Chapter 2 – Solar PV supply chain vulnerabilities: Security-of-supply implications for clean energy transitions

Solar PV supply security in the pursuit of net zero targets

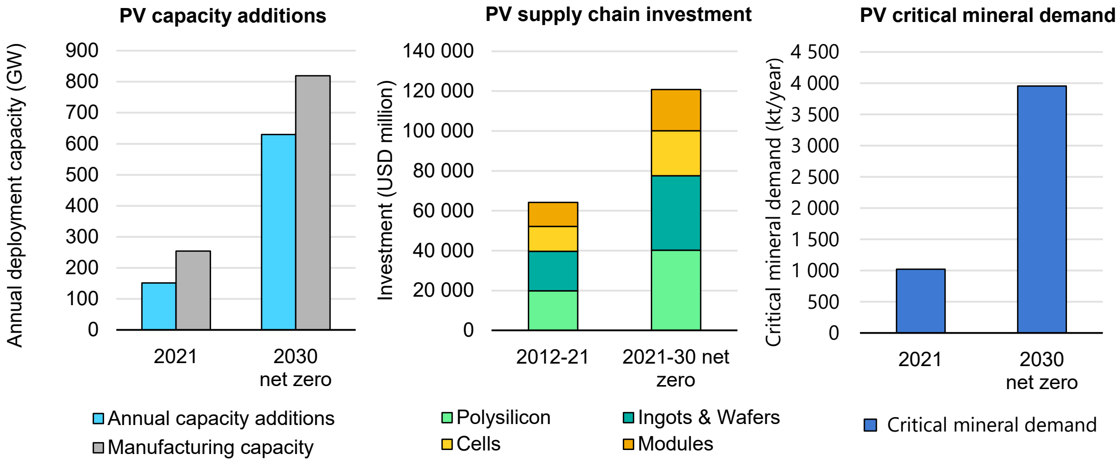
Achieving the IEA Net Zero by 2050 Scenario goals will require rapid solar PV uptake in the next decade. However, the rapidity of solar PV growth and its potential dominance of global energy supplies raise security-of-supply concerns. This chapter aims to identify the primary vulnerabilities along the solar PV supply chain that may slow the pace of expansion globally. Left unaddressed, these weak spots may lead to higher prices or supply constraints that could impede the transition to clean energy sources or make it more costly.

PV supply chain vulnerabilities have already created supply concerns in the United States. In June 2022, the country amended tariffs on solar panels because of “an emergency … with respect to the threats to the availability of sufficient electricity generation capacity to meet customer demand” (The White House, 2021a). The United States took this action to help alleviate solar PV supply concerns and maintain its energy security as well as GHG emissions reduction targets and affordable-energy objectives.

Globally, the average number of annual solar PV installations would need to nearly quadruple over the next decade to be consistent with the IEA Net Zero Scenario. By 2050, solar PV should provide one-third of total global electricity generation, up from 3% in 2021. According to current IEA forecasts, however, current government policies are not strong enough to boost solar PV demand to an adequate level.

Should governments establish policies consistent with their net zero ambitions, the solar PV supply chain, including mineral provision and polysilicon, wafer, cell and module production, would have to expand to support PV deployment. Under IEA Net Zero modelling, annual PV capacity additions grow to 630 GW in 2030, up from a record 150 GW in 2021.[7] Production capacity would need to reach 750-850 GW by 2030 to supply enough panels, since production plants cannot all operate at 100% capacity all the time. Material provision will need to expand as well: in fact, critical mineral demand would rise to 4 000 kt per year by 2030, up from 1 000 kt in 2021.[8]

Solar PV capacity additions (left), supply chain investment (centre) and mineral demand (right), 2021 and 2030 under the IEA Net Zero by 2050 Scenario



Sources: Left graph: IEA (2021f). Centre graph: IEA analysis based on BNEF (2022b), PVPS, PV InfoLink, SPV and RTS PV. Right graph: IEA (2021d).

Defining security of supply

This report is centred around security-of-supply concerns associated with manufacturing polysilicon, wafers, cells and modules, although it also provides some discussion on mining and installations. Manufacturing is the primary focus because security-of-supply aspects of critical minerals have already been considered in detail in *The Role of Critical Minerals in Clean Energy Transitions* (IEA, 2021d), and *Power Systems in Transition* (IEA, 2020b) addressed electricity provision.

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[7] Capacity additions cover utility and distributed solar technologies.

[8] A mineral is considered critical for the energy transition when energy sector demand for this material is anticipated to represent a significant share of global demand under clean energy transition scenarios. Copper is included, for example, because it is necessary for clean energy transitions and the energy sector is likely to be responsible for more than 40% of global demand by 2040 in a clean energy transition scenario. Steel is also necessary for clean energy technologies but is not included because even in a net zero scenario the energy sector would require only a small share of global demand. For solar PV, the focus minerals are silver, indium, silicon, copper, selenium, gallium and tellurium.

In the case of solar PV, a secure supply chain able to accommodate the needs of a net zero pathway would be adequate, resilient, affordable and sustainable:

- **Adequate:** The solar supply chain has the production capacity to meet growing demand in the long and short term.
- **Resilient:** The supply chain can absorb, accommodate and recover from both short-term shocks and long-term changes, including material shortages, climate change, natural disasters and other disruptions.
- **Affordable:** PV production remains cost-effective in meeting long-term climate goals in most markets.
- **Sustainable:** Production is sustainable in terms of financial, social and environmental viability.

Oil and natural gas have been at the heart of global energy security discussions since the 1970s. They have attracted much analysis, leading to the formulation of several policy frameworks globally as well as creation of the International Energy Agency. While mineral and material supply concerns still exist in the context of clean energy transitions, they differ in a number of ways from those that apply to oil- and gas-based energy systems:

- **Nature of impacts:** While sudden supply disruptions along the PV supply chain would impact PV deployment, they would not affect production from existing solar installations. This is fundamentally different from oil and gas supply disruptions, which have immediate and broad impacts on price and availability.
- **Material vs energy flows:** As solar panels are durable material goods that enable free solar energy to be converted into electricity, this study focuses on the provision of solar modules.
- **Global view:** While each country will have its own security-of-supply concerns and priorities, our analysis addresses supply security at the global rather than individual country level.

Each section below examines principal vulnerabilities and risks along the PV supply chain as determined through discussions with governments, industry and civil society, as well as through IEA analysis. Any state of the supply chain that leaves it susceptible to supply risks is considered a vulnerability. Each section provides examples of risks that have already or may yet impact security of supply, or price increases that could slow deployment.

Principal security-of-supply vulnerabilities and risk exposure

Vulnerability factor	Consideration	Potential associated supply chain disruption risks
Jurisdictional concentration	To what extent is the share of production concentrated in one single jurisdiction?	• Domestic policy changes • Geopolitical events
Geographic concentration	To what extent is the share of production concentrated in one single geographic area?	• Natural hazards such as earthquakes and fires, and extreme weather events such as drought and flooding • Technical failures of electricity, gas grids or other infrastructure
Facility concentration	To what extent is the share of production concentrated in one single facility?	• Above risks, plus: • Onsite equipment failure
Market concentration	To what extent is the share of production concentrated in one single company?	• Risk of collusion, price fixing and dumping
Pace and scale of growth	Are material supplies and production harmonised with demand?	• Long lead times for mining capacity and manufacturing facilities • Non-substitutability of some materials • Low labour and skills availability
Financial health of the PV sector	To what extent are manufacturers and integrated companies exposed to financial and bankruptcy risks?	• Bankruptcy risk from volatile prices • Changes to subsidies or other market changes
Trade restrictions	How globalised and dependent on international trade and trade policies is the PV supply chain?	• New or changing trade policies restricting the free flow of solar PV materials

Vulnerabilities of the solar PV supply chain

Supply chain concentration

The solar PV supply chain is highly concentrated in terms of jurisdictions, geographies, individual facilities and companies

Concentration along the PV supply chain at the jurisdictional, geographical, plant and company level make the supply chain vulnerable to single incidents, whether they be a country’s individual policy choices, a natural disaster, a war, a pandemic, technical failures or individual company decisions. Historically, all these risks have materialised, leading to higher prices and likely slowing the pace of solar PV deployment.

Jurisdictional, geographic and facility concentration

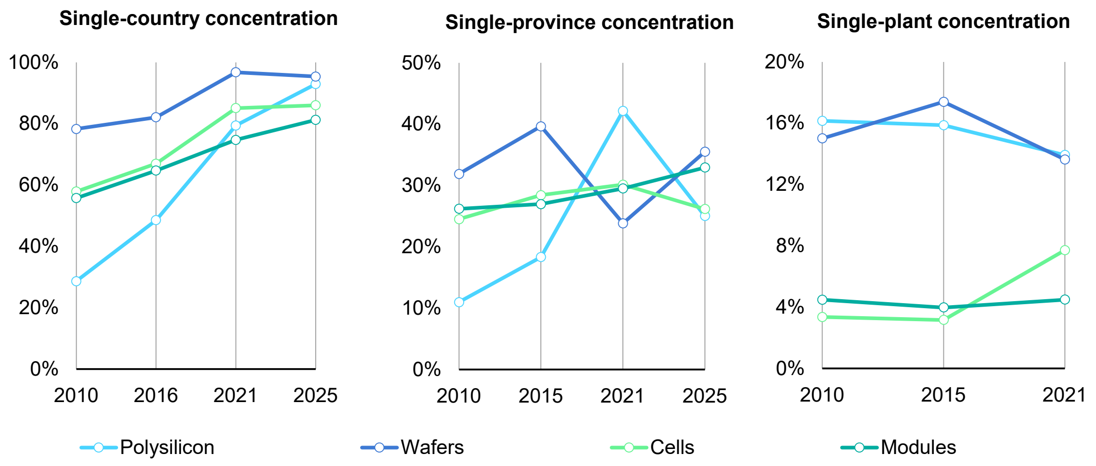
Polysilicon, wafer, cell and module manufacturing are concentrated in China, with as much as 42% of the value chain’s manufacturing capacity in one single Chinese province and up to 14% in one single manufacturing facility in 2021. While polysilicon and wafer manufacturing are generally more concentrated than cell and module production at the country, province and plant level, a survey of plants under construction and planned indicates that concentrations may increase in the next five years for most supply chain segments.

China was home to 79% of global polysilicon capacity in 2021, with 42% of it in Xinjiang province. This province also has the country’s largest polysilicon plant, which alone accounts for 14% of global production capacity. Several new polysilicon plants are planned for China, likely increasing the country’s market share, but they are outside of Xinjiang, which will help reduce concentration in that province.

Wafer manufacturing is the most concentrated supply chain segment, with China accounting for 97% of global capacity. However, it is more provincially distributed than polysilicon, with significant capacities in the Jiangsu, Yunnan, Inner Mongolia, Tianjin and Jiangxi provinces. The single largest manufacturing facility accounts for 14% of global production capacity.

Cell production concentration is lower than for wafers, with 85% located in China, and most of this capacity is in the three provinces of Jiangsu, Zhejiang and Sichuan. Cell production is less concentrated in one single facility than polysilicon and wafer manufacturing, but it is still significant at 8%.

Country, province and single-plant concentration as shares of global manufacturing capacity



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Note: 2025 values based on projects under construction, proposed and planned.

Source: IEA analysis based on BNEF (2022b), IEA PVPS, SPV Market Research, RTS Corporation and PV InfoLink.

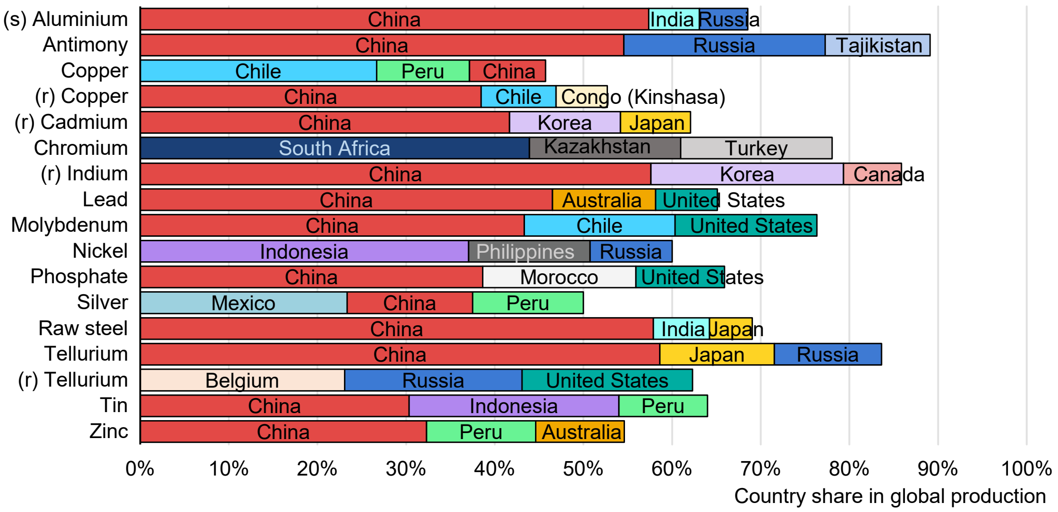
Module-manufacturing capacity is more distributed globally and across production facilities, but it is still relatively concentrated provincially in China. In 2021, the country held 75% of the world's module-making capacity, with 30% located in Jiangsu province. At the facility level, however, modules are the least concentrated, with just 4% of production capacity in the single largest plant. Viet Nam, Malaysia, Korea and India are home to 12% of the globe's module production capacity.

Raw materials used in solar PV manufacturing – for instance the silver used in crystalline silicon cells, the tellurium used in thin-film technologies, the copper used for cell and module connections, and the antimony used in solar-grade glass – are also concentrated in a small number of countries. For each of these minerals, the collective share of the top three producing countries is 50% or more of global supply.

Furthermore, just a handful of countries are the top producers of multiple raw minerals, as exemplified by China, which supplies the vast majority of aluminium, antimony, cadmium, molybdenum, tellurium, tin and zinc used in the solar PV industry, and also dominates copper refining. Although solar PV demand accounted for less than 5% of total global consumption of these materials in 2021 (with the exceptions of silicon [6%], silver [11%] and tellurium [47%]), as solar PV production expands, so will material demand.

While some of these materials can be partly or completely substituted, this generally entails module performance or manufacturing cost trade-offs. Plus, adapting manufacturing processes to use alternative materials can take time. This lack/slow pace of substitutability is a deployment risk, since module producers cannot switch quickly to other materials when prices are high.

Top three producing countries' shares in global production of selected minerals used for solar PV manufacturing, 2021



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Notes: (s) = smelter production. (r) = refinery production. Other values correspond to mine production.

Source: USGS (2022).

High provincial and facility-level concentrations present the greatest natural and technical disaster risks. For instance, a 2020 explosion at a polysilicon facility in China put 8% of global polysilicon production capacity out of operation. This is the largest of four polysilicon plant closures in 2020 resulting from flooding and technical issues. While each incident occurred at a different time, together they led to an estimated 4% decline in annual production in an already-tight polysilicon market, contributing to the near tripling of prices between 2020 and 2021. In 2021, silicon and wafer production in China were also curtailed when regulators required producers to cut production as part of energy-saving measures. As of early July 2022, a fire at polysilicon facility in Xinjiang and the ensuing maintenance requirements reduced global production by 0.5%. Even this comparatively small disruption contributed to price increases.

Concentrating production within a single geographical region or country also exposes the supply chain to risks from changes in diplomatic relations among countries as well as alterations in domestic policies and infrastructure. For instance, shipping times from China to US and European ports increased from around 40 days to more than 100 following the Covid-19 outbreak. In fact, shipping delays also continue to plague deliveries to Japan and Korea, which may slow deployment in 2022.

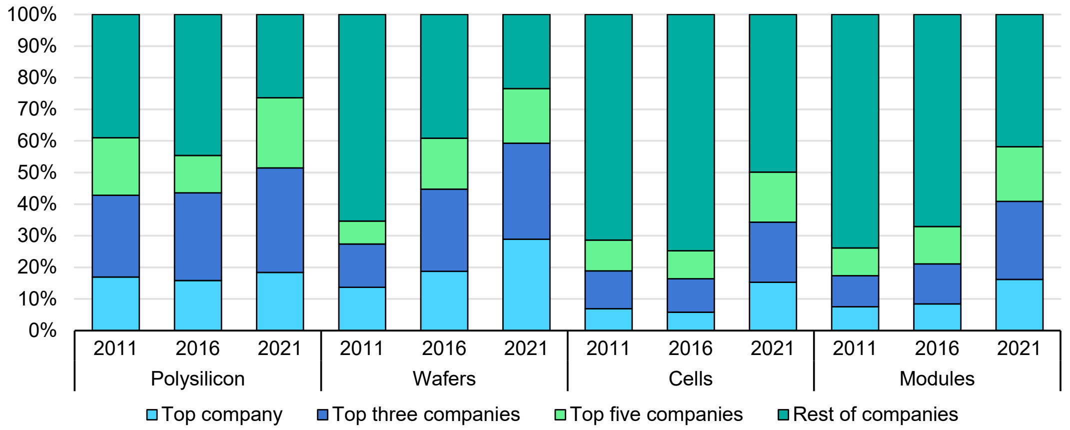
Overall, polysilicon, wafer, cell and module production capacities are all becoming more concentrated, leaving the supply chain more vulnerable to risks.

Market concentration

The production capacity of solar PV supply chain segments is also concentrated at the company level, introducing vulnerabilities to another set of risks. Similar to geographic concentration, a small set of companies accounts for an ever-larger share of global capacity.

Wafers are the most company-concentrated, with over 75% of manufacturing concentrated in the top five enterprises and the largest producer accounting for 29% of global output. For polysilicon production, company concentration is similar and just one company accounts for 18%. Company concentration for cells and modules is lower, but it has been increasing in the past five years.

Concentration by the top, three top and five top companies as shares of total capacity



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Source: IEA analysis based on BNEF (2022b), IEA PVPS, SPV Market Research, RTS Corporation and PV InfoLink.

Concentrating production capacity among just a few companies introduces the risk of having a small set of companies working together to increase profits at the cost of higher consumer prices and quicker dissemination. This situation can lead to collusion, price fixing, dumping and other behaviours that reduce competition and ultimately boost prices and retard deployment.

Wafer production capacity is considered moderately concentrated, according to US horizontal merger guidelines that indicate that mergers above a certain threshold could raise competitiveness concerns (DOJ, 2010). Polysilicon market shares are more distributed among the top five companies, so production is less at risk of competitiveness impacts than that of wafers. Meanwhile, cell and module-manufacturing capacity is more distributed than that of polysilicon and wafers, implying fewer competitiveness risks.[9]

To date, the United States, the European Union, India and Türkiye have levied antidumping duties on specific firms based on evidence of dumping and impacts on domestic companies (Federal Register, 2015; Gazette of India Extraordinary, 2019; Official Journal of the European Union, 2018; Türkiye, Ministry of Economy, 2017). However, these cases do not demonstrate collusion among companies, as they implicate individual companies only. Expertise is another commodity that can be concentrated among a small number of companies, limiting the pace of technology transfer.

Pace and scale of growth

Current and planned manufacturing capacity is insufficient to meet the IEA Net Zero trajectory

For production to expand at the strong pace and sustain manufacture levels prescribed by the IEA Net Zero Scenario, the solar PV supply chain will need to expand in step with solar PV demand. However, initiating faster and larger growth exposes the supply chain to the risks of material unavailability and industry capacity insufficiency. Project lead times present one critical risk, as mines and production facilities can be built only so quickly. Additionally, mining operations are exposed to climate risks as well as increasing environmental and social-performance scrutiny.

Polysilicon production capacity can be a limiting factor in global production capacity expansion, followed by ingot and wafer manufacturing. In fact, polysilicon production would have to more than triple from today's level by 2030 to support the IEA Net Zero trajectory. As of 2022, expected polysilicon capacity additions would close just one-quarter of this gap.

The production of ingots and wafers, and of cells and modules, would all need to nearly double by 2030 from today's levels. In addition to plants already under construction, Chinese companies have announced ambitious expansion plans

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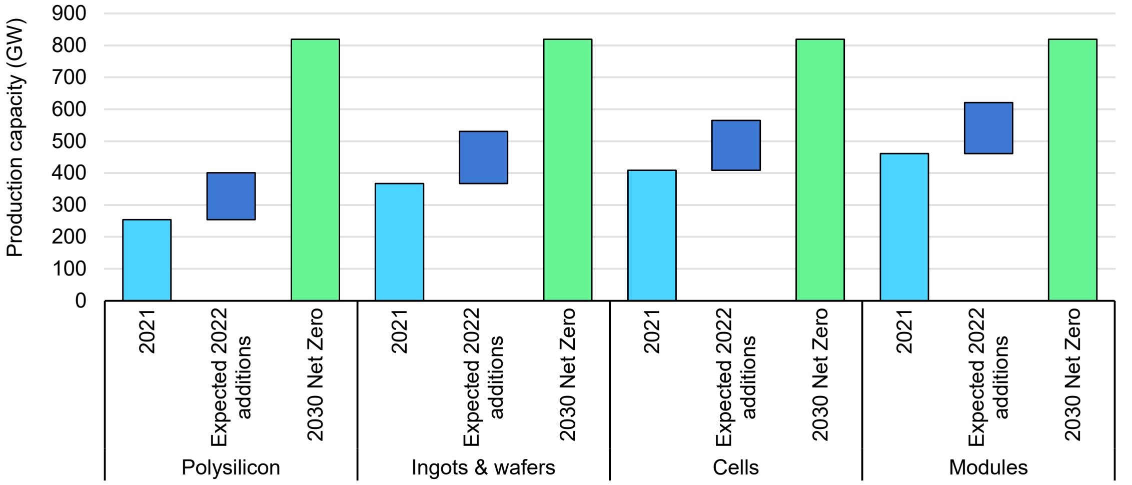
[9] One measure of market concentration is the Herfindahl-Hirschmann Index (HHI). In the United States, in markets with HHI scores above 1 500, mergers that increase the HHI by 100 warrant scrutiny for potentially serious competitiveness impacts (DOJ, 2010). In the European Union, regulators are unlikely to identify competition concerns in markets with HHIs between 1 000 and 2 000 if mergers increase the HHI by less than 250 (Official Journal of the European Union, 2004). In 2021, the wafer market's HHI was near 1 600 and polysilicon's was 1 300.

across the supply chain, which would further close the gap to achieve the IEA Net Zero trajectory. However, realisation of these plans remains uncertain, and investment decisions will depend on a number of factors, including demand, subsidy rates, prices, international competition and trade policies.

Solar PV supply chain capacity in operation and under construction, and gap to Net Zero by 2050 Scenario, 2021 to 2030



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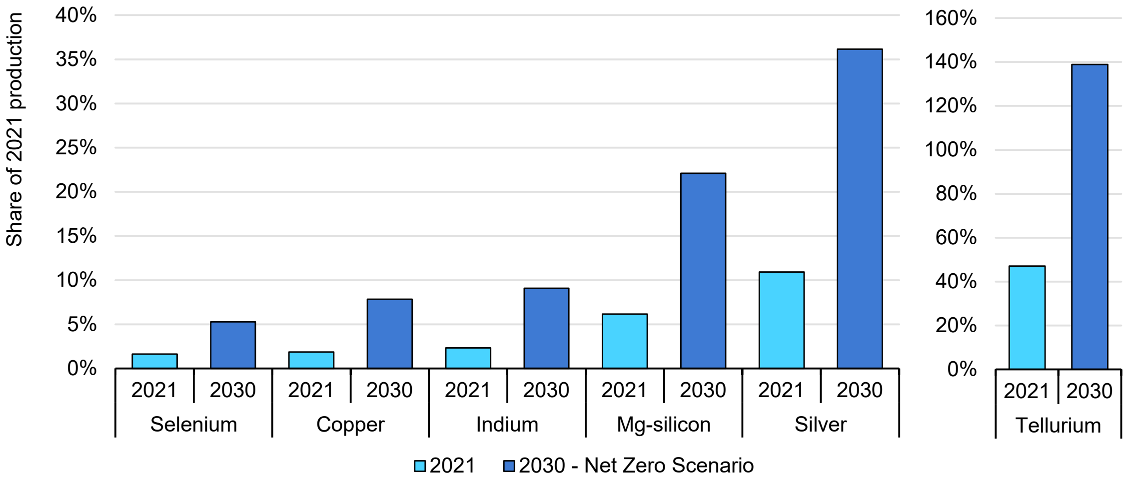
Sources: Under construction: IEA analysis based on PVPS, PV InfoLink, SPV and RTS. 2030 Net Zero: based on (IEA, 2021g), manufacturing capacity to satisfy 630 GW of annual capacity additions.

Ramping up solar PV production will also require adequate critical mineral supplies. In 2021, solar PV demand already claimed 11% of global silver production, over 6% of metallurgical-grade silicon and over 40% of all refined tellurium produced. We estimate that PV industry demand for critical materials would have to expand 150-400% by 2030 from the 2021 levels (depending on the material) to attain the IEA Net Zero trajectory.

This level of growth may increase the PV share of total critical material demand: for instance, solar PV silver demand in 2030 under the IEA Net Zero Scenario would be equivalent to over 35% of 2021 production. This assessment accounts for ongoing increases in material efficiency, stemming from both greater panel efficiency and less material usage per panel. For example, silver content per cell decreased one-third between 2009 and 2018 (CRU, 2018), and we assume the silver intensity per kW of solar PV to further decline by one-quarter through 2030.

PV industry demand for selected minerals in 2021 as percentages of global 2021 production, and in 2030 in the IEA Net Zero by 2050 Scenario



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Notes: Mg-silicon = metallurgical-grade silicon. For this figure, we assume CdTe modules to represent 4-5% of the global solar PV market between 2021 and 2030 and the market shares of CIGS modules to decline from 1% in 2021 to 0.8% in 2030. During the same period, the silver intensity of crystalline silicon PV is assumed to decline by one-quarter and polysilicon intensity is assumed to decline by one-fifth.

Sources: Based on IEA (2021d; 2021g) and USGC, 2022.

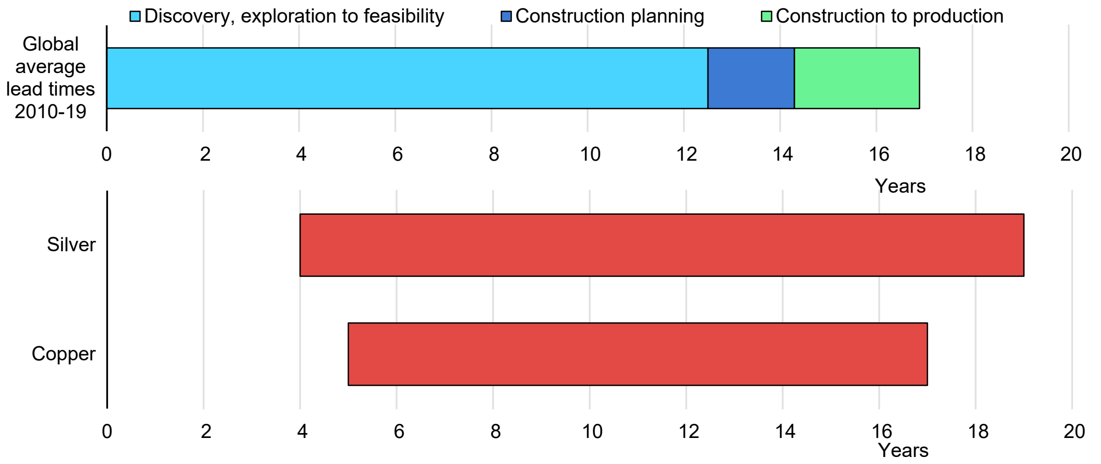
As solar PV production scales up, rising demand for raw materials may surpass mining and refining production capacity, especially given simultaneous demand growth from other clean energy technologies.

Long lead times may prove a hindrance to supply expansion

Lead times for mining operations averaged 17 years between 2010 and 2019, from discovery to first production, although the exact duration varies by mineral, location and mine type (IEA, 2021a). Exploration and feasibility studies often required 13 years, and construction 4 years. Such long lead times can result in timing mismatches between mineral demand and supply capacity. Solar PV is just one source of demand for materials such as copper, and overall clean energy technology consumption and its share of total demand is expected to increase on the IEA Net Zero trajectory (IEA, 2021a). Thus, any mismatches in supply in demand may have an impact on solar pricing and material availability.

Furthermore, antimony, cadmium, tellurium, indium and selenium, used primarily in thin-film technologies, are recovered as by-products of mining or refining primary mineral commodities such as copper, zinc, lead and gold. For some minerals, such as tellurium, this can imply a margin for higher recovery rates in existing production routes.[10] However, it also means that the production of these by-products depends on that of the primary mineral commodities, since it is often not economical to produce them separately. As a result, it can be difficult to adapt to rapidly changing demand for these by-product minerals. Both long lead times and by-product uncertainty can contribute to price variability, since supply can often lag behind demand for years.

Average mining project development lead times for silver and copper



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Note: Silver and copper mining lead times include for uses other than solar PV manufacturing.

Source: IEA (2021d), The Role of Critical Minerals in Clean Energy Transitions.

Lead times for manufacturing plants are shorter than for mining projects. However, they can vary significantly among different supply chain segments and from one country/region to another. New polysilicon manufacturing plants have longer lead times than wafer, cell and module facilities, with durations ranging from 12 to 40 months depending on the region. In addition to the lengthy period needed for construction, polysilicon facilities ramp up slowly to reach their full capacity. China has both the shortest construction times and quickest ramp-up periods.

For ingot and wafer plants, development timelines are usually shorter and lead times are relatively consistent among key countries/regions. Cell and module factories can be deployed in 3-12-months in most parts of the world. For all segments, lead times in the European Union and the United States are significantly longer than in other countries and regions, mainly due to lengthier development, permitting, land acquisition and construction timelines in addition to slower ramp-up.

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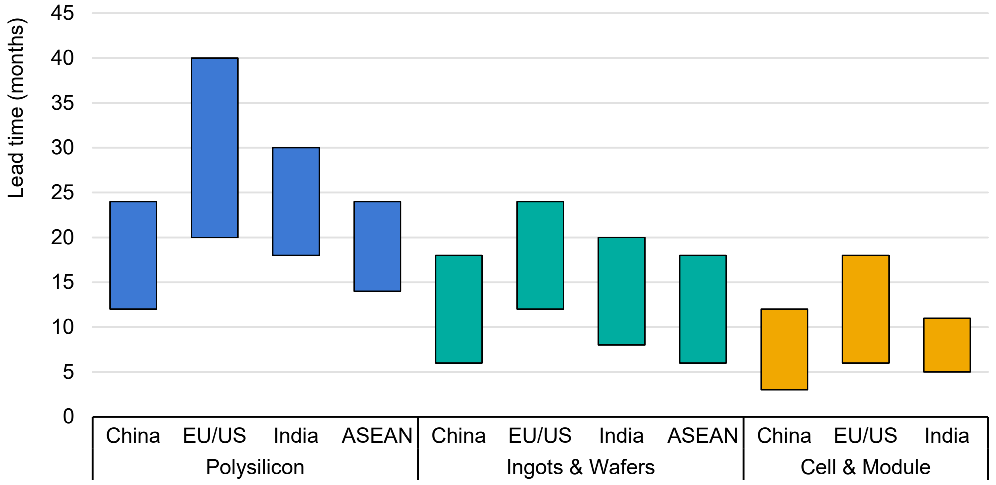
[10] Recent estimates suggest that more than two-thirds of tellurium contained in copper anode slimes generated during electrolytic copper refining is currently not recovered, indicating significant potential to increase supplies for thin-film PV technologies and other applications (Nassar et al., 2022).

Relatively longer development timelines for polysilicon facilities have led to supply shortages in the solar PV industry. For instance, annual solar PV installations doubled from 2003 to 2004 and increased another 30% in 2005, but global polysilicon supplies could not keep pace because manufacturers in Europe, the United States and Japan were not able to expand production for another 2-4 years. As a result, the polysilicon price gradually climbed from around USD 30/kg in 2003 to almost USD 400/kg in 2008, so shortages and high prices reduced the solar PV installation rate in 2005 and 2006.

The solar PV industry is currently facing another polysilicon shortage due to plant fires in China and annual additions expanding more than 20% from 2019 to 2020 and another 12% last year. As a result, polysilicon prices more than tripled from USD 10/kg in January 2021 to USD 34/kg in April 2022. As the price increased, polysilicon's share in module costs rose from 10% in early 2020 to almost 30% in 2022. These price increases were high enough to raise solar module prices, reversing a 20-year trend of declining costs.

Relatively shorter lead times in China are expected to bridge the gap between demand and supply by 2023 as new plants are commissioned. Nevertheless, overall rising module prices remain a challenge to faster solar PV expansion, increasing the risk of delays and cancellations, especially for developers that submitted lower bids in auctions and did not anticipate module price increases.

Lead times for solar PV manufacturing investment by supply chain segment and country/region



Notes: ASEAN = Association of Southeast Asian Nations. IEA analysis, based on lead times of projects already implemented as well as those announced by companies and governments, covers 2018-2022. Lead times cover the number of months from the announcement of projects to their commissioning.

Mining operations are faced with a host of other risks as well. For instance, copper mines are affected by declining ore quality and reserve exhaustion, or they are nearing peak production. Mining assets are also exposed to increasingly intense climate risks, water stress and greater scrutiny of social and environmental performance (IEA, 2021a).

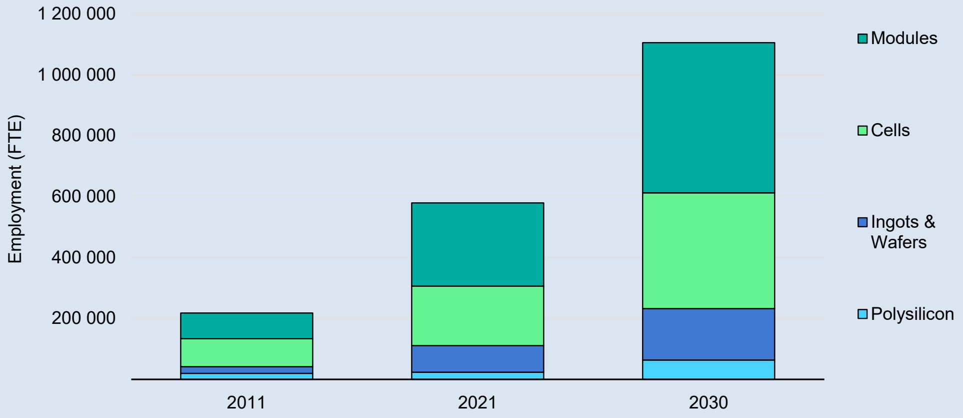
This combination of rising demand, long lead times and reliance on by-products increases the risk of supply and demand mismatches, which can lead to cost increases and shortages.

Could skilled labour and expertise shortages slow growth in PV manufacturing?

Globally, labour supplies are not keeping up with demand, and the gap is widening for clean energy sectors globally (ILO, 2019). However, the scale of the risk to PV supply chains is unclear because country-level and international assessments of employment needs and gaps along the PV supply chain are lacking. Nevertheless, there are signs that labour shortages could reduce the pace and scale of growth as well as production quality outside of China and the Asia-Pacific region.

On the IEA Net Zero pathway, employment in PV manufacturing would need to nearly double over the next decade, to support expanded polysilicon, wafer/ingot, cell and module manufacturing. Along the solar PV supply chain, almost 40% of workers require formal training (e.g. electrical engineers and technicians), while 60% require minimal formal training (IRENA, 2021). There are, however, overlaps with existing jobs: for instance, electrical engineers can work on solar projects as well as other, more traditional employment. Nevertheless, the scale of growth will require a net increase in certain skills and more training programmes for solar-specific jobs such as installation.

Global employment by segment in 2010 and 2020, and forecast to 2030



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Sources: Based on public employment reports and IEA (2021f).

The United States, Europe and India are all interested in building domestic solar PV supply chains, but they currently employ just a small share of the global workforce in this domain. Should these regions shun imports while neglecting to invest in their own labour markets, labour constraints could impair global PV deployment. In the **United States**, labour forecasts show a shortfall in workers such as semiconductor-processing technicians, structural metal fabricators and fitters and electricians that would be needed to support greater manufacturing capacity (The White House, 2021b).

The Department of Energy also notes that although the United States was previously a leader in silicon cell production, most of this area's intellectual property has moved to China, Southeast Asia and Europe. Expanding cell production would therefore require the United States to invest in technology development and to forge partnerships with companies and institutions from regions with the necessary intellectual capacity (DOE, 2022a). Expanding critical mineral supplies would also be challenging, as the US mining workforce is ageing, retiring or working abroad.

The **European Union** also suffers from a lack of specialisation in the solar industry across the supply chain (SolarPower Europe, 2020), and **India** is likewise short of workers, especially for research and development (JMK and IEEFA, 2021).

Nevertheless, this hurdle is surmountable. University and college programmes, certification courses, awareness campaigns and on-the-job training can all help enlarge the qualified workforce. It is essential, however, that governments align support for these programmes with production ambitions.

Furthermore, although not the focus of this study, a shortage of installers has been reported across major markets, including the United States, Europe, Australia and India, but direct price and supply impacts are difficult to establish. In the United States, 92% of project developers report difficulty finding qualified labour for construction (DOE, 2022b). Meanwhile, the solar industry in Europe is warning of a looming installer bottleneck (SolarPower Europe, 2020), and in India, labour shortages (exacerbated by Covid-19 restrictions) slowed solar PV deployment across the country in 2020 (JMK and IEEFA, 2021). In Australia, labour availability is already becoming a major challenge for solar installation companies, as one in three industry jobs (including electrician and installer jobs) is at risk of remaining unfilled in 2023 (Infrastructure Australia, 2021; PV Magazine, 2022).

Financial health of the solar PV sector

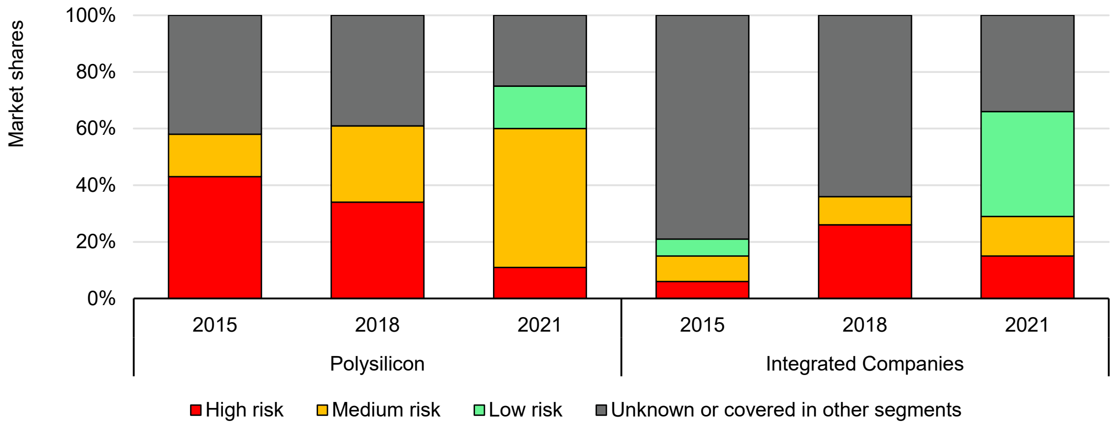
One-third of PV production capacity is at medium or high risk of bankruptcy

High company concentration in the solar PV supply chain makes the financial health of large companies key to the sector's long-term sustainability, especially considering the formidable investments and expansions needed by 2030. Based on key financial indicators such as profitability, leverage, liquidity and solvency (also called Altman-Z scores[11]), a considerable share of large companies within each solar PV supply chain segment have been at risk of bankruptcy since 2015.

In 2021, integrated companies with a high risk of bankruptcy operated 15% of global solar PV production capacity, down from 26% in 2018. Today, integrated solar PV companies make up two-thirds of the market share for ingots, wafers, cells and modules, and have operations in at least three segments of the value chain (polysilicon, ingots, wafers, cells and modules).

Owing to high polysilicon prices, the bankruptcy risk of polysilicon businesses dropped considerably in 2021. A return to low polysilicon prices could however, reverse this change. Despite current high prices, polysilicon remains the PV supply chain segment at highest risk, with 49% of global capacity considered at medium risk of bankruptcy in 2021 and 11% at high risk. In contrast, only 2% of companies involved in ingot, wafer, cell and module manufacturing were at high risk of bankruptcy in 2021.

Bankruptcy risks of polysilicon companies and integrated enterprises by market share, 2015-2021



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Source: IEA analysis based on BNEF (2022b), PVPS, PV InfoLink and RTS.

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[11] Altman-Z scores below 1.8 are considered at high risk of bankruptcy; between 1.8 and 3 are at medium risk; and scores above 3 have a low risk of bankruptcy.

In addition to high bankruptcy risks, the considerable financial support Chinese polysilicon companies receive in the form of grants and subsidies makes the polysilicon segment financially vulnerable. For instance, the largest polysilicon company posted net-losses between 2018 and 2020 despite government support. From a security-of-supply perspective, consistently poor financial performance within and across the solar PV value chain reinforces supply chain vulnerability to bankruptcies and underinvestment, which can reduce its resiliency, raise prices and limit PV deployment. Indeed, weak financial performance has contributed to bankruptcies in the past. For instance, following a major production capacity buildout in China, solar prices plummeted between 2011 and 2013 as supply far outstripped demand, causing a raft of bankruptcies across the industry. Although large companies such as Suntech Power Holdings (3% of production capacity at the time) were forced into bankruptcy, these bankruptcies did not slow global deployment because global production capacity remained higher than demand.

The overall long-term financial sustainability of the solar PV manufacturing sector is critical for the timely and cost-effective achievement of clean energy transitions. Bankruptcies and consolidation are part of industry maturation as more efficient companies outperform less efficient ones, and this process can indeed help reduce costs and strengthen PV supply chains. However, companies along the PV supply chain depend heavily on subsidies to maintain profitability, especially in China. Thus, sudden changes to subsidies would increase the bankruptcy risk for all companies, even the most competitive. Should competitive companies go bankrupt, this could lead to broader price increases and supply impacts, in addition to loss of the subsidy.

Trade restrictions

Trade barriers may slow deployment

Poorly designed and implemented trade policies, and uncertainty around them, can lead to price increases, delayed investment and slow solar PV deployment. As trade is critical to provide the diverse materials needed to make solar panels and deliver them to final markets, supply chains are vulnerable to trade policy risks.

China has become the primary exporter in the PV supply chain, as it now sends products to 42 countries.[12] China also imports materials, primarily polysilicon, when

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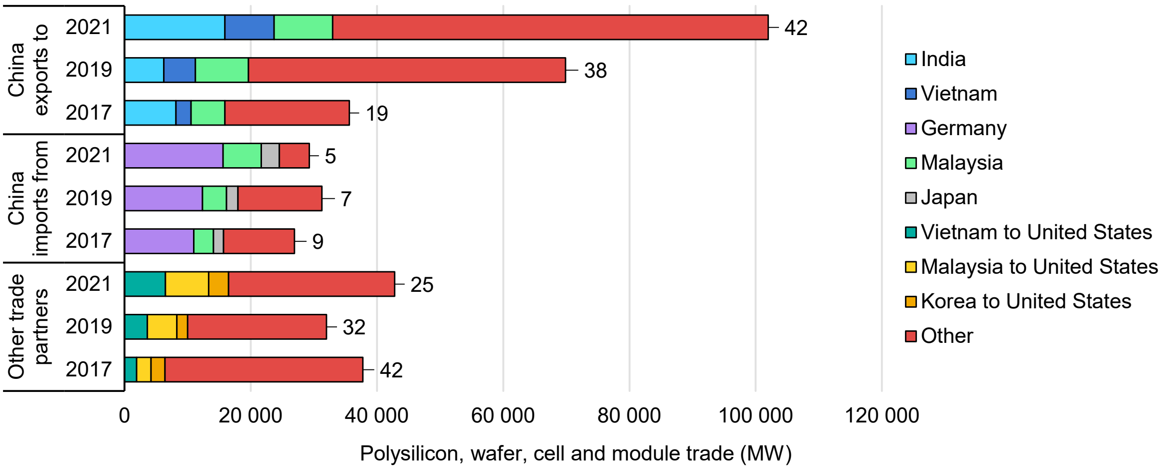
[12] Based on total polysilicon, ingot and wafer, and cell and module exports above 200 MW in a given year to a single country.

domestic supplies are unable to match demand. However, the number of countries it imports from decreased to just five in 2021.

Outside of China, there is an expanding trade network among other countries that does not directly include China. For example, trade from Viet Nam, Malaysia and Korea to the United States has more than doubled since 2017, following US policy changes and manufacturing capacity increases in these countries. While this report focuses on manufacturing, trade is also required for other materials and components used in the PV supply chain (e.g. steel, aluminium and silver, and finished equipment such as inverters).

Total trade, top trade partners and total number of trade partners, 2017-2021



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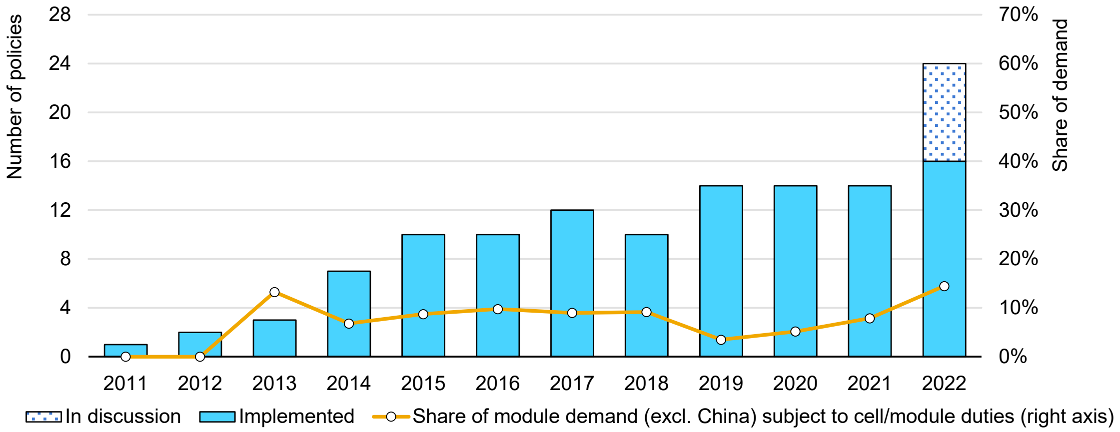
Note: Total trade is calculated based on amounts of at least 200 MW across the supply chain.

Sources: IEA analysis based on BNEF (2022b), PVPS, SPV and PV InfoLink.

Since 2011, the number of antidumping, import and countervailing duties levied against parts of the solar PV supply chain has increased from just one import tax (in Brazil) to 16 duties and import taxes, with another 8 other policies under consideration. For instance, to protect its polysilicon industry, China started imposing antidumping and countervailing duties on polysilicon producers in the European Union, the United States and Korea in 2014.

Similarly, India introduced antidumping and countervailing duties on glass for solar panels from China in 2016 and from Malaysia in 2019. In 2021, antidumping and countervailing duties and import tariffs on solar modules covered 8% of solar module demand, excluding China’s domestic demand. However, this share is set to climb to 15% this year because India has begun to impose a customs duty on modules from China.

Number of antidumping, import and countervailing duties, 2011-2022



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Note: Policies included for the EU, United States, India, Türkiye and Brazil representing two-third of global demand. Antidumping and countervailing duties are counted as one, import taxes or other duties are counted separately.

Source: Based on government-announced antidumping, import and countervailing duties applicable to all segments of the PV supply chain.

Trade actions can also extend beyond cost to address social and environmental considerations. For instance, both France and Korea have introduced carbon emission thresholds for solar panels to qualify for subsidies and tenders. Concerning social welfare, in June 2021 the US Customs and Border Protection agency issued a Withhold Release Order on shipments containing polysilicon from several producers in Xinjiang, China. The US Department of Energy estimates that this action led to 7 GW less solar panel imports, including 4.5 GW that were never produced and 2.5 GW that were redirected to other markets (DOE, 2022).

At the end of March 2022, the United States also launched an investigation into the circumvention of antidumping and countervailing duties on imports from Viet Nam, Malaysia, Cambodia and Thailand. These actions have contributed to the United States being “unable to import solar modules in sufficient quantities to ensure solar capacity additions necessary to achieve climate and clean energy goals, ensure electricity grid resource adequacy, and help combat rising energy prices” (The White House, 2021a). To ensure sufficient electricity capacity, the US government has removed duties on cells and modules from Cambodia, Malaysia, Thailand and Viet Nam starting in June 2022 for a maximum of 24 months.

Selected trade policies in force, 2021

Country	Trade action	Duty
United States	Antidumping and countervailing duties on crystalline silicon PV products produced in China (2015-2025) (US International Trade Commission, 2019) and Chinese Taipei (2015-2026) (US International Trade Commission, 2020)	Antidumping: 18.32-249.96% Countervailing duty; 14.78-49.79%
India	Basic customs duty of 25% on cells and 40% on modules starting in 2022 (India, Ministry of New and Renewable Energy, 2021) and antidumping and countervailing duties on solar glass and ethylene vinyl acetate (EVA) from China, Malaysia, Saudi Arabia and Thailand. Timing depends on country, but policies generally extend to 2023 (Gazette of India Extraordinary, 2019)	Duty depends on country, but ranges are USD 537-1 559/Mt for EVA and USD 52-136.21/Mt for glass
European Union	Antidumping and countervailing duties on imports from China, Malaysia and Chinese Taipei for solar glass, initiated in 2013 and extended to 2025 (Official Journal of the European Union, 2020a; 2020b)	Antidumping ranges from 17.5% to 75.4%. Countervailing duty is 3.5-17.1%
China	Antidumping duty on solar-grade polysilicon from the United States and Korea starting in 2014 and extended to 2025. (Federal Register, 2015)	Antidumping ranges from 4.4% to 113.8% for Korea and 30% to 57% for the United States
Türkiye	Import tax on all imports and antidumping duty on solar modules from China starting in 2017; no stated end date (Türkiye, Ministry of Economy, 2017)	Import tax set at USD 25/kg and antidumping duty at USD 20-25/m^2
Brazil	Import tax on PV equipment with some exemptions (Brazil, Ministério da Economia, 2022)	Up to 12% for modules and 14% for inverters

While individual trade measures may appear to reduce the number of installations in one jurisdiction only, their combined effect could be higher panel costs and compromised supplies, leading to fewer installations globally (Wang et al., 2021).

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Chapter 3 – Considerations for PV supply chain diversification

Supply chain disruptions during the Covid-19 crisis, record raw material prices and the Russian Federation's (hereafter, "Russia") invasion of Ukraine have raised numerous questions concerning the high dependency of many countries on imports of energy, raw materials and manufacturing goods that are key to their supply security. The solar PV supply chain is one of the most geographically concentrated supply chains globally, as China dominates raw material mining and refining and manufactures over 90% of critical inputs such as polysilicon, ingots and wafers. Key countries and regions with ambitious decarbonisation targets (including the United States, Europe and India) are therefore considering or already implementing policies to attract investment to localise manufacturing in multiple solar PV supply chain segments.

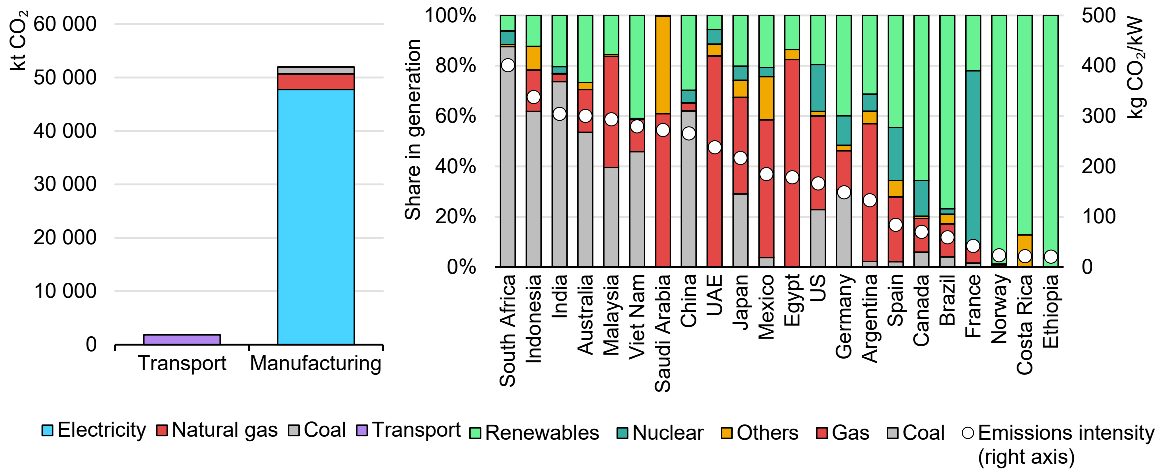
Diversification of the solar PV supply chain has both costs and economic benefits countries need to assess when designing and implementing policies. To assess these, countries should consider multiple factors such as job creation, investment requirements, electricity prices, CO_2 emissions, manufacturing costs and, finally, recycling. This chapter provides a comparative analysis of these elements, though all governments have their own specific policy goals and may thus emphasise just one, several or all factors in designing incentives for domestic solar PV manufacturing.

CO_2 emissions and electricity prices

Countries with a low-carbon electricity mix can offer decarbonisation as well as diversification benefits

A more geographically diversified solar PV supply chain could offer opportunities to reduce manufacturing emissions if new facilities are built in places with access to electricity that is less carbon-intensive than where current production is. At present, manufacturing modules generates far more emissions than transporting them to demand centres does. In fact, the single largest source of solar PV industry emissions is indirect emissions from electricity consumed in manufacturing. In 2021, the electricity used to produce solar panels was responsible for 89% of PV industry emissions globally, compared with just over 8% from direct consumption of fossil fuels and over 3% from transport. Thus, ambitious electricity decarbonisation goals in many countries will help reduce overall global solar PV manufacturing emissions.

Global PV industry emissions from manufacturing and transport in 2021 (left) and electricity generation by fuel source vs solar PV manufacturing emissions intensity for selected countries (right)



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Notes: Transport emissions includes the emissions from the trade of polysilicon, wafers, cells, and modules. US = United States. UAE= United Arab Emirates. “Emissions intensity” on right graph refers to the emissions factor for manufacturing polysilicon, wafers, cells, and modules for the solar PV industry. Shares in the electricity mix are for generation in 2021. Transport emissions includes the emissions from the trade of polysilicon, wafers, cells, and modules

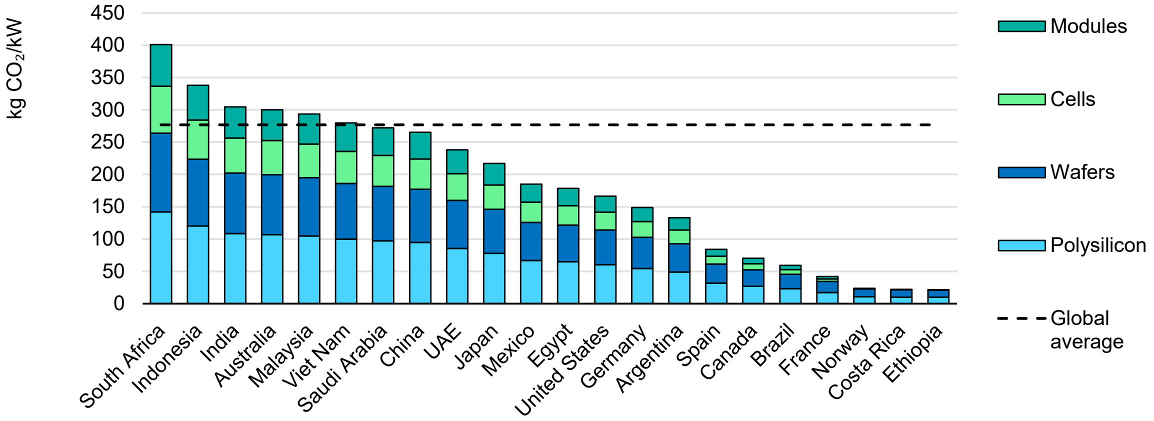
Source: Right graph: IEA (2022a).

As a result, the primary factor influencing the carbon intensity of solar PV manufacturing is the share of fossil fuels in a country’s electricity generation mix. In other words, countries that have higher shares of coal in their electricity mix would have higher indirect manufacturing emissions intensities than those that employ lower-carbon energy sources. For example, the hypothetical emissions intensity of producing all four PV manufacturing segments of the supply chain is high in South Africa, Indonesia, India and Australia because coal makes up over 50% of their power supply. Natural gas-dominated power grids, such as in Egypt and the United Arab Emirates, would manufacture products at slightly lower intensities based on their electricity mixes today.

Globally, the average carbon intensity of solar PV manufacturing is estimated at 270 kg CO_2/kW. However, there are over 100 countries where hosting the entire solar PV supply chain would emit less CO_2 compared to where production takes place today. Lower manufacturing intensities can be achieved if new production plants are built in places where the electricity mix has higher shares of low-carbon sources such as renewables or nuclear (e.g. Norway, Germany, Ethiopia and

Brazil). For instance, producing the entire PV value chain in Norway today, where the manufacturing emissions intensity would be around 25 kg CO_2/kW, could result in 90% lower manufacturing emissions than in China.

Hypothetical solar PV manufacturing emissions intensity for selected countries



Notes: Emissions intensities are based on estimated country-level energy mixes in 2021 for polysilicon, wafer, cell and module production. They do not include emissions from mining, extracting or processing raw materials, nor those associated with installing and constructing solar PV plants or distributed systems. They also exclude emissions from the production of module components including glass, backsheet, EVA and frames. Electricity prices, grid reliability and other key metrics for project viability are not considered.

Source: IEA (2021d).

Self-sufficiency is emerging as an option for diversification particularly among countries that aim to increase the share of solar PV in their electricity system significantly. In this sense, a trade-off between producing and importing could be considered. For instance, domestic manufacturing can reduce total CO_2 emissions if the local electricity mix is less carbon-intensive than in the importing country.[13] This would be the case for Germany, the United States and Brazil, where locally manufactured modules would be associated with 40-80% less emissions than those imported from China, Malaysia and Viet Nam. Emissions from transporting modules are relatively low compared with those from manufacturing, so this would be a deciding factor only if the energy mix in the other country or province is similar.

However, domestic solar PV manufacturing is not always less carbon-intensive than importing from China. For example, at today's power mixes, producing the entire supply chain in India or Australia would generate more manufacturing emissions than importing the finished modules from China. India's solar PV ambitions for both

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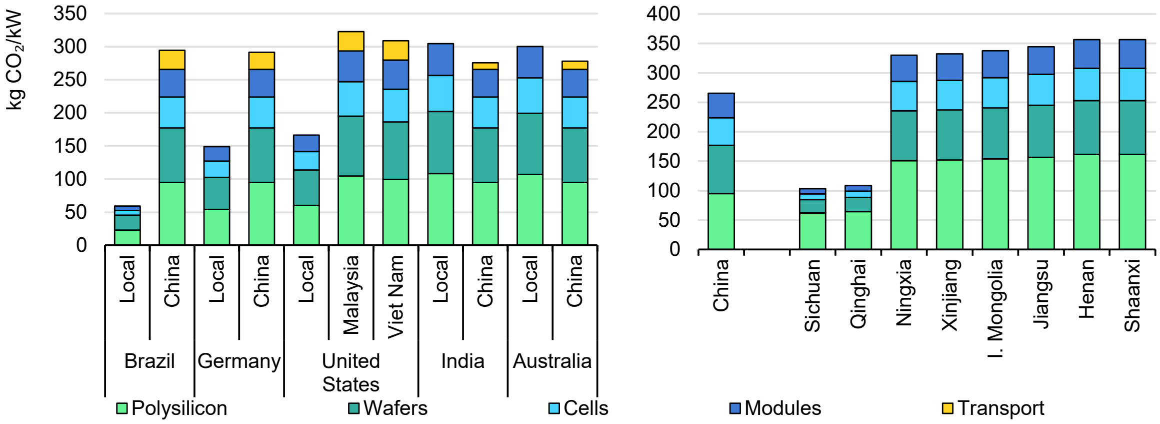
[13] Hypothetical manufacturing emissions intensities are calculated at the country level, based on yearly electricity consumption. However, more precise calculations of manufacturing intensity could be achieved if subnational and regional analyses were more granular and if temporal production variations were considered.

demand and supply, supported by concrete policies, are critical for solar PV supply chain diversification and resiliency. In the short term, however, manufacturing the entire solar PV supply chain in India would be almost 15% more emissions-intensive than in China. Therefore, a compromise between total or partial self-sufficiency and lower emissions will need to be reached while high-emissions-intensity countries work towards decarbonising their domestic power generation.

Less carbon-intensive manufacturing is also possible in China. While China's overall emissions intensity of solar PV manufacturing is relatively high, it varies significantly depending on which province solar PV supply chain segments are manufactured in. For instance, Shaanxi emits almost 360 kg CO_2 per kilowatt produced, whereas in Qinghai and Sichuan, hydropower accounts for the majority of power generation and their production intensity is around 105 kg CO_2/kW. Thus, solar PV imports from these two provinces would be associated with lower manufacturing emissions than imports from Germany, Japan or the United States. These spatial variations will be present in many countries. In addition, these hypothetical comparisons do not take the exact time of generation and consumption into account.

Hypothetical emissions intensity comparisons of local solar PV manufacturing vs imports from China (left), and emissions intensities of Chinese provinces (right)



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Notes: Emissions intensities based on estimated country- and provincial-level energy mixes in 2021 for polysilicon, wafer, cell and module production The graph represents the emission intensity if all segments are produced locally. Transport emissions cover only emissions related to shipping the final product (modules). Emissions intensity values for China are averages.

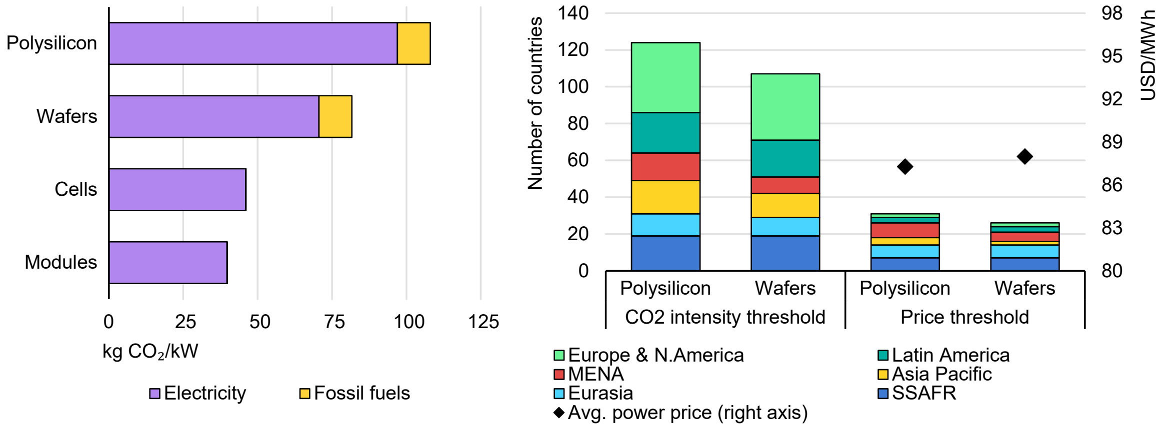
Source Left figure: IEA (2021a; 2021d). Right figure: IEA (2021a).

Manufacturing and transport emissions could be a key criterion for countries implementing carbon footprint assessments for solar PV products installed locally. For instance, France and Korea have already begun to include the embodied carbon footprint of solar PV panels as a criterion in their competitive tender evaluations for new power plants. Countries with ambitious climate targets are also considering policies for imported renewable energy goods, including solar PV (EU and the United Kingdom). Depending on policy design, greater scrutiny of the emissions intensity of manufacturing could encourage domestic manufacturing, which would contribute to supply chain diversification.

Diversifying and decarbonising require electricity to be both affordable and clean

Among all supply chain segments, the largest scope for reducing manufacturing emissions intensity through diversification is in polysilicon and wafers. The average carbon intensity of wafer manufacturing is currently around 82 kg CO_2/kW, and that of polysilicon production is 109 kg CO_2/kW. There are over 100 countries in the world that fall below the emissions intensity threshold, where manufacturing creates less emissions. Europe holds the highest potential, given the considerable shares of renewables and nuclear in its power mixes, followed by countries in Latin America and sub-Saharan Africa that have hydropower-dominated power systems.

Global emissions intensity from PV manufacturing by segment, 2021 (left), and countries below emissions intensity threshold vs average electricity tariffs for production (right)



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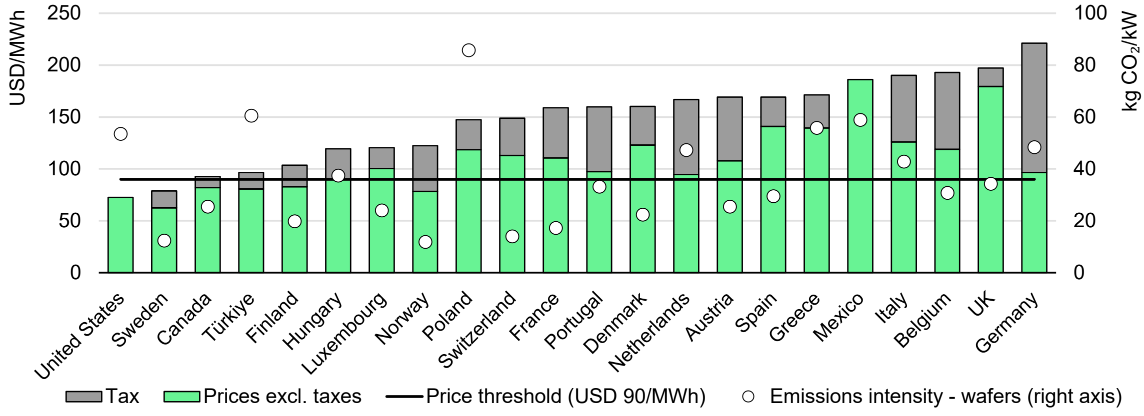
Notes: Left graph: Wafer manufacturing includes ingots. Emissions intensities refer to global emissions based on 2021 production values. Wafer intensity covers combined global production of both multi- and mono-crystalline technologies in 2021. Module intensity represents energy consumed to assemble cells and equipment into a module, not to produce each of the components (backsheet, glass, frame, etc.). Right graph: MENA = Middle East and North Africa. SSAFR = sub-Saharan Africa. Avg. power price = average retail industrial power price. Electricity prices are the weighted average of industrial retail prices in 2021, including VAT in polysilicon- and wafer-producing countries.

However, maintaining competitiveness in these segments will also require that manufacturers have access to electricity at costs comparable with or lower than today's global averages. For instance, the average price of industrial electricity is close to USD 90/MWh for polysilicon and wafer production. When this is taken into account, the number of potential locations where new manufacturing is competitively less carbon-intensive drops from 100 to around 30.

Given current electricity mixes, the number of potential locations for cleaner manufacturing could be higher if power prices were lower in Europe and Latin America. Except for Poland, every single European country could manufacture wafers below 75 kg CO_2/kW, which is less intensive than current production. However, only Sweden currently has low enough industrial power prices to manufacture these products competitively. Norway, Türkiye, Finland, the Netherlands and Hungary could also be candidates if their share of VAT and excise tax in industrial electricity prices were lower. In Latin America, about 20 countries could have manufacturing intensities below the global average for wafer and polysilicon production, but only Paraguay, Ecuador and Argentina have industrial electricity tariffs below USD 90/MWh.

Industrial electricity tariffs for selected countries in Europe and North America in 2021 and emissions intensity of wafer manufacturing



Note: Breakdowns of electricity prices into energy tariffs and taxes are not available for the United States and Mexico.

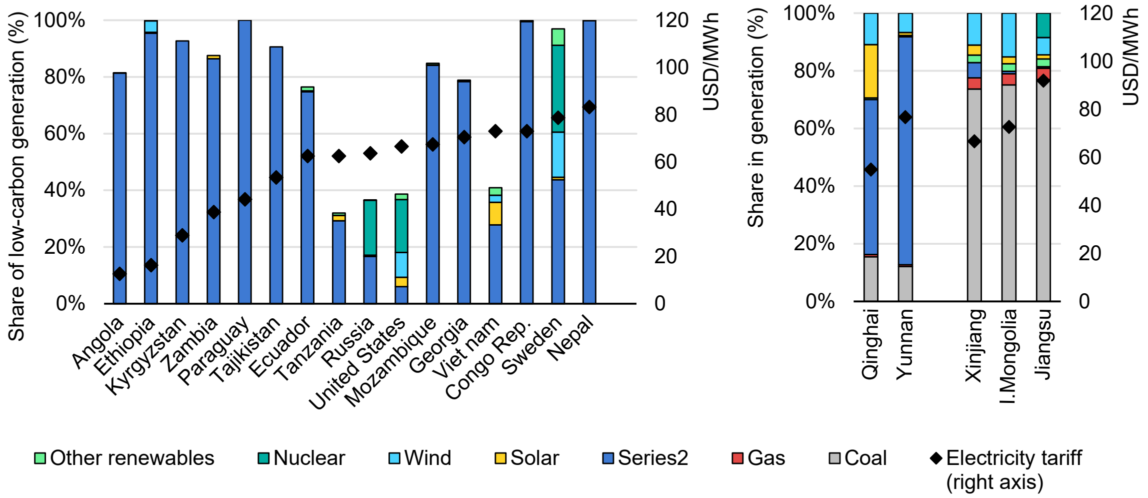
Sources: IEA (2022c), Energy Prices and Taxes for OECD countries 1Q 2022 (database).

In North America, the United States offers affordable low-carbon power, but retail prices in Mexico are currently too high. From a carbon-intensity perspective, manufacturing all PV segments in Canada would be suitable (70 kg CO_2/kW), but the price of electricity is at the threshold, which may be challenging considering cost-competitiveness, depending on the province.

In the Asia-Pacific region, relatively low electricity prices in Indonesia and Mongolia (below USD 80/MWh) present opportunities for cost-competitive solar PV manufacturing. However, today these countries have emissions intensities for manufacturing that exceed the global average due to high shares of coal in their power mixes. In India, new polysilicon or wafer production may be more economically challenging than in other countries in the region due to higher industrial electricity prices (USD 100/MWh). Considering India's electricity mix today, any new polysilicon and wafer manufacturing plants build in the country would also produce manufacturing emissions higher than the global average.

While industrial electricity prices in China are in the range of USD 60-80/MWh excluding subsidies, which enables cost-competitive manufacturing in many provinces, only five have carbon intensities lower than the global average today for polysilicon and wafers.

Shares of low-carbon generation and industrial electricity prices in selected countries with solar PV manufacturing intensities below the global average and electricity prices below USD 90/MWh (left) and in selected provinces in China (right)



Note: I. Mongolia = Inner Mongolia.

Sources: Left: IEA (2022a).

Roughly 30 countries offer competitive industrial electricity prices for new polysilicon and wafer production while at the same time presenting low manufacturing emissions intensities. The greatest number is in sub-Saharan Africa and Eurasia, where several countries have low-carbon shares exceeding 60% thanks to relatively high hydropower use. Hydropower could be key to lower emissions from wafer and polysilicon manufacturing because it offers affordable, carbon-free electricity to manufacture these products competitively. In fact, Angola, Ethiopia, Zambia and Mozambique all offer cleaner and less-expensive electricity than is currently being used to produce wafers and polysilicon in Xingjian, Inner Mongolia and Jiangsu.

Within China, however, hydropower also makes Qinghai and Yunnan provinces economically attractive sites with low-carbon intensities. Currently, several large manufacturers are moving polysilicon and wafer production to these provinces from more carbon-intensive Xinjiang. In Eurasia, hydropower offers clean, affordable electricity in Tajikistan, Kyrgyzstan and Georgia. A number of countries in the Middle East and North Africa, where gas makes up a large share of electricity production, also have affordable electricity tariffs for polysilicon and wafer production diversification.

Of the multiple pathways and business models available to decarbonise industrial electricity consumption and offer competitive electricity prices, some may also be applicable to polysilicon and wafer manufacturing. Industrial consumers can generate their own renewable electricity on-site for self-consumption and reduce their power bills, as the generation costs of most renewable electricity technologies are currently lower than retail industrial tariffs.

The most common technology for self-consumption is solar PV, but others such as wind, hydropower and biomass are also being used. These plants can be connected to the distribution grid or, alternately, be completely disconnected from the main network, in which case they are sometimes referred to as captive or off-grid plants. Large-scale captive solar PV and wind plants can produce electricity at USD 30-50/MWh – significantly below industrial retail prices. However, polysilicon and ingot production usually require a constant load for more than 24 hours. Thus, the economic viability of these captive plants will depend on how long a constant load will be needed for production and whether it needs to be collocated with storage, which would increase generation costs.

Other options include siting solar PV manufacturing facilities near other industrial consumers of renewable electricity (much like green hydrogen clusters or green steel consortia) to help aggregate demand and achieve economies of scale to cut costs. For instance, the renewable electricity demand of a large-scale electrolyser would be significantly higher than for polysilicon and ingot production, so co-locating these facilities would help reduce electricity costs. In addition, manufacturers could sign corporate PPAs that allow industrial consumers to purchase electricity directly from renewable power plants. However, some corporate PPAs are virtual in the sense that the power is still sourced from the grid and can be provided by non-renewable sources at the time of demand, thus not truly offsetting emissions in real time.

Investment costs

High investment costs for polysilicon and wafer manufacturing challenge the business case for projects outside of China

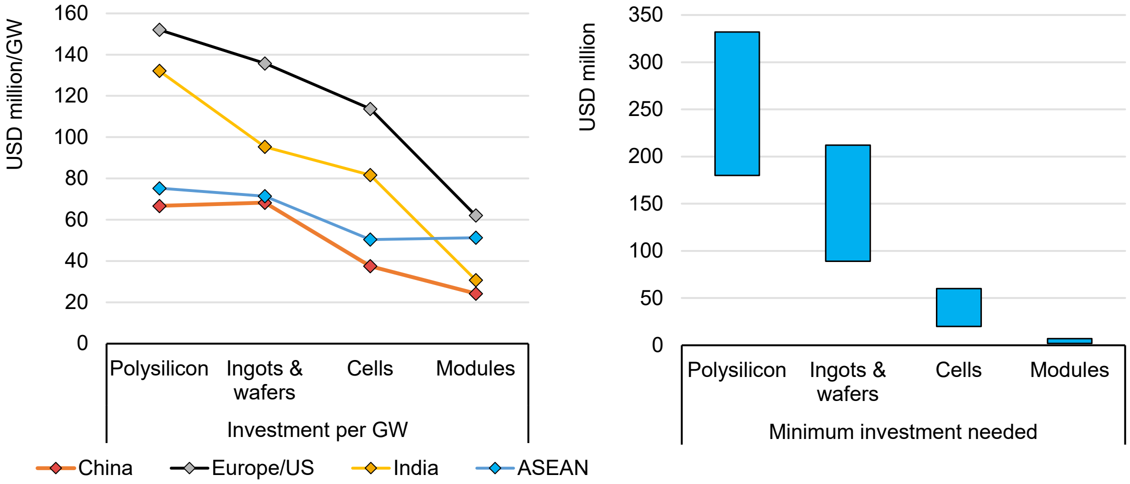
Capital requirements are a key consideration when companies consider investing in solar PV manufacturing and when policymakers design incentives to support businesses. High investment requirements for certain segments of the supply chain – especially polysilicon, ingots and wafers – usually increase project risks and reduce their bankability.

The amount of initial capital needed to establish a solar PV manufacturing facility varies significantly by country/region, type of equipment used, and costs associated with land, construction and financing. A manufacturing facility's size has a direct impact on the economies of scale that can be realised, affecting investment per megawatt. According to recently commissioned plant and equipment price data, polysilicon plants and ingot and wafer factories are significantly more CAPEX-heavy than cell- and module-manufacturing facilities. In addition, because of the considerable infrastructure investments needed (USD 200-400 million), greenfield polysilicon plants are not usually bankable for capacities of less than 10 000 Mt (around 3 GW).

For polysilicon, ingot and wafer manufacturing, benefitting from economies of scale is crucial to realise lower per-megawatt investment costs. Recent greenfield polysilicon plants in China range in size from 40 000 Mt to 100 000 Mt, almost tripling historical averages. For these projects, investment costs are around USD 60 million per gigawatt, with similar costs for ingot and wafer plants that have nameplate capacities of 5-20 GW per year, five times the capacity of facilities in other countries. Costs for energy-intensive polysilicon, ingots and wafers in Southeast Asian countries are estimated to be similar to China's, partly because they are developed mostly by integrated Chinese manufacturers.

Investment costs in the United States, the European Union and India are three to four times higher per megawatt than in China and ASEAN countries for polysilicon, ingot and wafer production. Longer construction and development timelines, considerable labour and material costs, the higher cost of capital, a lack of economies of scale and a dearth of knowhow in developing mega-scale PV manufacturing facilities remain key reasons for higher costs. For instance, experience in developing large-scale ingot and wafer manufacturing facilities is very limited outside of China, as the country holds over 95% of the market share.

Investment costs (left) and minimum investment requirements (right) by PV manufacturing segment



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Notes: ASEAN = Association of Southeast Asian Nations. Investment costs are based on investment estimates announced by companies for more than 100 manufacturing projects in various supply chain segments. For countries that do not have any commissioned manufacturing facilities for certain supply chain segments, data from feasibility projects or estimates were used.

For cells and modules, minimum investment requirements are low compared with the energy-intensive part of the PV supply chain. Cell and module-manufacturing plants could be as small as 100 MW, requiring very low minimum investments of around a few million US dollars. For solar cells, the scale of production remains important to achieve lower investment costs per megawatt, with costs estimated to be significantly higher outside of China due to much greater equipment, land and construction costs in Europe and the United States. Plus, the cost of European and American manufacturing equipment is three to four times higher than for machinery made in China and Southeast Asia, which explains the investment cost differentials between cell and module manufacturing.

Manufacturing costs

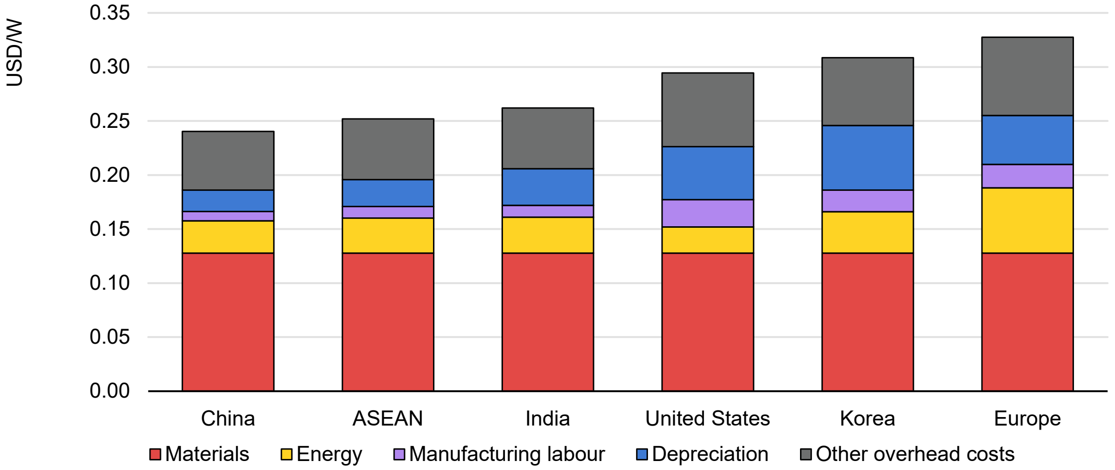
Energy, labour and investment cost differentials dictate cost-competitiveness in solar PV manufacturing

Manufacturing cost parity across regions and countries is critical for solar PV supply chain diversification. While cost differentials dictate whether a country's solar PV products are cost-competitive, they are also critical for policymakers to design policies that effectively support the solar PV sector, including manufacturing plants. Solar PV production costs currently vary widely across both components and locations.

Based on modelled assumptions for each supply chain segment, the total cost of producing modules in key countries and regions varies from USD 0.24/W in China to USD 0.33/W in Europe, excluding profit margins, taxes and transport fees. Although the cost of materials, which accounts for the largest portion of final module costs, can vary by country/region depending on purchase agreements and prices, most material inputs used in solar PV manufacturing are traded globally as commodities, which explains small differences across countries and regions.

Relatively low energy and investment costs (which lead to lower depreciation costs) and inexpensive labour make China the most cost-competitive location to manufacture all components of the solar PV supply chain. In the ASEAN region, total module-manufacturing costs can be around 5% more than in China, mainly due to slightly higher overhead and labour costs. Large variations in energy, labour and depreciation inputs (due to relatively high investment costs) make PV manufacturing 9% costlier in India and around 20-35% more expensive in the United States, Europe and Korea.

Total production costs for mono PERC c-Si solar components by input, 2022



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Notes: ASEAN = Association of Southeast Asian Nations. Values exclude subsidies as well as additional costs such as transportation, company profits, taxes and tariffs. Thus, total cost inputs may not match final market sale prices. Polysilicon prices include the processing of metallurgical-grade silicon. The following prices from June 2021-May 2022 were used in this analysis: glass, USD 590/Mt; aluminium, USD 2 875/Mt; polymers, USD 6 000/Mt; silica sand (quartz), USD 100/Mt; copper, USD 9 680/Mt; silver, USD 760/kg; zinc, USD 3 520/Mt; lead, USD 2 330/Mt; tin, USD 38 950/Mt; other, USD 18 700/Mt.

In the absence of subsidies and manufacturing support, achieving significant reductions in energy and labour costs remains challenging. Thus, diversifying solar

PV manufacturing will depend on the ability of nascent and new markets to match the cost efficiencies evident in China. For instance, realising economies of scale and integrating plants and processes can reduce variable costs to increase competitivity.

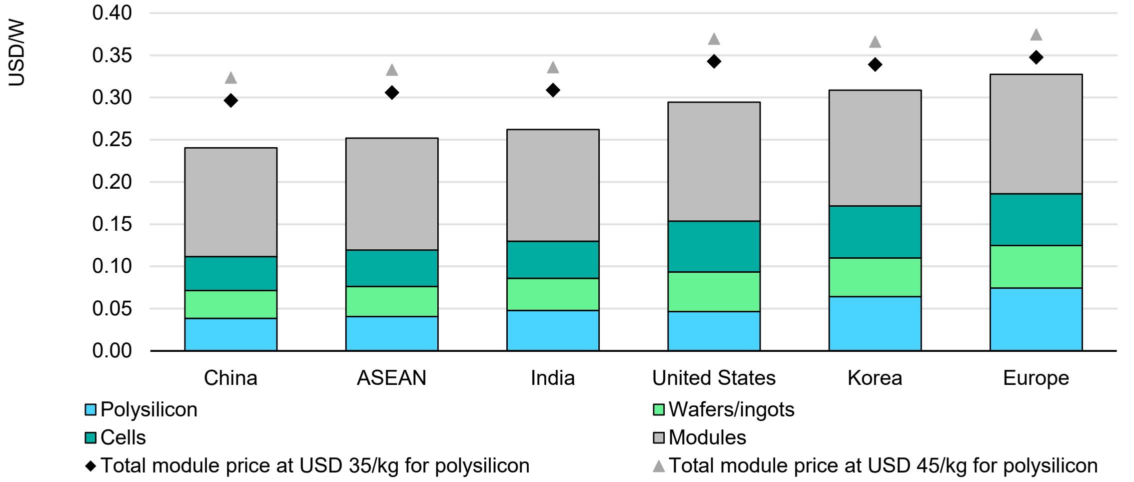
Higher prices on globally traded commodities impact all solar PV module manufacturers

Module assembly makes up 40-50% of total manufacturing costs because it includes multiple key processed materials (e.g. glass, copper, aluminium frames, backsheets, EVA and junction boxes). These input products are traded globally, limiting the amount of manufacturing cost variation among markets. Despite requiring less material in terms of weight, cell manufacturing is in general the second-largest cost component because it relies on relatively expensive silver in addition to zinc, lead and tin. However, manufacturing costs vary among key markets due to differences in depreciation, overhead expenses and labour costs.

Meanwhile, the raw materials used to produce metallurgical-grade silicon, polysilicon and wafers remain inexpensive (e.g. silica sand/quartz). Relatively low electricity prices have made polysilicon production less costly in China than in other regions, with expenses totalling roughly USD 0.04/W (USD 14/kg) including overhead and depreciation costs. Excluding these, marginal costs in China are around USD 0.02/W (USD 7/kg). In Europe and Korea, higher electricity prices push polysilicon production costs to almost double those of China. In the United States, high labour, overhead and depreciation costs outweigh low industrial electricity prices, resulting in nearly 20% higher costs than in China.

Commodity price increases have raised overall solar PV module costs significantly over the last year. The market price of polysilicon increased the most quickly, almost quadrupling since 2019 to USD 35/kg in 2022 due to the tight supply situation. The price of polysilicon in commodity markets is significantly higher than the estimated cost of manufacturing it in all markets, enabling polysilicon producers in both Europe and China to announce healthy profits in the first quarter of 2022. In contrast, during 2015-2019 polysilicon manufacturers in Europe, Japan, Korea and the United States recorded reduced profitability and losses when polysilicon prices were around USD 14/kg, less than half the current level due to a global supply gut and aggressive pricing that caused several companies to close their plants or halt solar-grade polysilicon production.

Total production costs for mono PERC c-Si solar components by supply chain segment, 2022



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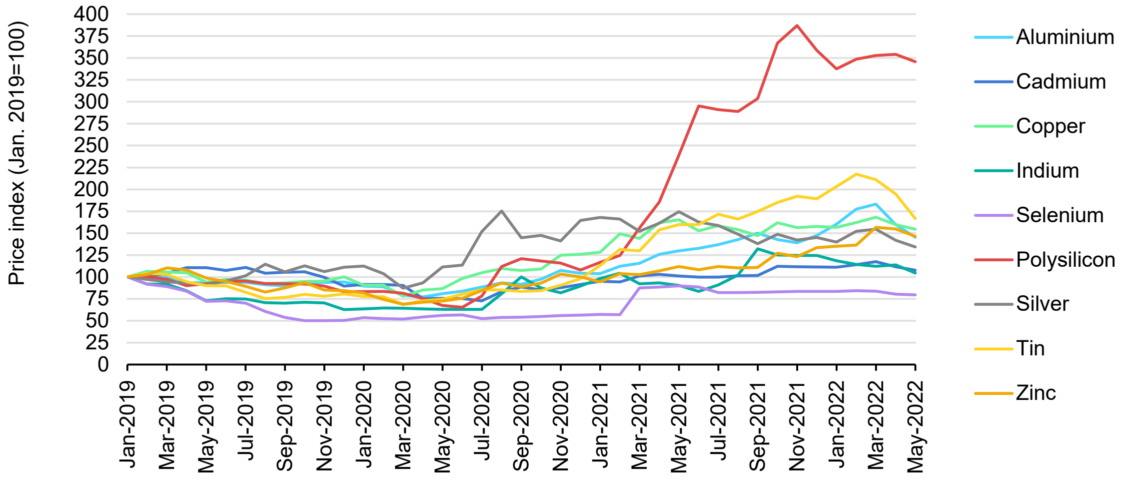
Notes: ASEAN = Association of Southeast Asian Nations. Values exclude subsidies as well as additional costs such as transportation, company profit taxes and tariffs. Thus, total cost inputs may not match final market sale prices. Polysilicon prices include the processing of metallurgical-grade silicon.

Source: IEA analysis based on NREL (2018); Fraunhofer (2021); BNEF (2022c); TERI (2019); and CSTEP (2018).

As ingot and wafer manufacturers usually pay the market price for polysilicon (their main material input), high prices are resulting in around 25% higher final module costs of almost USD 30/W in China and USD 35/W in Europe.

Indexed monthly prices for main solar PV module material inputs



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Source: Bloomberg (2022a).

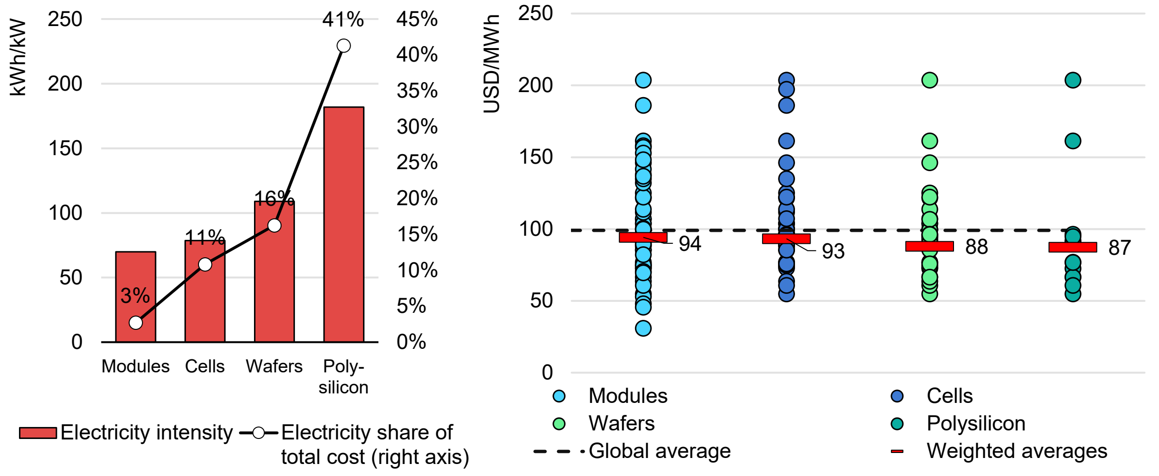
In addition to polysilicon, prices for other key materials, including silver, tin, copper and aluminium, have risen 50-80% since 2019, boosting overall module production costs 25-35% over the last year. Solar PV manufacturers are passing these cost increases on to their customers, leading to higher auction and corporate PPA prices in multiple regions.

Low-cost electricity is key for competitive polysilicon and ingot production

Energy costs remain an important reason for total module cost differences among key countries and regions. Retail electricity prices are one of the factors that determine whether markets can produce solar PV supply chain elements competitively, especially energy-intensive polysilicon, ingots and wafers. For wafers, electricity accounts for nearly 20% of production costs, and for polysilicon over 40%. In fact, manufacturing wafers and polysilicon can consume up to two to three times more energy per watt of production than making cells and modules does, depending on the process.

Around 80% of the electricity involved in polysilicon production is consumed in Chinese provinces at an average price of USD 76/MWh, almost 30% below the global industrial average. Hence, the average price of electricity used to make polysilicon and wafers is just under USD 90/MWh, or about 10% below the global industrial price average.

Electricity intensity and share of electricity in production costs by segment (left), and regional industrial electricity prices for each country of production by segment (right)



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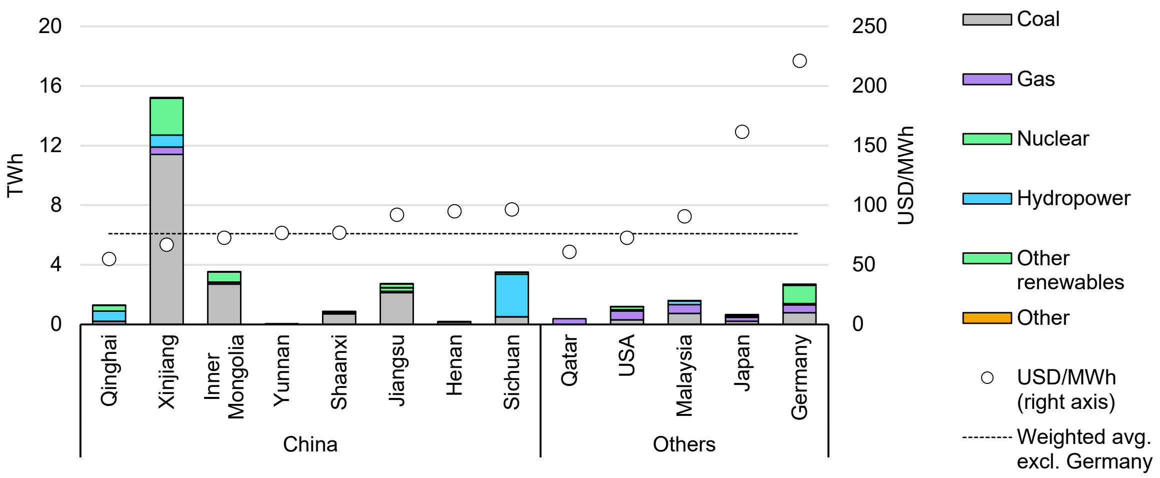
Notes: Each dot in the right-hand graph represents the electricity price in a country, or a province in China, where the segment is produced. Prices include VAT and demand charges.

Sources: Right graph: IEA (2021c), World Energy Prices (database); BNEF (2022d), Power Prices.

Low electricity prices in China are a result of access to relatively low-cost coal, particularly in Xinjiang, Inner Mongolia and Jiangsu, where it makes up three-quarters of the generation mix. However, these prices may not represent the true cost of power, as additional subsidies or preferential rates can apply at the provincial level. Polysilicon production does occur at higher prices in Japan and Germany, but these producers find it difficult to compete with those in China and Southeast Asia, especially when polysilicon demand or prices fall.

Polysilicon electricity consumption by region and electricity price, 2021



Sources: Electricity prices from IEA (2021g), World Energy Prices (database); BNEF (2022d), Power Prices.

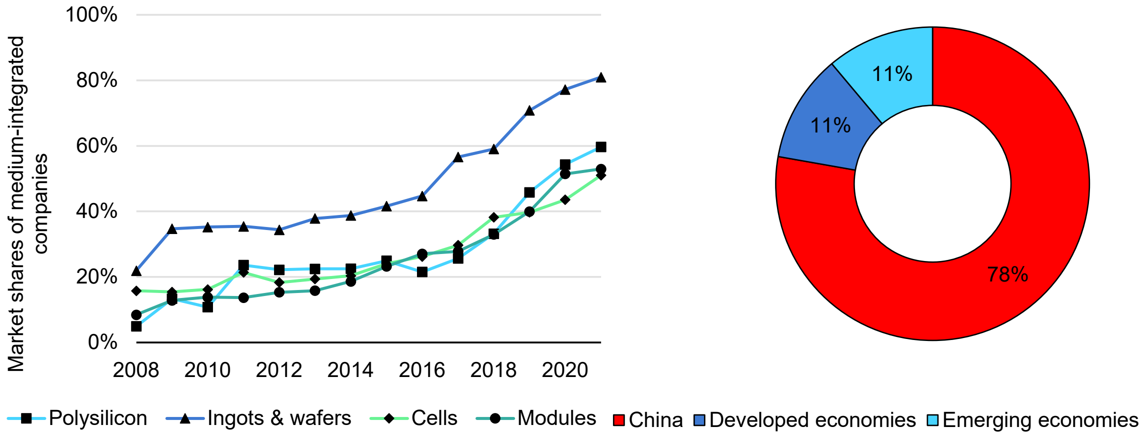
For wafers, electricity prices also influence regional cost differentials, but to a lesser extent than for polysilicon. Markets outside of China and the ASEAN region have higher depreciation, overhead and labour costs, making it more difficult for them to be competitive. Higher investment costs in Korea, the United States, India and Europe lead to elevated depreciation costs compared with China due to a lack of economies of scale.

Supply chain integration can offer cost advantages and increase competitiveness

More than in any other region, companies in China have increasingly consolidated manufacturing in each segment of the supply chain over the last decade, such that they now provide almost 80% of the world's integrated solar PV supplies. Large and medium-sized integrated solar PV manufacturers produce three out of four supply chain products, accounting for 80% of global polysilicon production and 50-60% of wafer, cell and module-manufacturing capacity.

The cost efficiencies resulting from integration and the consequent ability to absorb price shocks allow these firms to produce the lowest-cost solar PV equipment while also introducing labour and manufacturing efficiencies to reduce variable costs. Accordingly, companies outside China may also need to integrate various segments to improve their competitiveness. Integrating supply chain segments must be made a priority, as the fragmented nature of component manufacturing could lead to higher costs in each segment.

Integrated solar PV manufacturer market shares by supply chain segment (left) and by country/region (right)



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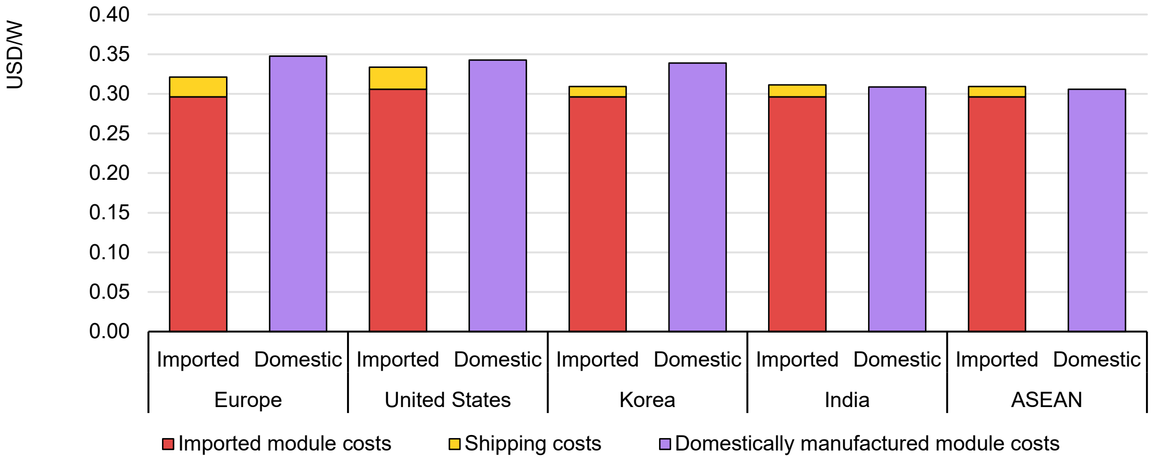
Note: A vertically integrated company manufactures products in at least three segments of the PV supply chain. Of the 62 integrated companies at present, 49 are in China.

Elevated freight prices are closing the gap between low-cost imports and domestically manufactured modules

Since 2019, overseas shipping prices have increased more than sixfold. Prior to the Covid-19 pandemic, transportation costs had little influence on the cost-competitiveness of domestically-produced solar PV modules versus imported ones. However, transport charges have now closed the gap in India and ASEAN countries, where the cost of domestically-produced solar PV modules (including polysilicon, wafer and cell manufacturing as well as assembly) is on par with Chinese imports. In Europe, the cost differential has shrunk to 8% because of the long distances involved in importing from China and the ASEAN region, and in the United States the difference is only 3%.

Cost of imported modules, including overseas shipping, vs domestic modules, 2022



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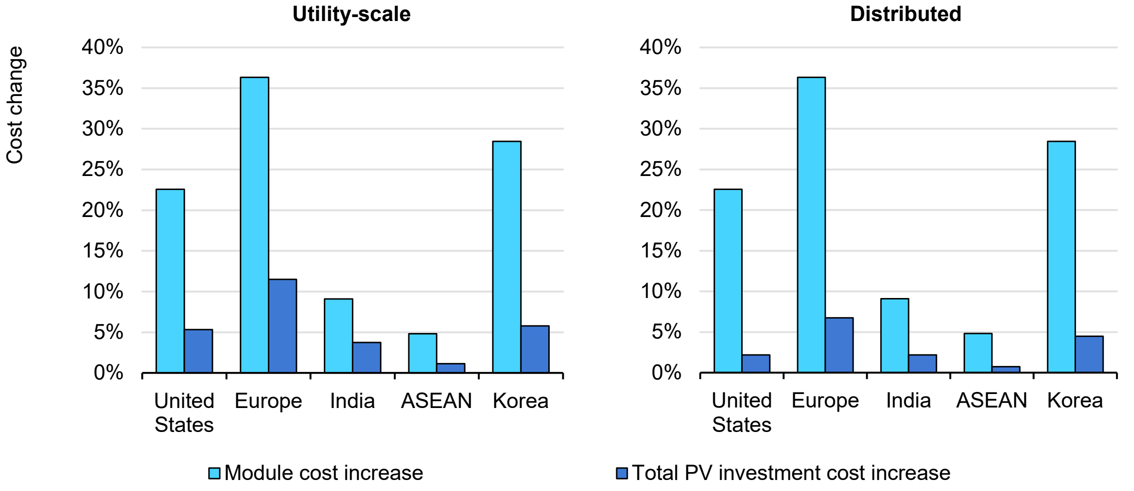
Note: ASEAN = Association of Southeast Asian Nations.

Solar PV manufacturing costs vary significantly, but they do not strongly affect overall PV generation costs

For governments, policies supporting renewable energy technologies must consider overall electricity generation costs. These are largely dictated by the investment cost of the entire PV system, which is comprised of expenses for both modules and non-module elements such as inverters, cables, mounting structures, installation and financing. Although domestically manufactured modules may cost more than Chinese or ASEAN imports, the majority of upfront expenditures come from balance-of-system costs. Thus, the additional expense of domestic modules will have only a limited impact on the cost of investment and, consequently, on generation costs.

In fact, balance-of-system costs can represent as much as 71% of utility-scale system installation costs in the United States or as little as 58% in India, with modules making up a much lower share for distributed applications. For example, manufacturing the entire module supply chain in the United States, the European Union or Japan may result in 20-35% higher module costs than in China, but only 5-11% higher investment costs for utility-scale and 2-7% for distributed PV projects. In India and ASEAN countries, a similar trade-off would lead to only a 1-4% increase in overall utility PV system costs.

Cost increase from domestic vs lowest-cost (Chinese) module use and share of module expense in total PV investment cost



Note: ASEAN = Association of Southeast Asian Nations.

Source: IEA analysis based on IRENA (2022).

Job creation

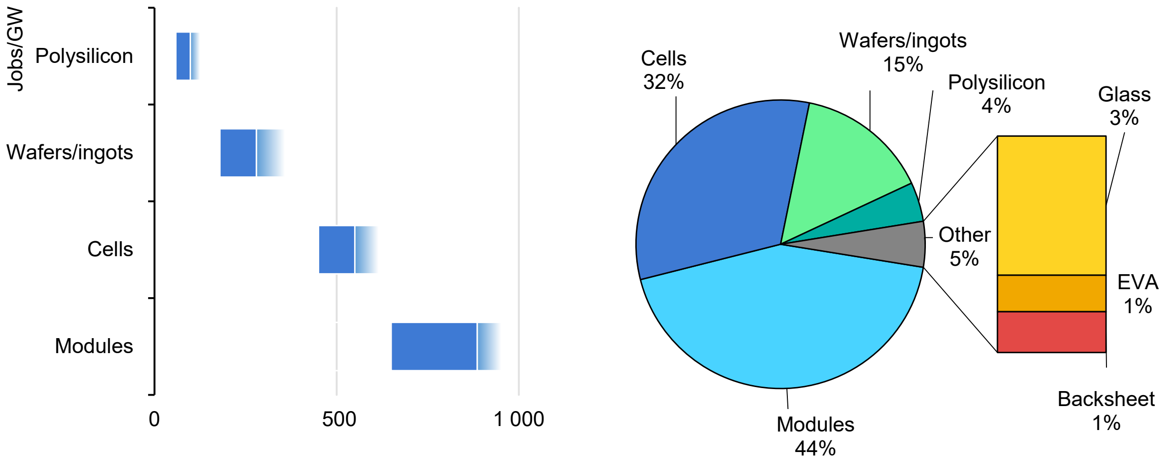
The solar PV industry could create 1 300 manufacturing jobs for each gigawatt of production capacity

Job creation is one of the main arguments for expanding domestic manufacturing of any product, as many governments consider manufacturing jobs to be sustainable. Thus, given solar PV's critical role in the energy transition and its job-creation potential, it is a key industry for the global expansion of manufacturing jobs.

To be on track to meet IEA Net Zero by 2050 Scenario demand growth, the solar PV manufacturing sector needs to nearly double the number of jobs globally by 2030. Plus, the manufacturing of components such as glass, EVA, backsheets, inverters and mounting systems would create over another quarter-million jobs at the same time.

For policymakers, the job intensity of various solar PV supply chain segments can be an important factor, especially when designing incentives to support the manufacturing sector. For instance, we estimate that producing 1 GW of c-Si solar module capacity per year could create as many as 1 300 full-time manufacturing jobs, covering polysilicon, ingots, wafers, cells, modules and other materials such as glass, backsheet and EVA. Thin-film module manufacturing, which is less job-intensive than c-Si technology, creates only around 200 jobs per gigawatt because it entails fewer production steps and they are mostly automatised.

Jobs per GW of manufacturing capacity and share of jobs per supply chain segment



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Notes: Values are weighted averages based on production capacities and employment levels published in government statistics and company reports from 2005 to 2021. Markets include Brazil, Cambodia, Canada, China, Chinese Taipei, the United Kingdom, France, Germany, India, Indonesia, Japan, Malaysia, Mexico, Norway, the Philippines, Singapore, South Africa, Korea, Sweden, Thailand, the United States and Viet Nam.

In China and Southeast Asian countries, established solar PV manufacturing markets create fewer jobs (1 000-1 100 per gigawatt of polysilicon, ingots, wafers, cells and modules produced annually) because the immensity of new manufacturing plants (i.e. 10-20 GW) allows for higher levels of automation and efficiency. For smaller manufacturing facilities that cannot realise the same economy-of-scale benefits, labour requirements could increase up to nearly 60%.

The most job-intensive segments along the PV supply chain are module production (requiring 600-900 jobs) and cell manufacturing (450-650 jobs). Over the last decade, however, job automation and automated guided vehicles reduced the job intensity of solar PV manufacturing significantly, especially for cells and modules. Nevertheless, despite their relatively high-efficiency levels, module and cell manufacturing have greater job intensity because the multiple steps involved in assembly and quality control still require manual labour even though other stages can be highly automated.

Polysilicon and wafer production are the most geographically concentrated segments. Although their diversification would provide security-of-supply benefits, their job-creation potential is relatively low compared with the manufacturing of other components. For instance, 1 GW of polysilicon production can create 50-100 jobs, while wafer and ingot manufacturing can generate 180-400 (the high ends of these ranges reflect the greater labour needs of markets that have low capacity per manufacturing plant). Low job intensity in the polysilicon and ingot domains stems from the long production times required for large batches that do not require extensive manual work. However, a key advantage of these manufacturing segments is that they can serve multiple key sectors, including the semiconductor industry.

PV manufacturing requires a diversity of workers, including production engineers, material handlers and assemblers. Due to the current geographical concentration of the solar PV supply chain, the majority of skilled personnel is based in China and Southeast Asia, so diversification will require a concerted effort to train new employees. Thus, any strategy to increase PV manufacturing capacity must include a workforce training component. While governments and employers have already introduced training programmes for new employees, training must be co-ordinated and scaled up to provide the amount of labour needed to secure investment in local manufacturing facilities. There is not currently enough trained labour for PV manufacturing, especially in small or emerging manufacturing markets, given the low amount of job opportunities available.

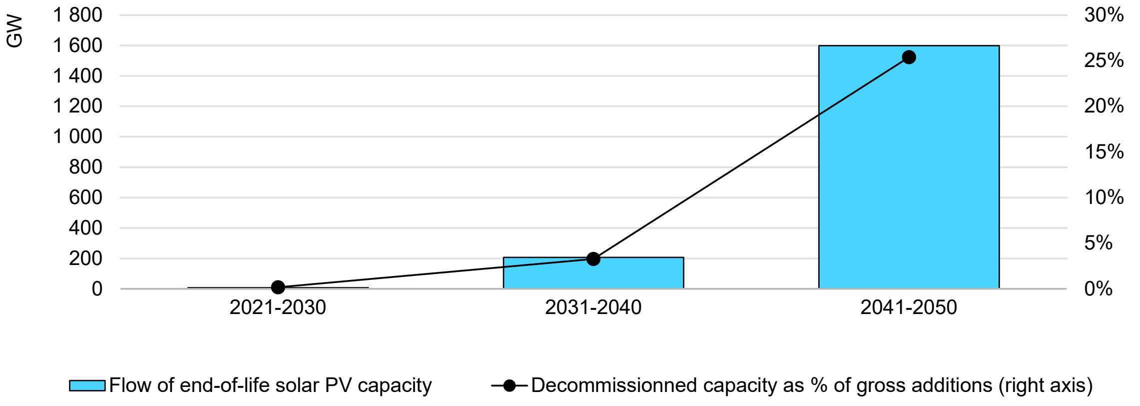
End-of-life management and recycling

Accelerating solar PV growth introduces new challenges for end-of-life management and opportunities for recycling

As ever-increasing amounts of solar PV equipment will reach the end of their lifetime in upcoming years, recycling could make a significant contribution to material supply chain diversification in the medium and long term.

Solar PV modules currently have an estimated average service lifetime of 25-30 years, after which time their performance can deteriorate and they can be subject to failures. Considering historical capacity additions, we estimate that the global cumulative flow of decommissioned solar PV capacity will reach around 7 GW by 2030 and could increase to over 200 GW by 2040. This represents 400-600 kt of embodied materials cumulatively by 2030 and 11-15 Mt by 2040. As setting up effective policy frameworks and value chains can take time, it is crucial that governments, industries and other stakeholders prepare now to manage the future surge of solar PV waste from a systemic, circular-economy perspective.

Expected flows of decommissioned solar PV capacity, 2020-2050



Notes: Values are based on historical capacity additions as well as additions modelled in IEA Net Zero by 2050 Scenario. Solar PV module lifetimes before decommissioning are assumed to follow a Weibull distribution pattern, with median lifetimes of 25 years for utility-scale installations and 30 years for distributed.

Source: Calculations based on IEA (2021f).

Solar PV recycling can offer environmental, social and economic benefits while enhancing energy security

Managing end-of-life (EoL) flows of solar PV equipment is an environmental challenge. In addition to contradicting circularity principles, putting PV panels in landfills can cause environmental pollution and health issues due to the presence of hazardous materials such as lead.[14] In this context, the benefits of recycling are manifold: it provides not only an alternative to landfilling, but also the opportunity to recover valuable elements and secure a reliable secondary source of raw materials for the PV industry and other sectors. Thus, by relieving pressure on primary supply requirements and offering a relatively predictable supply flow, recycling can reduce the price volatility of raw materials.

Furthermore, because it provides a domestic supply alternative, recycling can alleviate energy security concerns for countries heavily dependent on imports. It also helps avoid negative environmental, social and health impacts associated with raw-material mining, and can reduce the energy and environmental footprint of solar PV. Moreover, reconditioning and recycling can generate employment opportunities and support local economic activity.

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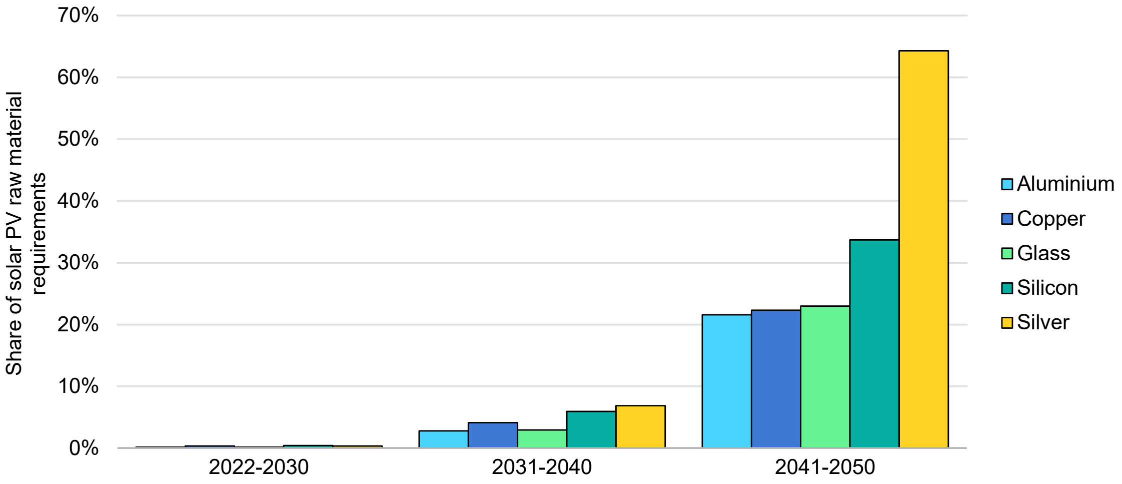
[14] EoL solar PV panel management is already becoming an important issue in some developing countries, where a growing number of small standalone solar devices with relatively short lifetimes are being improperly disposed of due to a lack of appropriate collection and recycling infrastructure, leading to adverse environmental and public health impacts (ACE, 2021).

Assuming systematic collection of EoL modules and a material recovery rate of 85%, cumulative secondary supplies from recycling all EoL solar PV modules could meet 3-7% of the solar PV industry's demand for aluminium, copper, glass, silicon and silver required under the IEA Net Zero Scenario during 2031-2040, and over 20% during 2041-2050. Presuming that the silver intensity for c-Si modules continues to decrease in line with the current trend, solar PV recycling has the potential to supply about two-thirds of the silver needed for new solar PV additions during 2041-2050.

Potential contribution of module recycling to solar PV material demand under the Net Zero by 2050 Scenario for selected materials, 2022-2050



Note: Calculations take into account the historical evolution of material intensity in the different generations of solar PV modules put on the market since 1990 and assume further material intensity improvements of 10% over 2020-2050 for glass, 30% for silicon and 75% for silver. For the sake of simplicity, calculations assume a recovery rate of 85% for all materials. However, recovery rates above 90% for silver and up to 95% for silver and copper are considered achievable (Huang et al., 2017).

Sources: Calculations based on IEA (2021d; 2021f).

Despite its strong potential to offer multiple benefits, recycling can be technically and economically challenging

Solar PV recycling is relatively complex from a technical standpoint. The EoL solar PV module flow is not homogeneous in size, technology, composition or condition. Moreover, existing solar PV panels were not designed to be recycled: durability and performance requirements have led to sandwich-like, sealed and encapsulated structures, making the separation of constituent materials difficult (IEA-PVPS, 2021). Nevertheless, various recycling processes have been developed in the past two decades for both crystalline silicon and thin-film PV panels (Lunardi et al., 2018). While some are still at the research or demonstration stage, others have already been implemented at industrial scale, for instance in the European Union and the United States.

PV module recycling generally starts with manual removal of the cables, junction box and frame, from which copper and aluminium can be recovered easily. It then proceeds with mechanical, thermal and/or chemical treatment to separate the module's other constituents. The presence of certain elements, such as fluoropolymers used in some backsheets, can require special handling or can constrain technical operations, increasing recycling costs.

In addition to copper and aluminium, recoverable materials can include glass, silver and semiconductors (e.g. silicon from c-Si PV technologies, and cadmium and tellurium from CdTe panels), which can then be reprocessed or refined, while polymers are sometimes used as refuse-derived fuel.[15] Recovery rates and valorisation routes for each material depend on the exact process employed. Overall, including downcycling, the valorisation rate of a framed c-Si module can exceed 94% by weight (Soren, 2022).

However, existing PV recycling processes are encountering economic challenges. Current recycling technologies for c-Si modules struggle to generate enough revenue from the recovered materials to cover the cost of the recycling process (IEA-PVPS, 2021). Moreover, the volume of EoL PV modules was relatively low until now, limiting opportunities to achieve economies of scale.

Recycling revenues – as well as the technical relevance of the process – depend largely on the ability to limit contamination between materials, isolate hazardous substances and recover homogeneous and high-purity fractions of scarce, energy-intensive and/or high-value materials. Research efforts are ongoing to enhance material value retention, for instance by developing technologies and processes capable of recovering intact wafers, glass and frames to be reused for the fabrication of new modules (e.g. Xu et al., 2022).

In parallel, proper recycling design is critical to enable higher-value recycling and reduce process complexity and costs in the long term (IEA-PVPS, 2021). However, further research is needed to better characterise the complex trade-offs that can arise between module recyclability and durability (service life), performance, cost, and possible material revenues from recycling. It must also be remembered that

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[15] In practice, incinerating cells and polymers is still commonplace in c-Si recycling, whereas high-value recycling to recover semi-conductor material is well established for CdTe panels (Stolz et al., 2017).

efforts to reduce the material intensity of high-value materials in PV modules will also compromise recycling revenue potential.

Assuming that improved recycling processes can recover 85% (by weight) of solar-grade silicon, silver, aluminium, glass and copper with high purity for reuse in the PV industry, revenues of more than USD 15-16 per module could be achieved at 2021 market prices, with silicon and silver contributing the majority. This could enable the development of a profitable c-Si module recycling business without additional financial support (Huang et al., 2017).

Last but not least, in addition to recycling, circular approaches aimed at improving solar PV designs for reuse, enhancing product longevity and developing remanufacturing will be pivotal to diversify the solar PV supply chain and shrink its environmental footprint (IEA-PVPS, 2021). While a reemployment market for modules is already emerging, the solar PV reuse sector is still mostly unregulated and would benefit from the establishment of technical guidelines and quality standards to ensure homogeneous product quality and build customer trust in second-hand panels.

Importantly, current markets for second-hand modules are located mostly in low-income regions such as Africa, Western Asia and Southeast Asia, where appropriate recycling regulations and infrastructure are often insufficient or lacking (PV Cycle, 2021). This raises environmental concerns about the management of solar PV modules reaching the end of their second lifetime in these regions and calls for rapid implementation of adequate and holistic policy strategies.

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Chapter 4 – Policy strategies for solar PV manufacturing and recycling

The increasing geographic concentration of solar PV manufacturing and ongoing supply chain challenges since the Covid-19 crisis are prompting governments to implement policies to stimulate domestic manufacturing. However, most global policy discussion has historically been focused downstream, on how to bolster the business case to sell solar PV electricity. These policies have been successful in achieving cost reductions and rapid deployment over the last decade, but little attention has been paid to upstream policy options to stimulate local manufacturing, or to the role of recycling in supplying future material needs.

Policy frameworks to promote local solar PV manufacturing

A country's policy and macroeconomic environment is critical to attract investment in manufacturing facilities for any industry. For solar PV, governments worldwide have implemented multiple policies and incentive schemes, with varying success. In simple terms, solar PV manufacturing policies can provide **direct** support to manufacturing investors, or they can **indirectly** stimulate investments by creating an attractive investment environment. Support policies can be applied on the **supply side** (upstream) or the **demand side** (downstream), through four possible combinations described below.

The IEA's proposed policy framework aims to categorise distinct policy types while also providing a non-exhaustive list of tools within each category. Historically, governments have supported PV manufacturing through a combination of supply and demand policies, but within these broad policy categories they choose from among many different tools. Although many indirect policies are excluded from the list (such as those targeting the general macroeconomic environment, financing or foreign direct investment), they may affect how well manufacturing investment can be attracted to various segments of the solar PV supply chain.

Policies that directly or indirectly support solar PV manufacturing investment

	Direct	Indirect
Supply	• Manufacturing tax credits for one or multiple solar PV supply chain segment manufacturing facilities. • Grants for one or multiple solar PV supply chain segment manufacturing facilities, including to cover land and infrastructure costs. • Low-cost financing for greenfield solar PV manufacturing facilities, or for their expansion or operation. • Lower energy prices for energy-intensive PV manufacturing facilities. • Lower income tax rates for solar PV manufacturing companies. • Lower import tariffs and VAT rates for imported manufacturing equipment. • Government funds to reduce labour costs through lower charges. • Incentives for to exported goods manufactured domestically.	• Import tariffs or trade duties to raise the cost of imported solar PV equipment and related products. • Import bans on solar PV products not meeting certain sustainability standards or regulations, to set standards for imported PV equipment. • Border CO2 tax adjustment for imported solar PV products. • Carbon footprint standard for modules in tenders. • R&D and innovation funds, or funds for academics and the private sector to develop solar PV technologies. • Tax incentives to employ highly skilled labour for R&D. • National or sub-national funds to educate skilled labour for solar PV manufacturing. • Government investment to upgrade infrastructure, including for logistics, waste management and power, including industrial clusters.
Demand	• Local-content requirements for domestically manufactured equipment attached to policies to stimulate solar PV demand. • Solar PV power plant auctions/tenders linked to commissioning new manufacturing facilities.	• Policies to stimulate domestic solar PV demand (tax credits, FITs, auctions). • Local-content premiums for domestically manufactured equipment attached to policies to stimulate solar PV demand. • Low-cost financing for domestically manufactured equipment attached to policies to stimulate solar PV demand.

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Direct supply policies: Subsidies transferred directly to manufacturers

Policies providing incentives directly to a solar PV manufacturing facility can improve its business case, depending on the level of support. The first of two general forms of support are incentives that directly reduce the investment cost burden through grants, free or low-cost land and preferential financing, or that reduce the price for imported equipment through lower taxes or import tariffs. The second type consists of incentives that directly reduce manufacturing facilities' operational costs through investment tax credits (which reduce future tax expenses), subsidised electricity or other energy costs (offering relatively low retail tariffs), funds to reduce labour costs, and subsidies to encourage the export of solar PV goods.

Direct supply policies thus directly bolster the business case for solar PV manufacturing by reducing the initial investment requirement while making domestically manufactured goods more competitive. While policies such as grants, low-cost financing or government loan guarantees are usually provided during the initial investment period, other incentives may be offered over multiple years.

The effectiveness of direct supply policies can often depend upon how long support is provided, especially for incentives designed to reduce the operational costs of manufacturing facilities. If investors do not use direct supply incentives to invest in the long-term competitiveness of their products, they may lose their domestic or international market shares once subsidisation ends.

Indirect supply policies: Incentives and regulations that facilitate PV industry investment

Indirect support policies aim to create an inviting environment for investment by either establishing conditions for growth or eliminating investment challenges. The former category includes incentives connected to R&D, innovation and skills. These help industries accelerate innovation, which could in turn increase their competitiveness. Funds for R&D can help improve the efficiency of technologies already on the market or be directed to technologies that have not yet reached the commercialisation stage. While not all R&D funding results in scalable commercial activity, innovation and skill development helps create a better investment environment.

Indirect supply policies aim to create an investment-enabling environment, which may not always be available to an investor, particularly in places where price differentials between domestic and imported products are deemed unfair. The most common indirect supply policies are thus trade policies, as they aim to create a level playing field. Meanwhile, the ability of import tariffs or duties alone to attract direct investment in manufacturing facilities is limited, especially in countries where existing domestic supply is significantly lower than demand.

As import tariffs or countervailing duties increase the price of imported goods while neither improving the business case for new manufacturing investments nor eliminating other potential obstacles, using these tools without other policy measures may just translate into more expensive solar PV products on the domestic market. Trade policies have, however, helped attract investment in solar PV module assembly lines, as manufacturers usually import most value-added supply chain elements such as cells and then assemble them into modules that are sold in the domestic market.

Direct demand policies: Power plant tenders that require domestic manufacturing investment

This category refers to the linking of incentives for new solar PV power plants with a requirement to use domestically manufactured equipment, for example through long-term power contracts that require developers to build a solar PV manufacturing facility for one or multiple supply chain segments. Although power purchase contracts associated with this policy remunerate energy produced from power plants, part of the tariff is directly transferred to the manufacturing facility. Usually, the developer and the manufacturer create a consortium to allocate remuneration fairly for construction of both the power plant and the manufacturing facility (see the sections on India and Türkiye below).

Indirect demand policies: Incentives directed to power plant developers

Creating domestic demand for solar PV through FITs, auctions or renewable portfolio standards can indirectly lead to the development of local solar PV manufacturing for multiple segments. However, because these policies remunerate only the electricity from solar PV power plants, developers are often incentivised to purchase the cheapest module options to maximise their profits, and these modules might not be from the domestic market. Thus, these policies alone may not be sufficient to stimulate local manufacturing, particularly if imported products are more affordable or operating costs are high.

These policies can also include a local-content premium on top of the base power purchase tariff for one or multiple components of the solar PV system, or a carbon footprint evaluation. In this case, local content is not required but optional. The size and continuity of local demand and the competitiveness of domestic manufacturing are key factors to attract investment in the domestic solar PV industry.

Policy assessments for selected countries

The effectiveness of policies that directly or indirectly target solar PV manufacturing is difficult to assess due to the complexity of multiple policy interactions and context-specific market developments. However, for governments, the main indicator that its incentives have been successful is the establishment of manufacturing capabilities to produce one or multiple products within the solar PV supply chain (polysilicon, ingots, wafers, cells, modules, glass, tracking or mounting). In the best-case scenario, domestic or foreign investment should create jobs, expand local skills and knowhow, stimulate technology transfer, reduce imports and enable the export of added-value products while raising tax revenues in the long term.

What is the secret to China’s dominant position in solar PV manufacturing?

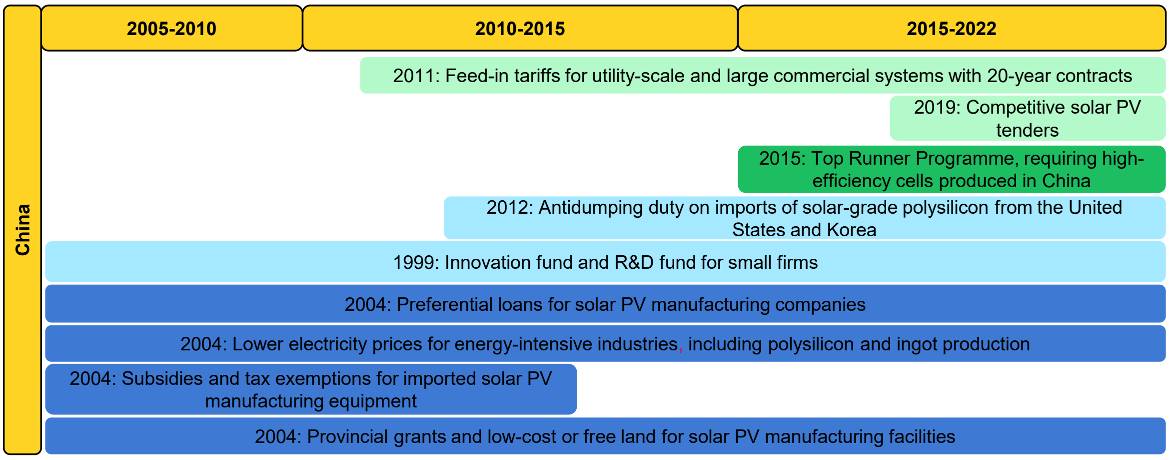
In the early 2000s, the Chinese government selected solar PV as a key industry to enrich its economy and exports. In its 10th Five-Year Plan for 2001-2005, China’s State Economic and Trade Commission released a vision for expanding the industrialisation of renewable energy technologies, including by scaling up solar PV cell and module manufacturing. This vision and strategy thus mark the introduction of central and provincial-level incentives for solar PV manufacturing.

In its 11th Five-Year Plan, China identified PV manufacturing hindrances such as its lack of polysilicon capacity (at that time, China imported 95% of the polysilicon it used for PV manufacturing) and dependence on imported manufacturing equipment. The government therefore decided to promote domestic polysilicon and equipment manufacturing through grants.

Because of the considerable export opportunities available, China's incentives initially targeted direct supply rather than domestic demand creation. Grants, low-cost loans from state banks and funds from the Science and Technology Ministry thus led to the establishment of several pioneering domestic manufacturers.

The Chinese government also provided grants and tax incentives to import manufacturing equipment from Europe and the United States, but they were discontinued after a few years because Chinese companies then developed their own equipment technology. In the absence of domestic demand, Chinese manufacturers had to improve their competitiveness. They therefore focused on economies of scale and integration of supply chain segments to reduce costs, increase exports and expand their global market share.

Supply and demand policies targeting solar PV manufacturing in China, 2005-2022



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Notes: Light green = indirect demand. Dark green = direct demand. Light blue = indirect supply. Dark blue = direct supply.

Chinese incentives directly targeting supply have also been sustainable both centrally and provincially. Grants, low-cost financing and preferential energy prices have been in place since 2005, and following the global financial crisis in 2008, the government introduced economic recovery packages for provinces through low-cost financing from the China Development Bank (CDB). Solar PV manufacturing was among the industries targeted, with the aim of expanding China's manufacturing capabilities throughout the entire supply chain.

China's initial industrial solar PV strategy focused on wafers, cells and modules manufactured from imported polysilicon (in 2007, China imported around 75% of its polysilicon from Europe and the United States). However, financing from the CBD, tax breaks, provincial subsidies targeting energy-intensive industries to reduce energy costs, and grants to expand manufacturing enlarged China's manufacturing to include polysilicon in 2009. In 2012, China introduced an antidumping duty on polysilicon imports from the United States and Korea to reduce imports and further expand its own manufacturing capabilities. Chinese dependency on imported polysilicon thus fell to 40% in 2014 because domestic manufacturing capabilities had increased sevenfold since 2009.

Meanwhile, China has also become the largest demand centre for solar PV owing to the FITs and competitive auction policies that shelter its manufacturing industry from volatile demand outside of the country. The first major subsidy programme supporting demand (the Golden Sun programme) was introduced in 2009. It provided grants for 650 MW and required Chinese manufacturers to install efficient and proven technologies. From 2005 to 2011, module prices fell from USD 4.5/W to around USD 1.5/W as manufacturing capacity expanded massively thanks to the incentives.

With lower PV costs, China introduced a FIT in 2011 to boost domestic demand to support climate change mitigation efforts and to create sustainable demand for its domestic manufacturing industry. At the same time, the government continued to incentivise new and more efficient cell technology through the Top Runner Programme, which allocates demand incentives to developers that provide the most efficient technologies. The programme has also prompted Chinese manufacturers to shift their focus from multicrystalline to more efficient monocrystalline technology.

How far can demand and R&D policies advance domestic solar PV manufacturing in Germany, Korea and Japan?

Japan, Korea and Germany became the largest manufacturers of polysilicon, wafers, cells and modules globally in the late 1990s and early 2000s owing to a combination of direct demand and indirect supply policies. The mixture of general industrial policy for manufacturing, government funds for solar PV-specific RD&D, and demand-side incentives has successfully supported solar PV manufacturing companies.

The earliest policies these three countries introduced were R&D incentives specific to solar PV for public and private institutions as early as the late 1970s and 1980s, spurred by the 1973 oil crisis. This support has been more or less continuous in all three countries and resulted in greater solar PV cell efficiency and high-end equipment and machinery development for solar PV manufacturing.

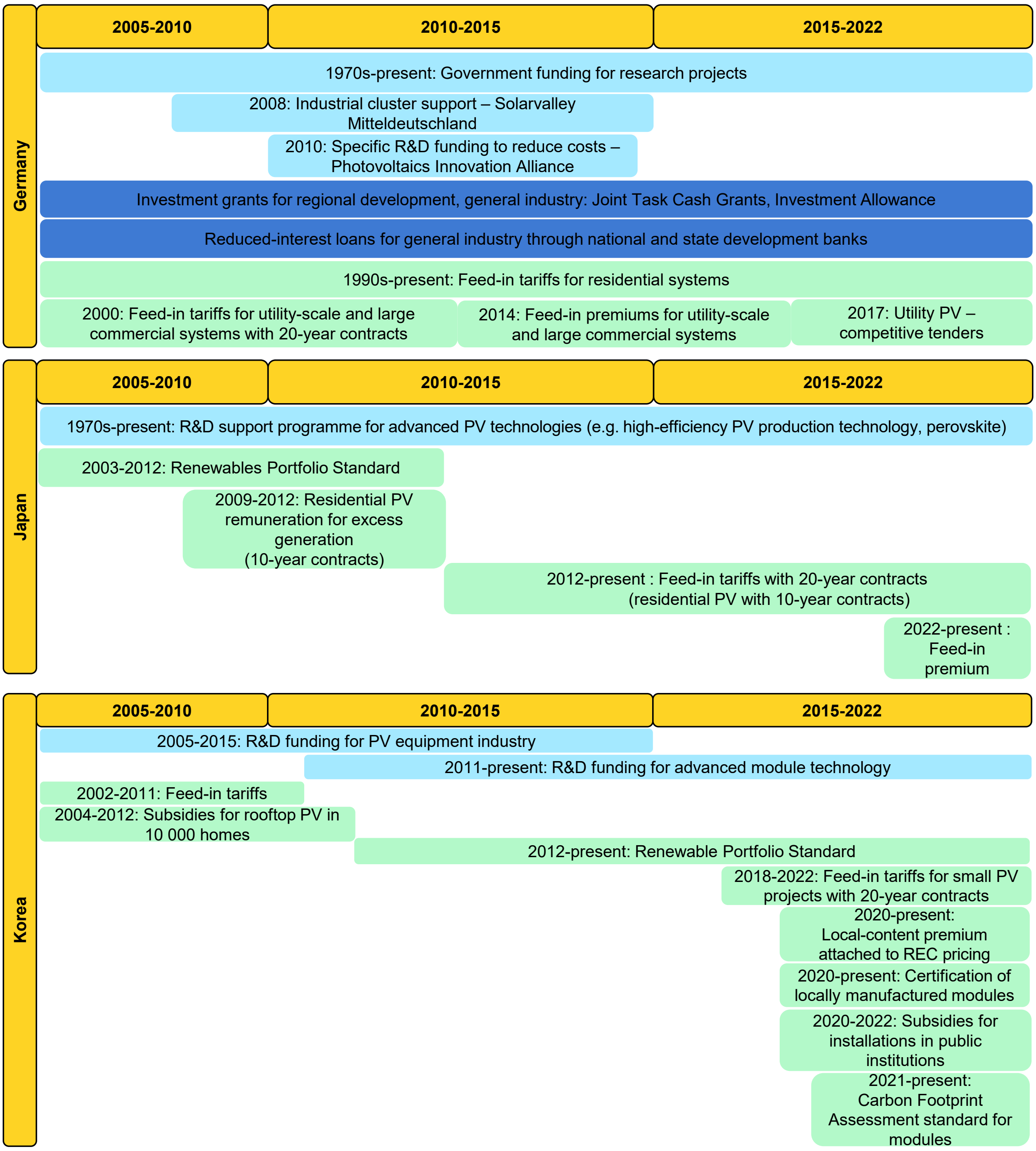
Germany, Korea and Japan also have distinct industrial policies in place: national or federal grants, tax incentives, and loan programmes for the machinery and high-technology manufacturing sectors. In Japan and Korea, industrial strategy has historically targeted large, vertically integrated conglomerate companies active in multiple sectors, while in Germany small and medium-sized companies have been the main recipients of government support. In all three countries, regional and industrial development funds were also used to support solar PV component and equipment manufacturers.

In Germany, the Joint Task Cash Grants and Investment Allowance programmes supported solar PV companies active in polysilicon, wafer, cell and module manufacturing through grants for CAPEX and operating costs, with the requirement that subsidised equipment remain in the investment location for at least five years. Similarly, Japan and Korea provide comparable industrial incentives for the manufacturing sector. All three countries have developed companies that manufacture equipment for polysilicon, wafer, cell and module production, and advanced automation industries in these countries have also contributed to the solar PV manufacturing equipment industry.

Germany, Korea and Japan were also at the forefront in providing subsidies for demand creation in the early 2000s through FITs or long-term remuneration to create local demand. Rising domestic demand, supportive industrial policies and export opportunities made it financially attractive for many German SMEs and large Japanese and Korean companies to launch businesses in multiple segments of solar PV manufacturing, making them global leaders until 2012/13.

In Germany, domestic demand began to decline in 2011 following a downward revision of the FIT, at the same time as China was investing heavily in solar PV manufacturing capabilities targeting exports. The oversupply of solar PV modules and aggressive pricing of Chinese manufacturers pushed prices down significantly and reduced the profitability of German manufacturers who had higher labour and energy costs than their Chinese counterparts.

Supply and demand policies directly or indirectly targeting solar PV manufacturing in Germany, Japan and Korea, 2005-2022



Notes: Light green = indirect demand. Dark green = direct demand. Light blue = indirect supply. Dark blue = direct supply.

Sources: Based on Korea, MOTIE (2009; 2018; 2019a; 2019b; 2020; 2021); The Korea Industry Daily (2009); Solar Today (2010); Today Energy (2012); Lee (2021); and Hankyoreh (2021).

A similar trend occurred in Japan, where major manufacturers divested themselves of solar PV supply chain products because they could not compete with Chinese polysilicon, wafer, cell and module producers. While all three countries raised their deployment targets and continued to stimulate PV demand, manufacturing capabilities declined or plateaued due to bankruptcies and loss-making PV-related business segments, mainly because direct supply policies and private capital investments were lacking.

The United States has long offered federal support for R&D and demand, but results of supply policies are mixed

The United States has one of the longest-lived R&D programmes for solar PV worldwide. The US federal government has incentivised R&D through two programmes: the Solar Energy Technologies Office and the Infrastructure Investment and Jobs Act. The Solar Technology Office provides grants and loans to develop low-cost, high-efficiency PV technologies, such that today US companies are world-leading manufacturers of cadmium telluride thin-film technology, holding nearly 80% of global capacity.

Policies to increase demand have been the primary driver of solar PV expansion growth in the United States. A monetary production incentive was introduced in 1992 and later transformed into a tax credit in 2006, and these federal investment tax credits have been subsequently extended numerous times. US solar PV demand increased tenfold over the last decade, which helped spur the creation of thin-film module manufacturing and c-Si module assembly capacity throughout the country.

The two direct supply policies incentivising solar PV manufacturing the United States has introduced – loan guarantees (2009-2011) and advanced manufacturing credits (2009-2011) – have had varying degrees of success. Of the 16 projects covered by Section 1705 federal loan guarantees, 4 were manufacturing facilities and only 1 (a wafer manufacturer) is still in business. For the other three, one solar company defaulted on its USD 535-million loan, another received only part of its loan before closing, and the last one never met the programme requirements (Congressional Research Service, 2015). Overall, the US federal government has guaranteed almost USD 750 million for solar PV manufacturing.

Meanwhile, the Advanced Energy Manufacturing Tax Credit (MTC) programme provided a 30% tax credit to advanced energy manufacturers that invested in new, expanded or re-equipped facilities located in the United States. The programme selected around 30 projects with over USD 700 million worth of tax credits.[16]

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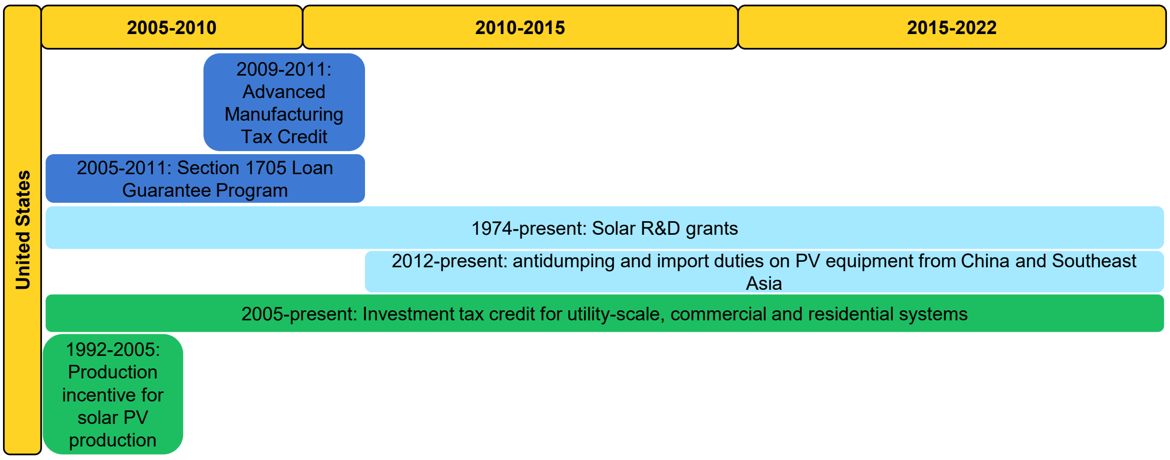
[16] Some companies were unable to monetise their tax credits due their insufficient tax base.

Polysilicon producers and cadmium telluride thin-film manufacturers were among the largest recipients of the MTC, mostly to expand their existing facilities. However, the programme also supported c-Si cell and module manufacturers as well as glass, inverter and coating material producers. The United States recently announced it intends to boost solar PV manufacturing through the Defence Production Act, though it is too early to assess its impact.

While the MTC has helped enlarge US manufacturing capacity, it did not deliver a major increase in production capabilities. Today, US polysilicon manufacturers provide limited output and serve mostly the semiconductor industry because China has introduced import tariffs. For wafers, the country has negligible manufacturing capacity, and for cells it can meet less than 10% of demand. The proposed Solar Equipment Manufacturing for America Act would create tax incentives per manufactured output for each supply chain segment.

The United States also has trade restrictions and tariffs in place on solar PV equipment manufactured in China and other Southeast Asian nations. Since 2012, it has imposed antidumping and import duties on companies in China, Malaysia, Thailand and Viet Nam.

Supply and demand policies directly or indirectly targeting solar PV manufacturing in the United States, 2005-2022



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Incentives also exist at the non-federal (state) level, including tax and local-content incentives to manufacture and source equipment in certain markets.

Has the switch from direct demand to direct supply policies increased PV manufacturing capabilities in India and Türkiye?

India and Türkiye have followed a similar policy pathway as the United States to support solar PV manufacturing. Both countries initially instituted demand policies that were successful in increasing annual capacity additions.

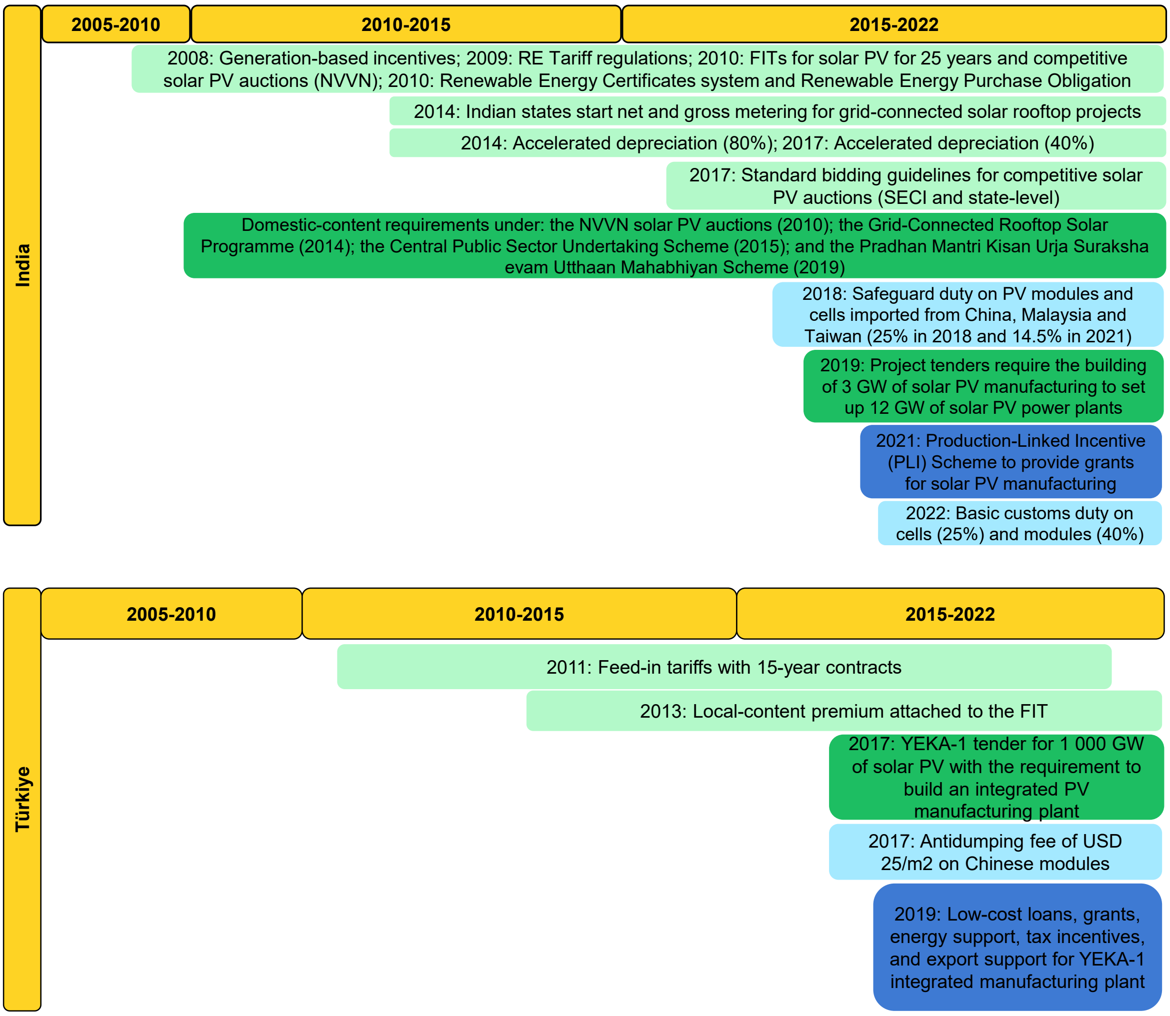
In 2013, Türkiye introduced a local-content premium on top of its base FIT to stimulate manufacturing. The premium increased dependency on locally manufactured components based on their added value, and local module assembly plants began to emerge. Low-cost cells imported from China were assembled with imported or locally produced glass and frames to be eligible for the premium, and since 2013 module assembly capacity in Türkiye has increased to around 7 GW. India also introduced domestic-content requirements for several government purchasing programmes, and this policy as well as rising local demand have led to around 12 GW of module assembly capacity, with growing use of locally produced glass and frames.

After having established a small manufacturing base, both Türkiye and India introduced trade measures against Chinese cells and modules to protect their own industries from dumping. However, rather than stimulating local cell manufacturing, this adversely affected the market by causing local prices to increase due to inadequate cell-manufacturing capabilities.

In 2017, Türkiye launched a competitive tender for a 1 000-MW solar PV plant and required the corresponding construction of an integrated plant to manufacture all components, from wafers through modules. A few years later, in 2021, India organised a similar tender for 12 000 MW of capacity, the largest of its kind globally.

At the same time, both Türkiye and India also began to introduce direct supply policies in the form of additional financial incentives to make manufacturing investments bankable. For the manufacturing-linked tender held in 2017, Türkiye introduced additional financial enticements – i.e. multiple direct incentives in the form of grants, low-cost loans, energy subsidies, tax breaks and funds for exported goods. In 2020, following these incentives, Türkiye commissioned Europe’s largest integrated wafer-to-module manufacturing plant (1 200 MW).

Supply and demand policies directly or indirectly targeting solar PV manufacturing in India and Türkiye, 2005-2022



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Notes: Light green = indirect demand. Dark green = direct demand. Light blue = indirect supply. Dark blue = direct supply.

Sources: IEA (2022), Policies and Measures Databases; India, MNRE (2022).

Meanwhile, India's production-linked incentive (PLI) programme for solar PV provides grants to companies manufacturing high-efficiency cells from locally produced supply chain components, from polysilicon to modules. As the government received significant interest from companies in the first phase of this scheme owing to the level of incentives and rising domestic demand, in 2022 it announced additional funding that could increase local manufacturing capacity by four times.

Although subsidies and industrial policy frameworks combining demand and supply incentives have led to manufacturing investments in both Türkiye and India, existing and proposed manufacturing capacity is still too low to achieve the high economies of scale attained in China and Southeast Asia. As a result, raising the competitiveness of manufacturing facilities in both Türkiye and India remains a challenge in the long term. While process improvements, further capacity expansion and growing demand could reduce manufacturing costs, the sustainability of their solar PV manufacturing industries may require continuous support in the form of both subsidies and trade measures.

Policies to develop PV recycling

The share of end-of-life (EoL) PV modules being recycled varies considerably by region and country, depending on the policy environment. Currently, less than 10% of EoL modules are recycled in the United States, whereas this share is near 95% in the European Union, where specific national policies mandate PV module recycling (NREL, 2021).

Supportive policy frameworks can significantly boost PV recycling

Various voluntary schemes have been developed for solar PV recycling. Some consist of individual voluntary takeback or product stewardship programmes set up by manufacturers, who either manage the collection and recycling process themselves or contract third-party service providers to do it. Others consist of collective initiatives financed by industry members and possibly developed in partnership with regulators, such as the PV Cycle initiative established in Europe in 2007 and later restructured to comply with new European regulations. While such voluntary approaches offer indirect benefits (including reputational) to manufacturers and the industry, the non-profitability of current recycling processes is an obstacle to their diffusion.

Regulatory frameworks are therefore key to scale up PV recycling capabilities by defining stakeholder responsibilities as well as financing models for EoL management, and establishing targets and minimum requirements for collection and recycling. Regulatory approaches can be categorised according to where they place responsibility for EoL module disposal and treatment: on society (taxpayers); on final owners (consumer responsibility); or on manufacturers or sellers (the extended-producer-responsibility principle) (IRENA and IEA-PVPS, 2016).

Financing models often rely on the collection of recycling fees, either upfront when the module is first placed on the market or downstream at the time of disposal (pay-as-you-go). Upfront fees can be set based on estimates of what recycling costs will be when the module reaches the end of its lifetime, or can reflect the cost to recycle current volumes of EoL panels at the time of purchase. Depending on the financial scheme, specific arrangements may be required to cover the cost of recycling modules placed on the market before the regulation was in force (i.e. historical modules) or those manufactured by companies that no longer exist and thus cannot be held liable (i.e. orphaned modules).

Specificities of different fee-based financing schemes for solar PV recycling

Time of fee collection	Indexing of fees	Responsibility/ liability	Specific issues or advantages
Upfront fee (when the module is first placed on the market)	Based on estimated future costs of recycling the module at end of life	Consumer or producer	• Difficult to estimate future costs of recycling. • Needs to also account for the recycling of historical modules (i.e. placed on the market before the regulation was in force). • No issue of orphaned EoL modules. • Can incentivise producers to improve module design for recycling.
	Set up to cover recycling scheme costs at the time of purchase (at current EoL volumes)		• Guarantees the financial balance of the scheme at any time. • No issue of orphaned EoL modules.
Pay-as-you-go (end-of-life disposal fee)	Based on actual costs of recycling	Consumer (last owner)	• Using later-year project cash flows can be financially easier than paying an upfront fee. • Risk of improper disposal from owners trying to avoid the cost of recycling. • No direct motivation for producers to improve module design for recycling.
		Extended producer responsibility (EPR)	• Producers have an incentive to improve module design for recycling since they directly bear the costs of the process. • Needs to account for orphaned modules (for which producers no longer exist) by sharing their recycling cost among remaining producers. The scheme may be complemented by “last-man-standing” insurance, or a joint-and-several liability scheme.

Although domestic markets are expanding rapidly, many countries (including China, Japan, India, Australia and the United States) still lack specific regulations for managing EoL PV modules, which are often treated under a general regulatory framework for hazardous or non-hazardous solid waste (Sharma, Pandy and Kolhe, 2019; Lunardi et al., 2018).[17]

The European Union was the first jurisdiction to adopt a PV-specific waste regulation mandating the recycling of all solar PV modules and setting up minimum requirements and targets for collection and recycling. This mandate was implemented under the 2012 revision of the Waste Electrical and Electronic Equipment (WEEE) Directive (2012/19/EU), and it has since been transposed into national laws in EU member states. The European framework follows an extended-producer-responsibility approach, making producers or sellers who put PV modules on the EU market liable for the costs of collection, handling and treatment of their products, either through their own takeback and recycling programme or through producer compliance schemes.

Policy priorities for a more secure solar PV supply chain

In IEA Net Zero by 2050 Scenario modelling, solar PV expands more than any other clean energy technology, providing one-third of global electricity generation by 2050. However, quickly expanding solar PV capacity to the level required will be possible only if stable policy frameworks are established and barriers to deployment are lifted. A resilient and sustainable supply chain ensuring the timely and cost-effective delivery of solar PV modules worldwide will also be needed. Globally, policies to date have focused mostly on increasing demand and lowering costs, with only limited attention paid to solar PV supplies.

Rapid solar PV technology deployment implies a significant increase in raw material usage and investment in manufacturing capacity along with other clean energy technologies. However, several weak spots along the solar PV supply chain make it vulnerable to risks. For instance, it is the most geographically concentrated of all clean energy technology supply chains, and current investment plans indicate further concentration by 2025.

The PV supply chain is also vulnerable to rising commodity and raw material prices, trade restrictions and supply chain bottlenecks, which have all resulted in higher

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[17] In the United States, while no specific solar PV regulation exists at the country level to date, initiatives are emerging at the local level, such as the local solar panel recycling law implemented by Niagara County (NY) in 2021 (Niagara County, 2022).

prices in the past, as well as to delays in module delivery. Plus, a lack of transparency along the PV supply chain raises concerns about environmental, social and financial sustainability risks.

The goal should be to enhance the security and resilience of the solar PV supply chain while maintaining a commitment to principles of open and transparent markets and avoiding barriers to trade. Securing adequate supplies will require a number of actions, including advancing understanding and tracking of security-of-supply risks; diversifying the supply chain; improving the environmental, social and financial sustainability of the industry; investing in innovation; and mainstreaming high-value recycling of PV panels.

Turn policy attention towards solar PV supply security as part of clean energy transitions

This report is a first attempt to identify principal vulnerabilities and risks globally along the solar PV supply chain. However, all countries have unique political, economic and energy contexts, so they will also have different vulnerabilities and risk-mitigation capabilities. As an initial step, governments should consider assessing their domestic solar PV supply chain vulnerabilities and risks.

Based on assessment results, governments may then consider developing strategies and actions to address their country's particular vulnerabilities. For instance, PV supply chain concentration could be mitigated by investing in domestic manufacturing for certain segments of the solar PV supply chain or by diversifying supply sources. International co-ordination and collaboration on regular vulnerability assessments and the sharing of practices and experiences among countries could also help raise policy attention and help governments reduce risks.

Increase diversification to improve PV supply chain resilience

Disproportionate geographical/jurisdictional and facility-level concentrations of raw material processing and manufacturing make the solar PV supply chain vulnerable to supply chain disruptions. Supply source diversification – through international co-ordination and trade that avoids restrictive import/export policies – is thus essential to reduce this vulnerability.

Polysilicon and ingot/wafer manufacturing should take policy priority in diversification efforts because they have the highest market concentrations, require the largest initial capital investments, and need low electricity prices to be cost-competitive.

However, diversifying the solar PV supply chain will also require industrial policy tools beyond government incentives to support demand, and a collaborative effort between the public and private sectors will be needed to secure the solar PV technology supply chain. For instance, China's role in solar PV manufacturing hinges upon not only its industrial priorities and targets, but the incentives the government has provided continuously for more than a decade.

While these incentives have contributed to the rapid scale-up of global PV manufacturing capacity and reduced module costs, some policies have also prompted investigations into dumping and resulted in multiple trade restrictions. Thus, international co-ordination on subsidy design and financial support to encourage domestic production while avoiding trade restrictions is critical to diversify the solar PV supply chain and improve its resilience.

Expanding domestic solar PV manufacturing capacity is an option to increase solar PV supply chain resiliency at the country level. Considering the multiple steps involved in manufacturing segments and the geographic location of raw materials, full self-sufficiency is not usually a practical option (nor is it economical, except in a few countries). Thus, regional co-ordination will be essential to secure the raw materials, manufacturing investments and trade required for supply chain diversification. Many countries will need to rely on imports alone to satisfy domestic demand, in which case diversifying import sources will be critical to reduce supply risks.

De-risk investment

A competitive and financially healthy industry requires a range of conditions, including clear, long-term and predictable demand policies in line with the IEA Net Zero by 2050 Scenario, international co-operation on subsidies and trade measures, and transparent and traceable pricing mechanisms for components and raw materials.

Over the last two decades changing government policies and company decisions have led to supply gluts and demand volatility leading to the poor financial health of solar PV manufacturing companies in many PV supply chain segments. Government could consider tailoring demand support policies (e.g. auctions) in order to take into account long-term financial sustainability across solar PV supply chain segments.

Considering the strategic importance of polysilicon, ingots and wafers, direct supply policies through finance and tax policies, and other measures to de-risk PV manufacturing investment could support diversification. Governments could encourage public-private collaborations involving research institutions and labs and increase public clean energy funding to catalyse private investment.

Ensure environmental and social sustainability

Environmental and social sustainability are fundamental for PV supply chain security. Fortunately, increasing supply chain resiliency through diversification provides governments new opportunities to concurrently achieve their sustainability goals. Differing standards and a lack of transparency in many countries do, however, continue to hinder the achievement of sustainability objectives.

Solar PV is one of the lowest-GHG-emitting electricity technologies. Total lifecycle GHG emissions of solar PV modules are twenty times lower on average than those of coal-fired power plants. Plus, a solar PV module will generate 20 to 30 times more renewable energy over its lifetime than the amount of fossil fuel-based energy consumed during its manufacturing. Nevertheless, as an energy-intensive manufacturing sector, there is considerable potential to reduce its emissions.

Decarbonising power grids is one way to reduce solar PV manufacturing emissions, especially in countries that already produce panels. New manufacturing facilities could also be built in countries with relatively high clean energy penetration, helping to reduce emissions and diversify the supply chain. Taking advantage of the latest innovations can also improve the energy and material efficiency of both cells and the manufacturing process.

The growth in the PV supply chain offers long-term employment opportunities for both skilled and low-skilled workers. Policies can help ensure these are quality, well paid jobs that protect and benefit workers and communities. The Global Commission on People-Centred Transitions recommends a focus on skills development, worker protection, social inclusion and direct engagement with citizens (IEA 2021). These actions benefit not only workers, but also help to establish a secure supply chain. A focus on skills development, worker protection and engagement can ensure an ample, educated and supportive workforce. Employment standards and transparency as well as corporate and government policies could help improve employment conditions and reduce trade concerns.

Consider the solar PV sector's financial health in policymaking

Over the last two decades changing government policies and company decisions have led to supply gluts and demand volatility leading to the poor financial health of solar PV manufacturing companies in many PV supply chain segments, with low profitability and high bankruptcy risks. This situation could slow the pace of the transition if companies are unwilling to invest because of low profitability or are unable to withstand sudden changes in market conditions.

A mix of long-term and predictable demand and supply policies can help secure investment based on country experiences to date. However, governments should also consider how best to avoid supply gluts and restrictive trade policy reactions. One approach is to coordinate on both demand and supply policy design to drive diversified investment while maintaining trade and competition (OECD, 2022). In addition, transparent and traceable pricing mechanisms for components and raw materials, can also reduce risk by improving knowledge on costs.

Continue to foster innovation

Innovation can make the supply chain less vulnerable to risks by reducing critical material dependency and generally supporting cost reductions.

Innovation is key for technological advances across and along clean energy supply chains. Technological innovation throughout the solar PV supply chain has increased the conversion efficiency of solar cells, reduced material usage and improved energy efficiency per module. Since 2010, solar PV cells have become nearly 60% more efficient and generation costs have fallen almost 80%. Without public and private investments in R&D all along the supply chain, solar PV would not be the most affordable electricity generation technology in many parts of the globe.

Today, monocrystalline silicon technology dominates the solar PV market owing to its high efficiency and cost-competitiveness. Technology innovation in manufacturing processes to reduce material intensity, especially for critical minerals such as silver and copper, remain key to minimise supply chain vulnerabilities. However, new solar cell designs are also essential to achieve further efficiency gains while reducing material intensity and manufacturing costs significantly. Tandem and perovskite technologies are being developed by multiple companies, but further investment in innovation will be needed to bring them to full commercialisation. Regardless of the technology, efforts to improve panel design for recycling and reusability as well as greater durability can also help reduce material demand.

Develop and strengthen recycling capabilities

As capacity additions ramp up worldwide, so will the volume of end-of-lifetime (EoL) solar PV equipment in upcoming years. While managing EoL flows of solar PV modules is an environmental challenge, recycling offers opportunities to secure a reliable secondary source of materials for the PV industry and other sectors; avoid the negative environmental, social and health impacts associated with raw-material mining; shrink the energy and environmental footprint of solar PV; and generate employment to support local economic activity. To capture these multiple benefits, governments, industries and other stakeholders must prepare now to manage the future surge in solar PV waste from a circular-economy perspective.

It is particularly crucial to develop and implement comprehensive regulatory frameworks to define stakeholder responsibilities, financing models and minimum requirements for collection and recycling, as PV recycling is not currently a profitable business. These frameworks must mitigate the risks of improper PV waste disposal, cover the diversity of EoL module situations (e.g. historical, orphaned and reused modules, etc.), and prioritise high-value recycling over downcycling.

Moreover, PV recycling is still technically challenging, and further research is needed to boost recovery rates and improve material value retention. Policy efforts should target not only downstream recycling processes but also upfront module design to help reduce the complexity and cost of recycling future EoL equipment. Finally, recycling policies should be complemented by strategies to extend overall module service lifetime through reuse, repair and remanufacturing.

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