Global Supply Chain Report

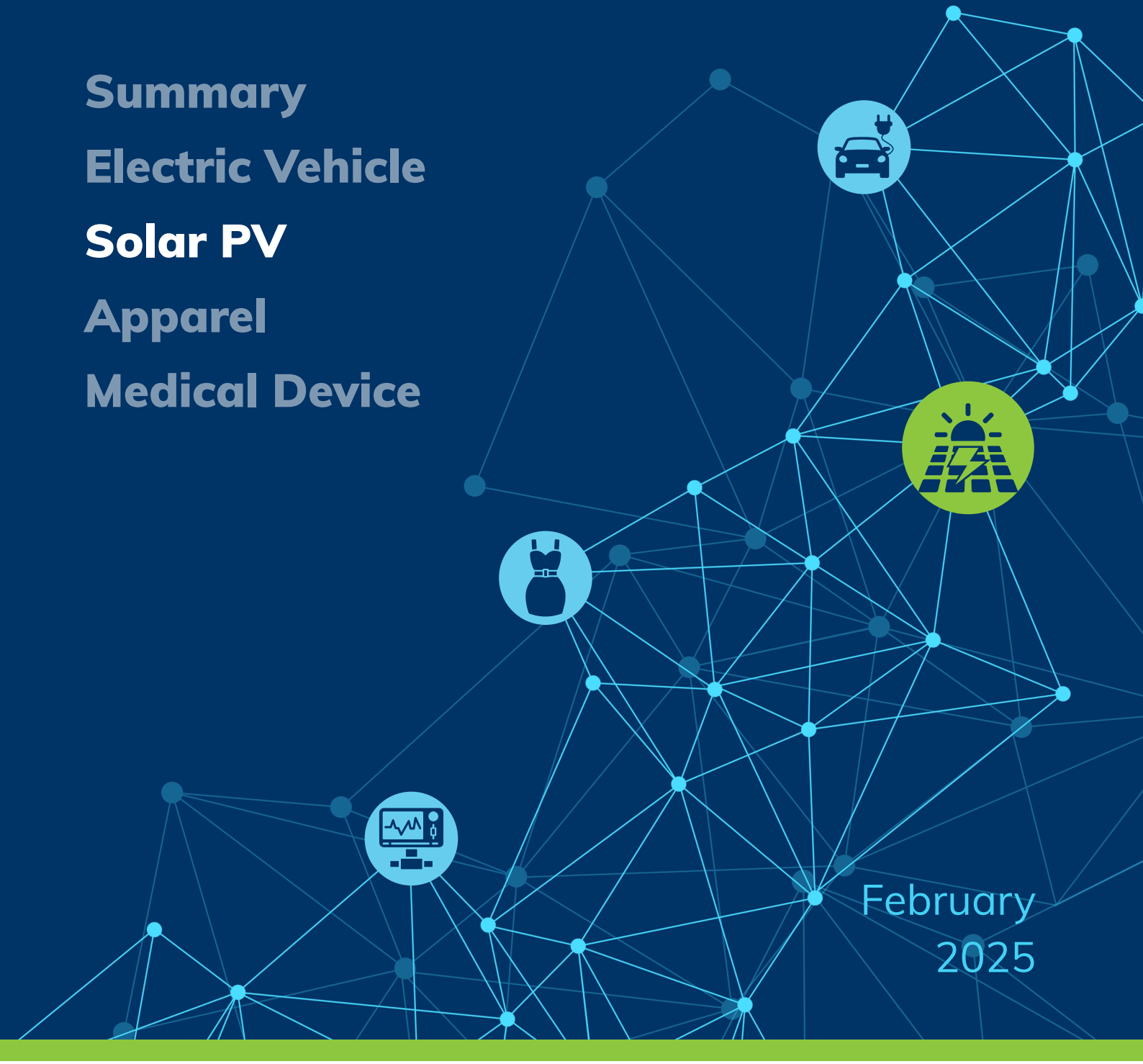
Summary

Electric Vehicle

Solar PV

Apparel

Medical Device



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HKUST LI & FUNG
SUPPLY CHAIN INSTITUTE

Chasing the Sun: Will the Global Solar Supply Chain Find New Horizons?

Executive Summary

Solar power, the third largest renewable energy source in global electricity generation, is a vital pillar in the renewable energy landscape. Solar power has experienced remarkable growth in recent years: Boosted by a significant expansion in solar PV installed capacity, the contribution of solar power to global electricity generation increased to 5.5% in 2023. This upward trend is expected to continue, due to improving cost-effectiveness of solar energy, greater application offerings, as well as the pressing needs for renewable energy sources to combat climate change and for energy security in an increasingly complex geopolitical landscape.

Today, most solar panels in use are crystalline silicon panels. These solar panels are produced by a global supply chain, which encompasses the entire production cycle from the mining of raw materials (quartz) and the refining of polysilicon to the manufacturing of solar cells and the assembly of solar panels. The global aspect of the solar supply chain further reveals a complex network intricately woven into the fabric of global economic and political dynamics.

Amid the world's transition towards a cleaner and more sustainable energy future, the global solar supply chain will continue to evolve, driven by a complex interplay of geopolitical, technological, economic, social, and environmental factors.

Geopolitical tensions between countries have escalated in recent years, leading to an increased levy of import tariffs and other duties on solar products. Meanwhile, supportive domestic policies, such as financial incentives and support mechanisms, could bolster local solar production. FTAs, on the other hand, could help reduce or eliminate tariffs on solar products among signatory countries, facilitating solar sourcing based on cost considerations and the development of regional solar supply chain.

The supply of raw materials and components, and sourcing costs, are crucial determinants of competitiveness in the solar industry. Any country relying on imported materials and components would leave their solar supply chain vulnerable to risks. Meanwhile, any producer incurring a particularly high production cost would just become non-competitive in the market.

Significant progress has been made in solar technology over the past decade. The widespread and rapid adoption of new technologies could not only lower costs and enhance competitiveness, but also help set global technological mainstream trends in the solar industry.

ESG factors are also increasingly shaping the solar supply chain landscape. Growing awareness of climate change and renewable energy adoption is driving investment in solar technologies as well as solar manufacturing, impacting the solar supply chain as a result.

Regarding the geography of the global solar PV supply chain, China has been the undisputed leader in solar manufacturing over the last decade. It has leveraged its scale of production, vertically integrated supply chain, technological prowess, and cost efficiency, together with government support, to excel in all facets of the global solar supply chain. While the protectionist duties imposed by the US and other countries since early 2010s have prompted some shifts in solar cell and panel manufacturing from the Chinese mainland to other countries and regions like the Southeast Asia, China continues to control approximately 85% of panel production and over 90% of the upstream manufacturing stages currently.

Looking ahead, we expect China to maintain its absolute leadership in the global solar PV supply chain in the foreseeable future, buoyed by its competitive production costs, technological leadership, vertically integrated supply chain, and expansion in production capacities. China's pivotal role in the global solar PV supply chain is also exemplified by rising Chinese solar investment globally, spanning from Southeast Asia to the Middle East and the US.

Nevertheless, the global solar PV supply chain landscape is undeniably undergoing major transformations. On one hand, with new US duties on imported solar cells and panels from the four major panel producing countries in Southeast Asia, these countries are likely to experience setbacks in their solar manufacturing. On the other hand, the US and India, buoyed by trade protectionist measures and substantial government support, are emerging as serious contenders in the solar manufacturing arena, attracting investments from domestic and international players seeking diversification beyond China. These shifts are poised to reshape the dynamics of the global solar supply chain.

I. Introduction

The solar photovoltaic (PV) supply chain, a critical component of the renewable energy sector, is a network of interconnected industries and processes involved in the production, distribution, and deployment of solar panels (also called modules). It encompasses the entire production cycle of solar panels, from the mining of raw materials and the manufacturing of solar cells to the assembly of solar panels and their deployment worldwide.

Considering the solar PV supply chain from a global perspective further reveals a complex network that spans countries, continents, regulatory environments, and even great-power competition. At the heart of the global solar supply chain are the major producing countries scattered across continents, each having unique strengths and facing different constraints in solar production. The global aspect of the solar supply chain also extends beyond manufacturing to encompass the intricate web of economic and political relations among countries, as well as the current wave of industrial policies adopted to promote domestic solar manufacturing, among other things.

Understanding the dynamics of the ever-changing global solar supply chain is crucial in analyzing the opportunities and challenges in the solar sector. This will also allow the world to better advance renewable energy goals and address sustainability concerns on a global scale.

In this article, we will offer a comprehensive breakdown of the solar PV supply chain, delve into the dynamic landscape of the global solar supply chain, and explore the latest trends and developments shaping the evolution of the solar industry. By examining emerging trends in the global solar supply chain, we aim to provide insights into how the industry is adapting to recent changes and addressing the challenges it faces. From market forces and regulatory changes to technological advancements and shifts in geopolitics and global trade dynamics, this article will highlight the key factors driving change in the global solar supply chain and the implications for the solar industry. We will also provide our forecasts concerning the shifts in the geographical distribution of the global solar supply chain landscape.

II. An Overview of the Solar Market

Two principal technologies are used to generate solar power: solar photovoltaic (PV) and concentrated solar power (CSP), and they work in completely different ways (see Table 1). As CSP represents less than 0.5% of worldwide installed capacity of solar power plants, this report focuses solely on solar PV.

Table 1: A comparison between solar PV and CSP

	Solar PV	CSP
Operating principle	Direct conversion of sunlight into electricity: When the solar cells absorb light, electrons will be knocked loose. A current is created when the loose electrons flow. This current is then captured and transferred into wires, generating a direct electric current, which will then be converted into alternating current electricity.	Indirect conversion of sun heat into electricity: CSP systems use mirrors/lens to reflect and concentrate sunlight onto a receiver, and this concentrated energy is then used to heat a fluid that generates steam to drive a turbine and generate electricity.
Scalability	It is capable of being deployed in various sizes, ranging from small rooftop installations to large-scale solar farms.	It requires substantial land and is typically deployed for utility-scale power generation.
Cost	Lower levelized cost of electricity (LCOE)[2].	LCOE is roughly double that of solar PV.

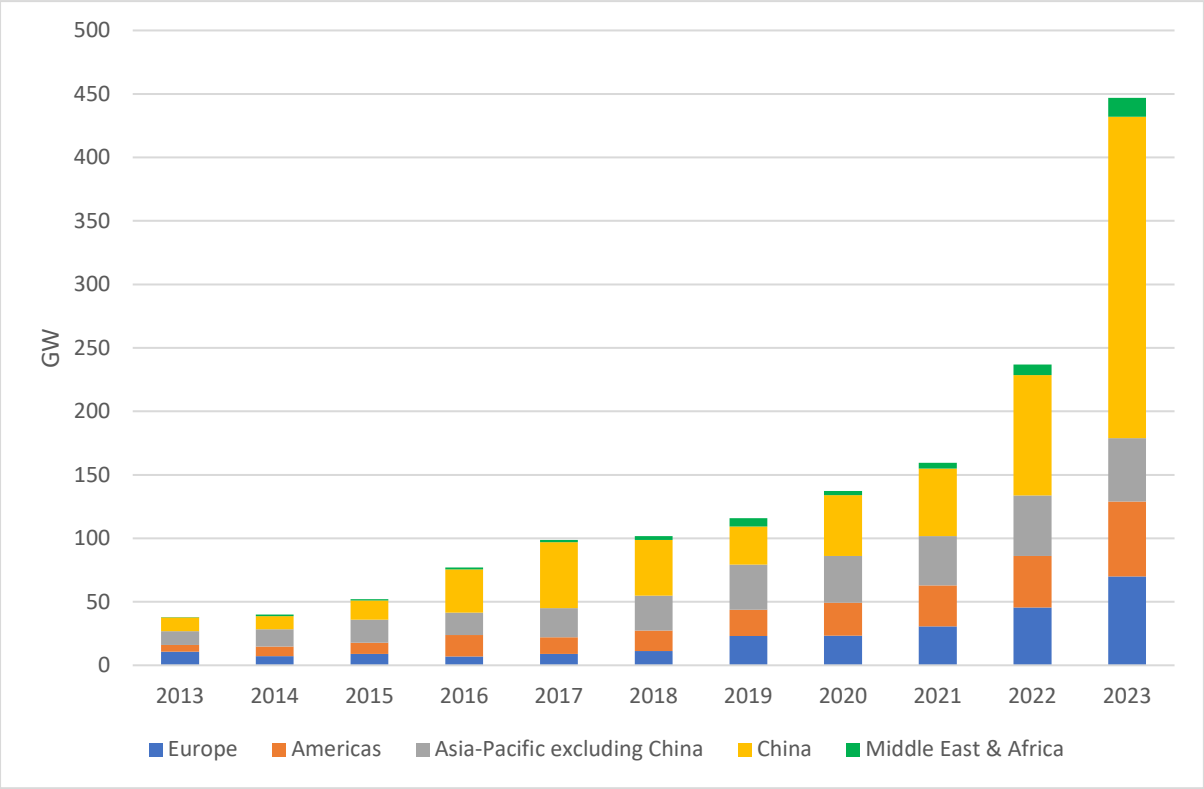
1. Global solar PV installed capacity continues to surge

The solar energy market has seen significant growth in recent years. According to SolarPower Europe, a total of 447 gigawatts (GW) of new solar PV capacity was installed in 2023, accounting for a whopping 78% out of 576 GW of newly installed renewable power generation capacity. The 447 GW of new solar PV installed capacity is a record high and marks an impressive 87% growth compared with 2022's addition of 239 GW (see Figure 1).[3]

[2] The LCOE is a measure of the average cost of electricity generation for an energy system over its lifetime, including construction costs, operations, and maintenance costs, etc.

[3] SolarPower Europe (2024, June). *Global Market Outlook for Solar Power 2024-2028*. https://www.solarpowereurope.org/insights/outlooks/global-market-outlook-for-solar-power-2024-2028

Figure 1: Annual solar PV installed capacity, 2013-2023



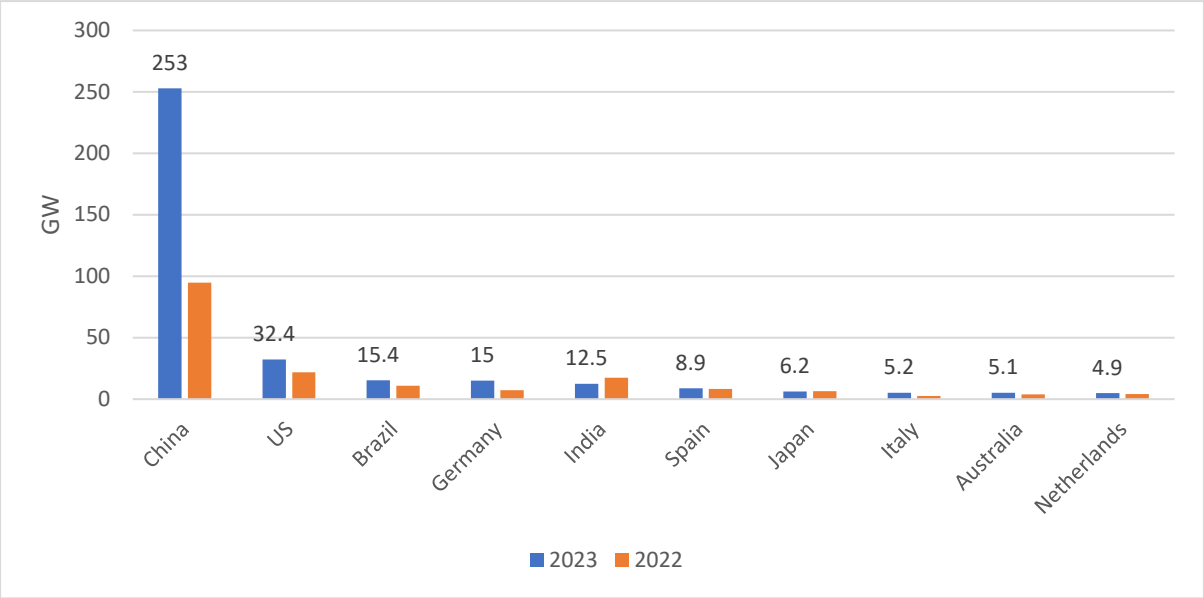
Source: Global Market Outlook for Solar Power 2024-2028, SolarPower Europe

2023 saw an unprecedented growth in new solar PV installed capacity, but it is important to note that the majority of this expansion was driven by China. As the leading solar product supplier and market for years, China accounted for more than half of the newly installed solar PV capacity in 2023 and added a record 253 GW of new capacity, representing a 167% year-on-year (yoy) growth. In comparison, the rest of the world managed to install only 194 GW of new solar PV capacity in 2023, a more modest 35% increase compared with the previous year.

Besides China, other major solar PV markets include the US, Brazil, India, and European countries such as Germany and Spain (see Figure 2).

The global solar PV installed capacity reached over 1,600 GW as of the end of 2023. This represents an eight-time increase from around 178 GW installed globally in 2014. With this surge in installed capacity, solar power is contributing a larger and larger share of global electricity generation: It accounted for 5.5% of the world's total in 2023, up by a percentage point from the previous year. Solar power is now the third biggest renewable energy source behind hydropower and wind power in terms of global power generation.

Figure 2: Top 10 solar PV markets, 2022-2023



Source: Global Market Outlook for Solar Power 2024-2028, SolarPower Europe

2. Key trends in the global solar PV market

Apart from surging market demand, key trends in the global solar PV market include:

(a) Increasing affordability: Driven by improvements in manufacturing efficiency, economies of scale, and technological advancements, the global average LCOE from utility-scale solar PV projects dropped 90% during 2010 to 2023, from US$ 0.460/kilowatt hour (kWh) to US$0.044 kWh, which was 56% lower than fossil fuel-fired options.[4] As solar PV technology becomes more cost-effective and price-competitive compared with traditional fossil fuel-based electricity generation, it becomes more accessible to a wider range of consumers and businesses.

(b) Expanding geographic reach: Solar deployment is no longer concentrated in a few leading markets. Although China and the US remain the top solar PV markets globally, countries across Asia, Europe, the Americas, and Africa have seen significant growth in their solar capacities in recent years.

(c) Diversification of applications: Apart from large-scale ground-mounted solar farms, the solar PV market has also witnessed growth in rooftop solar, community solar, and distributed generation projects for residential, commercial, and industrial end-users.

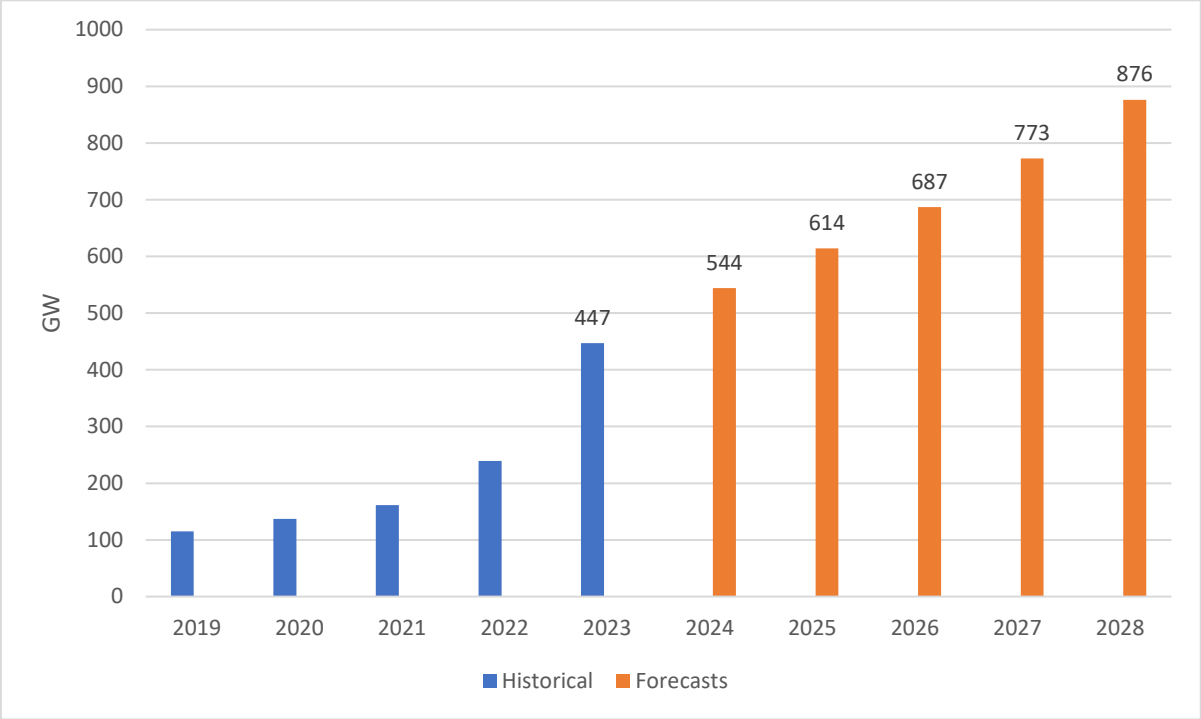
[4] International Renewable Energy Agency (2024). *Renewable Power Generation Costs in 2023*. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2024/Sep/IRENA_Renewable_power_generation_costs_in_2023.pdf

3. Outlook of the global solar PV market

The global solar PV market is expected to continue its growth trajectory in the coming years, driven by the increasing cost-competitiveness of solar energy due to ongoing advancements in technology, increased product offerings, the urgency for renewable energy sources to address climate change challenges, and the need for energy security in a world where geopolitics are becoming increasingly complex.

SolarPower Europe projects that, under the medium scenario, the global solar PV market will reach 614 GW in 2025, a 13% increase from 544 GW in 2024. The market is expected to further increase to 876 GW in 2028 (see Figure 3).[5]

Figure 3: World annual solar PV market forecasts (medium scenario), 2024-2028



Source: Global Market Outlook for Solar Power 2024-2028, SolarPower Europe

[5] SolarPower Europe (2024, June). *Global Market Outlook for Solar Power 2024-2028*. https://www.solarpowereurope.org/insights/outlooks/global-market-outlook-for-solar-power-2024-2028

III. Breaking down the solar PV supply chain

Solar panels are produced by a global supply chain. Today, most solar panels in use are crystalline silicon panels, which represent over 97% of the global production in 2023. Thin-film PV technology[6] is the second most common PV technology after crystalline silicon, representing about 2.5% of the global market. Given the relatively small market share of thin-film technology, this section will focus on the crystalline silicon solar PV supply chain.

The supply chain for crystalline silicon solar panels starts with the refining of polycrystalline silicon (polysilicon) from quartz. Polysilicon is then melted at high temperatures to grow silicon ingots, which are sliced into thin sheets called wafers. Silicon wafers are then processed to make solar cells. Finally, the cells are assembled to make solar panels.

The following sections examine solar PV supply chains from raw materials all the way to the finished product, spanning the four main segments of the manufacturing process: refining of polysilicon, production of wafers, fabrication of cells, and assembly of panels.

Table 2: Principal segments of crystalline silicon solar supply chain and their key features

	Refining of polysilicon	Production of wafers	Fabrication of cells	Assembly of panels
Capital requirement	High	Moderate	Moderate	Low
Energy intensity	High	High	Moderate	Low
Labour intensity	Low	Low	Moderate	High
Technology requirement	Moderate	Moderate	High	Moderate
Industry revenue	Low	Medium	High	Medium

[6] Thin-film PV technology is based on the use of thin-film layers of photovoltaic materials to absorb and convert sunlight into electricity. There are several materials that can be used for thin-film solar cells, but cadmium telluride (CdTe) is the most commonly used, representing about 95% of the thin-film PV market. Thin-film PV technology reached its peak in late 1980s accounting for 30% of the solar PV market, but its market share has declined since then. As thin-film technology uses different materials from crystalline silicon-based solar technology, it has an entirely different production process and supply chain.

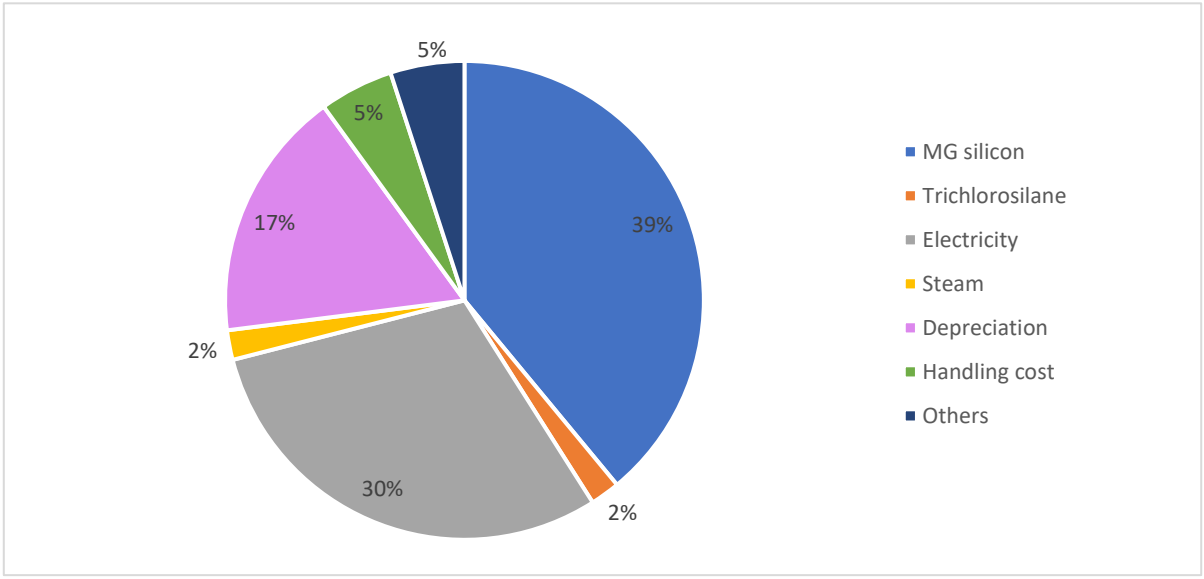
1. Polysilicon

(a) Refining of polysilicon

The silicon incorporated in solar panels comes from silicon dioxide (also known as silica). Silicon dioxide is a natural compound made of silicon and oxygen, and is found in nature as quartz or sand.

Quartz or silica sand is processed into metallurgical-grade (MG) silicon by removing the oxygen through a reaction with carbon. MG silicon is then refined to remove impurities and produce solar-grade polysilicon. The most commonly used technique for producing solar-grade polysilicon is the Siemens method.[7] The end results of the Siemens process are U-shaped silicon rods, which are then broken into small chunks. Whereas MG silicon is 99% pure silicon, solar-grade polysilicon typically has a purity of at least 99.9999%.

Figure 4: Cost structure of polysilicon production in China (Siemens method)



Source: Baiinfo.com

(b) Major producers of polysilicon

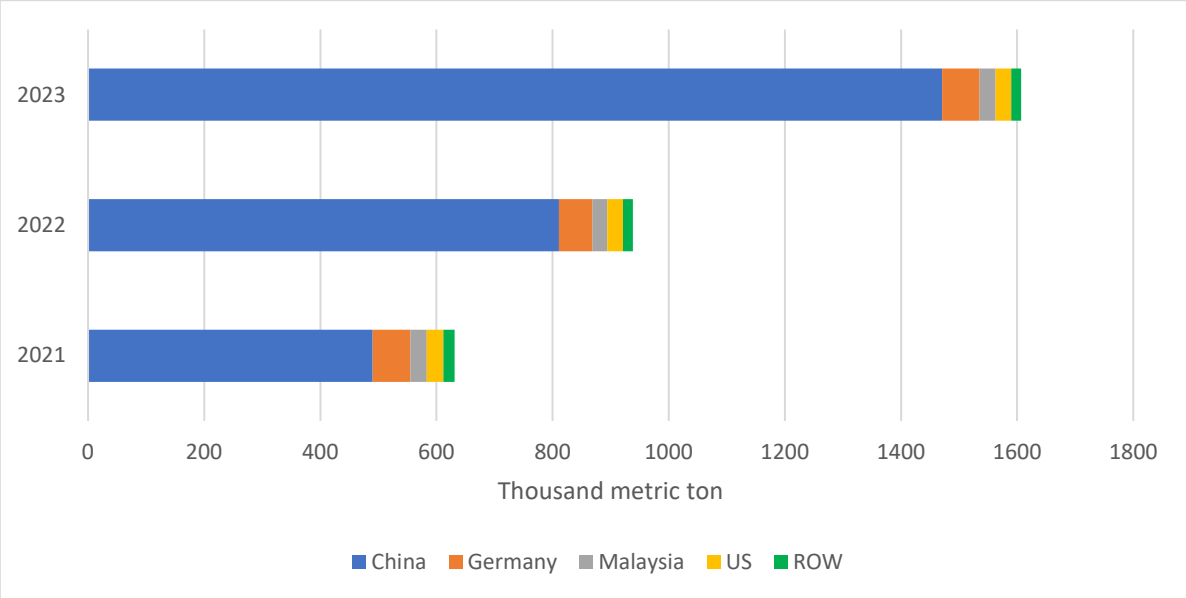
During 2010-2015 and 2021-2023, polysilicon producers in China ramped up their production capacity, leading to a significant increase in global polysilicon production capacity.

According to data released by Beijing Antaike Information, at the end of 2023, the global annual polysilicon production capacity reached 2.256 million metric tons, of which China's annual production capacity was 2.1 million metric tons, accounting for 93% of the world's

[7] Siemens process is a chemical vapor deposition based process, in which highly purified silane gases such as trichlorosilane (TCS) are heated in the presence of silicon rods. The silicon rods are heated electrically and are mounted into the reactor by graphite electrodes, sometimes called seed-chucks. The TCS then decomposes and ultra-pure silicon deposits on the heated silicon rods.

total. In 2023, the global polysilicon production totalled 1.597 million metric tons, of which China's production accounted for 92% (1.471 million metric tons), ranking first in the world for thirteen consecutive years (see Figure 5).

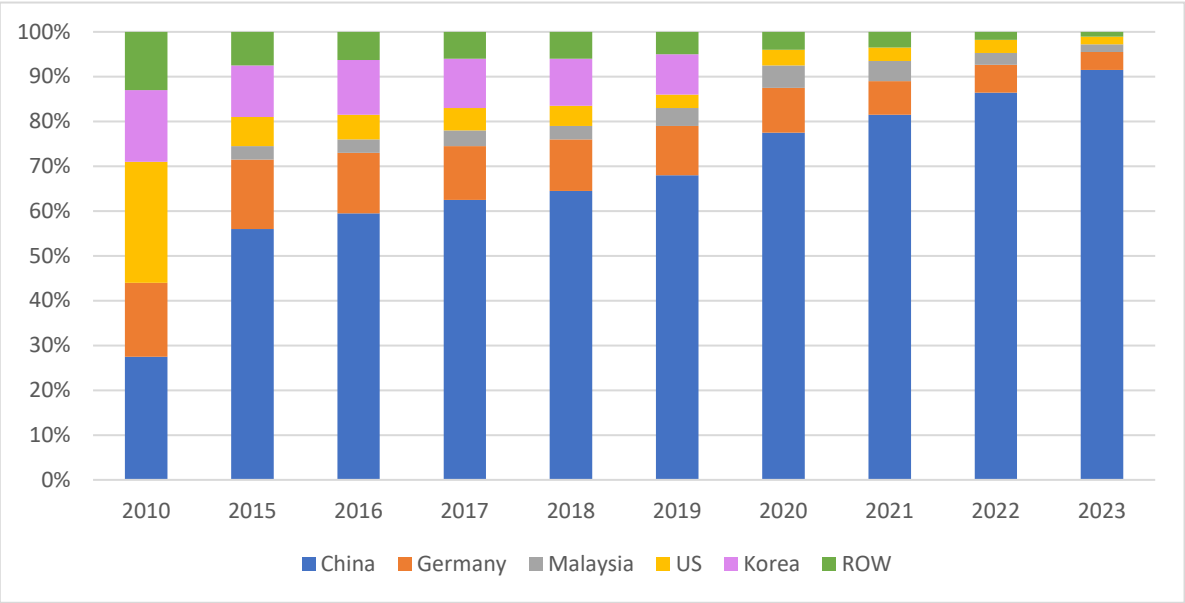
Figure 5: Global production of polysilicon, 2021-2023



Source: Beijing Antaike Information

Back in 2010, the production of polysilicon was more geographically diversified, with both China and the US accounting for a quarter of the world's total production and each of Germany and South Korea also holding market shares of around 16%. Since then, polysilicon production has become increasingly concentrated in China (see Figure 6).

Figure 6: Market shares of global polysilicon production by country, 2010-2023



Source: International Energy Agency (2010-2021); Beijing Antaike Information (2022-2023)

In 2022, the top 10 polysilicon producers consisted of eight Chinese companies, one German company (Wacker – which has plants in Germany and the US), and one Japanese company (Tokuyama – which has plants in Malaysia). The eight Chinese polysilicon producers alone accounted for over 80% of the world's production capacity in 2022 (see Table 3).

Table 3: Top 10 polysilicon producers by production capacity, 2010 and 2022

	2010			2022	
	Company	**Share of capacity**		**Company**	**Share of capacity**
1	Hemlock (US)	12.6%		Tongwei Solar (China)	22.8%
2	Wacker (Germany)	10.7%		GCL (China)	18.3%
3	OCI (South Korea)	9.5%		Xinte (China)	15.3%
4	GCL (China)	7.4%		Daqo (China)	9.1%
5	REC (US)	5.8%		Asia Silicon (China)	6.8%
6	Tokuyama (Japan)	2.9%		Wacker (Germany)	6.5%
7	MEMC (US)	2.7%		East Hope (China)	5.3%
8	LDK (China)	2.3%		Lihao (China)	3.8%
9	ReneSola (China)	2.1%		Tokuyama (Japan)	2.3%
10	China Silicon (China)	1.8%		Dongli (China)	1.5%
	Sub-total	57.7%		Sub-total	91.7%

Source: Beijing Antaike Information

Since most of the production of the immediate downstream products of polysilicon – silicon wafers – is conducted in China, China still had to import 62,900 metric tons of polysilicon in 2023, despite China accounting for over 90% of global polysilicon production.

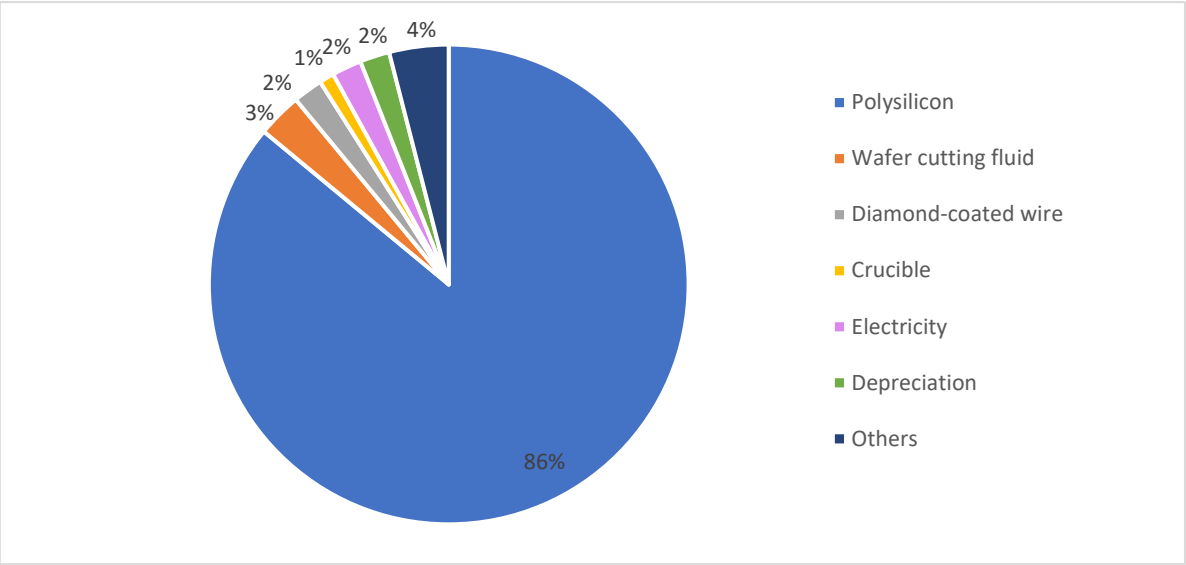
2. Wafers

(a) Manufacturing of wafers

Silicon wafers serve as the base of a solar cell, functioning as a semiconductor that generates electrical current within the solar cell. The continuous-Czochralski process is generally used to produce single-crystal silicon wafers (monocrystalline wafers) from polysilicon feedstock.[8] This method involves melting the polysilicon at over 1,400°C in a crucible, then solidifying the melt to grow a single-crystal cylindrical ingot. The resulting ingot will then be sliced, by means of diamond-coated wires, into thin wafers, typically 120-150 micrometres thick.

[8] Before 2019, polycrystalline (multicrystalline) wafers dominated the market due to their lower costs. However, with better photoelectric conversion efficiency, monocrystalline wafers have quickly replaced polycrystalline wafers since then. The market share of monocrystalline wafers increased from 45% in 2018 to 65% in 2019, 90.2% in 2020, 94.5% in 2021 and 99% in 2023.

Figure 7: Cost structure of wafer manufacturing



Source: Solarzoom

(b) Major producers of wafers

Nearly all global silicon wafer production capacity and manufacturing is located in China. According to data published by China Photovoltaic Industry Association, the global annual wafer production capacity reached 974.2 GW at the end of 2023, of which China's annual production capacity was 953.6 GW, accounting for 98% of the world's total. The global silicon wafer production was 681.5 GW in 2023, of which China's production was 668.3 GW, accounting for 98% of the world's total and ranking first in the world for ten consecutive years (see Table 4).[9] Meanwhile, Vietnam and Malaysia ranked second and third respectively in wafer production.

Table 4: Global production capacity and output of silicon wafers, 2020-2023

	Production capacity (GW/year)				Production output (GW)		
	Global	**China**	**Overseas**		**Global**	**China**	**Overseas**
2020	247.4	240.0	7.4		167.7	161.4	6.3
2021	415.1	407.2	7.9		232.9	226.6	6.3
2022	664.0	650.3	13.7		381.1	371.3	9.8
2023	974.2	953.6	20.6		681.5	668.3	13.2

Source: China Photovoltaic Industry Association

[9] China Photovoltaic Industry Association (2024 June). *2023-2024 nian zhongguo guangfu chanye niandu baogao* [2023-2024 China Photovoltaic Industry Annual Report].

In 2023, the top ten wafer producers were all Chinese, and the top three manufacturers (LONGi, TCL Zhonghuan, and JinkoSolar) produced nearly half of solar wafers in the world (see Table 5).[10]

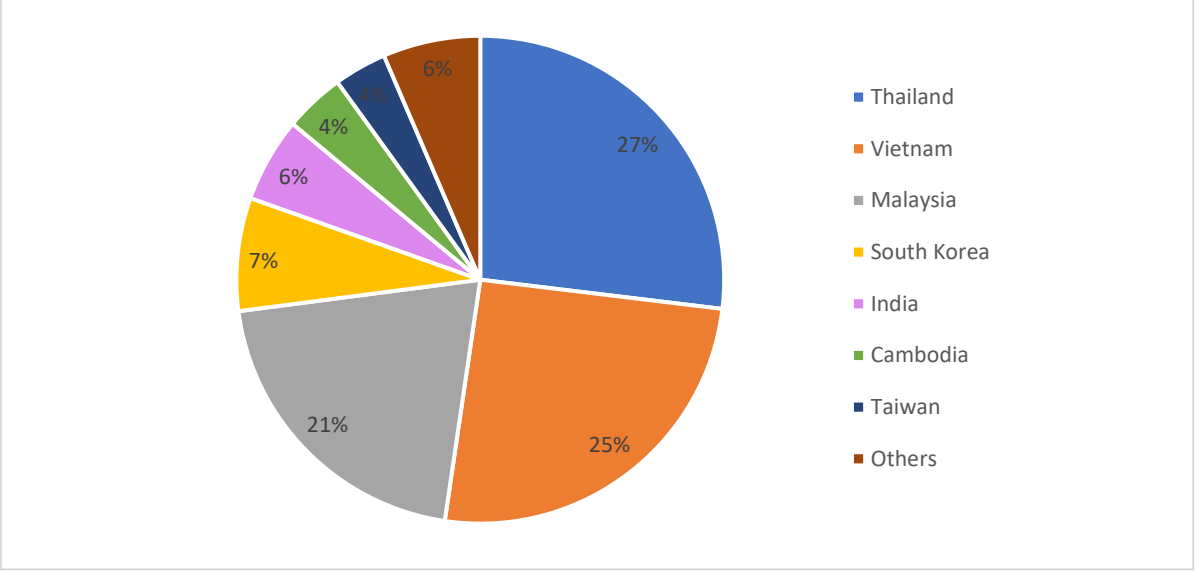
Table 5: Top 5 silicon wafer producers in the world, 2023

	Company	Factory location	Production capacity (GW/year)	Production output (GW)
1	TCL Zhonghuan	China	155	133.7
2	LONGi	China	167.4	124.9
		Malaysia	2.6	2.6
3	JinkoSolar	China	78	69
		Vietnam	7	7
4	GCL Group	China	58.5	51.1
5	JA Solar	China	78.5	45.4
		Vietnam	5	4.7

Source: The International Energy Agency Photovoltaic Power Systems Programme

Of the 668.3 GW of Chinese wafer production, around 12% (78 GW) was exported to other solar cell producing countries, in particular Thailand, Vietnam, and Malaysia, where Chinese solar cell manufacturers have substantial operations (see Figure 8).

Figure 8: Major export markets of Chinese silicon wafers by export value, 2023



Source: China Chamber of Commerce for Import and Export of Machinery and Electronic Products

[10] International Energy Agency Photovoltaic Power Systems Programme (2024). *Trends in PV Applications 2024*. https://iea-pvps.org/wp-content/uploads/2024/10/IEA-PVPS-Task-1-Trends-Report-2024.pdf

3. Solar cells

(a) Fabrication of solar cells

During the cell fabrication stage, silicon wafers will undergo various treatments, including texturing to reduce reflectance and improve light absorption, doping (adding other materials to change the electrical properties of the silicon), and creating electrical contacts, to transform the silicon wafers into functional solar cells.

The passivated emitter and rear contact (PERC) was the most commonly used solar cell technology from 2019 to 2023.[11] However, the tunnel oxide passivated contact (TOPCon) technology[12], with its superior power conversion efficiency[13] of 25% (2024) compared with 23.6% for PERC, has been rapidly overtaking the PERC. The structure of TOPCon cells is only slightly different from PERC cells, meaning that cell producers can just make minor upgrades to their production lines to produce TOPCon cells. According to industry sources, the top five solar cell suppliers in the world already shipped more TOPCon cells than PERC cells in the first half of 2024.[14]

TOPCon is projected to capture half of the market in 2024 and will remain the dominant solar cell technology over at least the next decade, while PERC cells will be phased out over the next few years.[15]

[11] Compared with conventional aluminum back surface field (Al-BSF) solar cells, PERC cells incorporate an additional passivation layer at the rear of the cells, which enhances light absorption and reduces electron recombination. PERC replaced the Al-BSF as the most popular solar PV technology in 2019. The market share of PERC technology reached its peak at 91% in 2021 but declined to 63% in 2023, rapidly losing market share to the TOPCon technology.

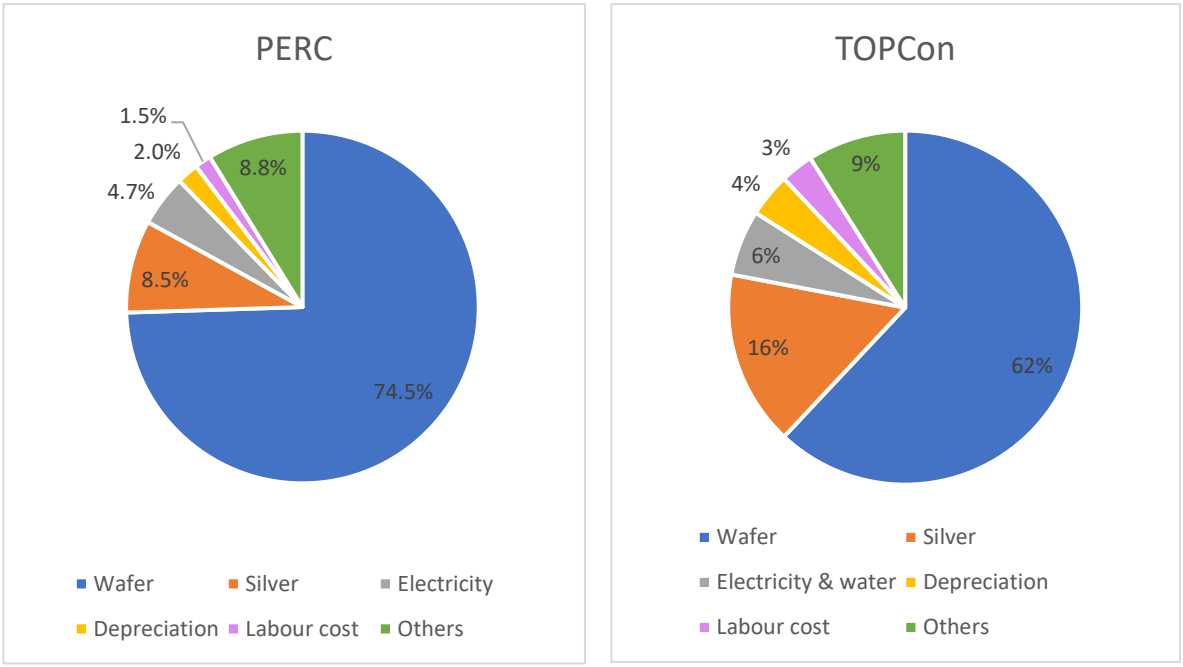
[12] The TOPCon cell is an upgraded and more advanced version of the PERC cell. TOPCon cells feature a thin tunnelling oxide layer between the silicon wafer and the passivating contact layer. This structure minimizes electron recombination and enhances the cell's overall efficiency.

[13] The power conversion efficiency of a solar cell is the percentage of solar energy that is converted to electricity.

[14] InfoLink Consulting (2024, August 5). *Cell shipment ranking 1H24: Top 5 reshuffle amid sagging market*. https://www.infolink-group.com/energy-article/solar-topic-cell-shipment-ranking-1h24-top5-reshuffle-amid-sagging-market

[15] VDMA (2024, May). *International Technology Roadmap for Photovoltaics 15th Edition*. https://www.vdma.org/international-technology-roadmap-photovoltaic

Figure 9: Cost structure of solar cells, 2022

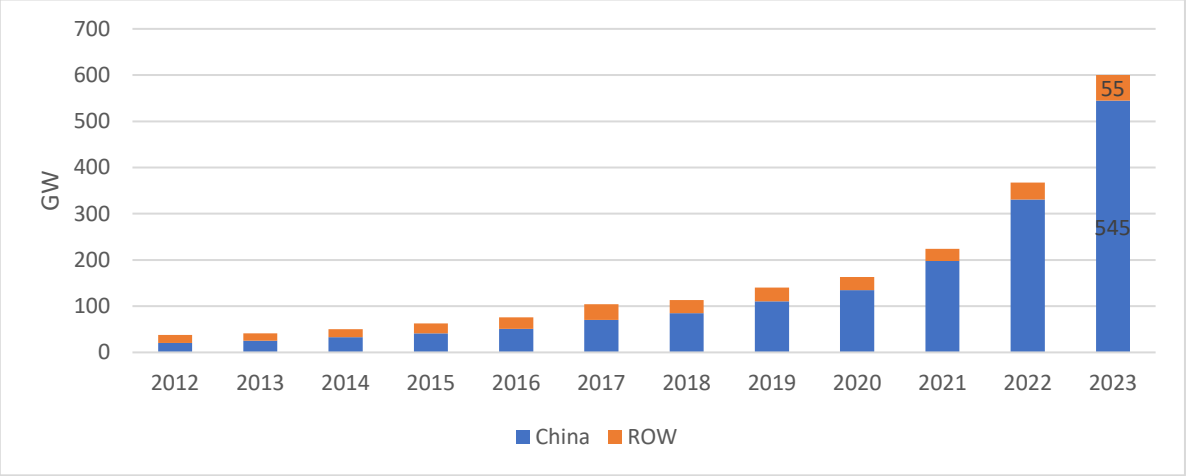


Source: Solarzoom

(b) Major producers of solar cells

From 2012 to 2023, the global production of solar cells grew rapidly from 38 GW to 600 GW, and China's production increased from 21 GW to 545 GW. China's cell production accounted for over 90% of global production in 2023 (see Figure 10). Meanwhile, the global annual cell production capacity reached 1032 GW at the end of 2023, of which China's annual production capacity was 930 GW, accounting for 90% of the world's total.[16]

Figure 10: Global production of solar cells, 2012-2023

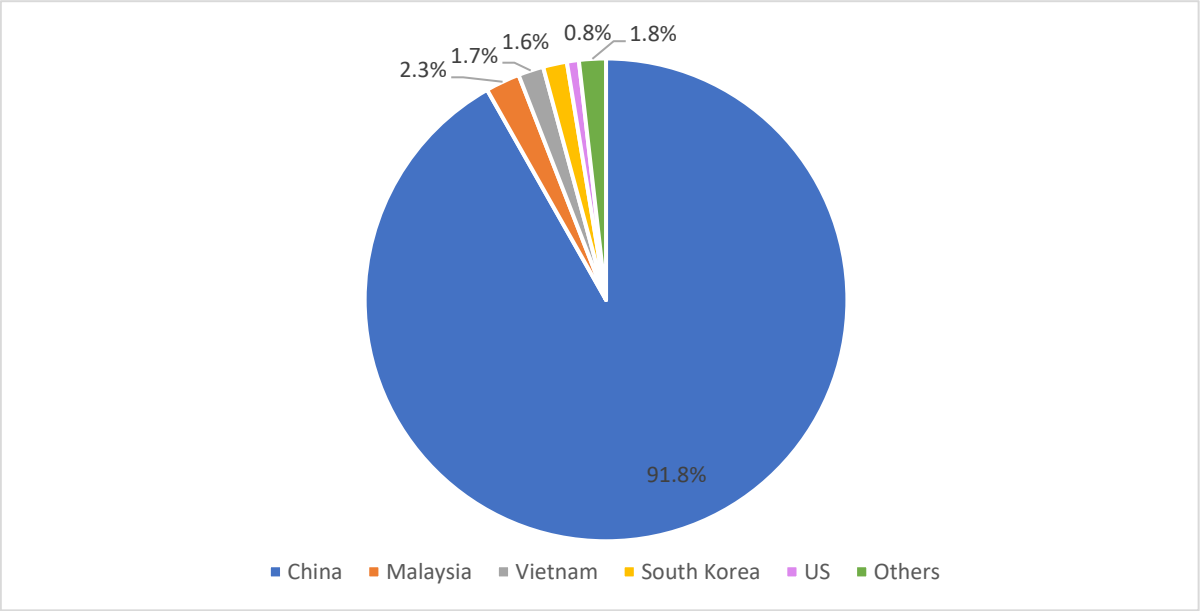


Source: China Photovoltaic Industry Association

[16] China Photovoltaic Industry Association (2024 June). *2023-2024 nian zhongguo guangfu chanye niandu baogao* [2023-2024 China Photovoltaic Industry Annual Report].

Besides China, Southeast Asian countries like Malaysia, Vietnam, and South Korea, and the US are the other major cell producing countries (see Figure 11). It is noteworthy that while the crystalline silicon solar cell is the mainstream PV technology in the global market, solar cell production in the US is mainly of the cadmium telluride (CdTe) thin-film technology.

Figure 11: Market shares of global production of solar cells by country, 2023



Source: The International Energy Agency Photovoltaic Power Systems Programme

In 2023, the top five solar cell producers in the world were all Chinese mainland companies. Tongwei was the world's largest producer with cell production of 80.8 GW, accounting for 13% of the world's total, while JinkoSolar and LONGi came in second and third respectively (see Table 6).

Table 6: Top 5 solar cell producers by production volume, 2022-2023

2022			2023		
	Company	**Production (GW)**		**Company**	**Production (GW)**
1	Tongwei	49.2	**1**	Tongwei	80.8
2	LONGi	36.2	**2**	JinkoSolar	63.9
3	Aiko Solar	33.7	**3**	LONGi	62.3
4	Trina Solar	33.6	**4**	JA Solar	45.5
5	JA Solar	32.7	**5**	Trina Solar	44.3

Source: The International Energy Agency Photovoltaic Power Systems Programme

However, it should be noted that since most of the major solar companies are integrated manufacturers and engage in various segments of the solar PV supply chain, usually a significant proportion of their cell production is used for in-house panel assembly. If measured by shipment volume of solar cells (i.e., including only external sales and excluding cell production for in-house panel assembly), a different picture emerges for the company ranking (see Table 7). While Tongwei remained the largest supplier of solar cells, Aiko and SolarSpace came in second and third respectively in 2023. Nevertheless, the top five solar cell suppliers in the world were all Chinese mainland companies from 2019 to 2023 (see Table 6).

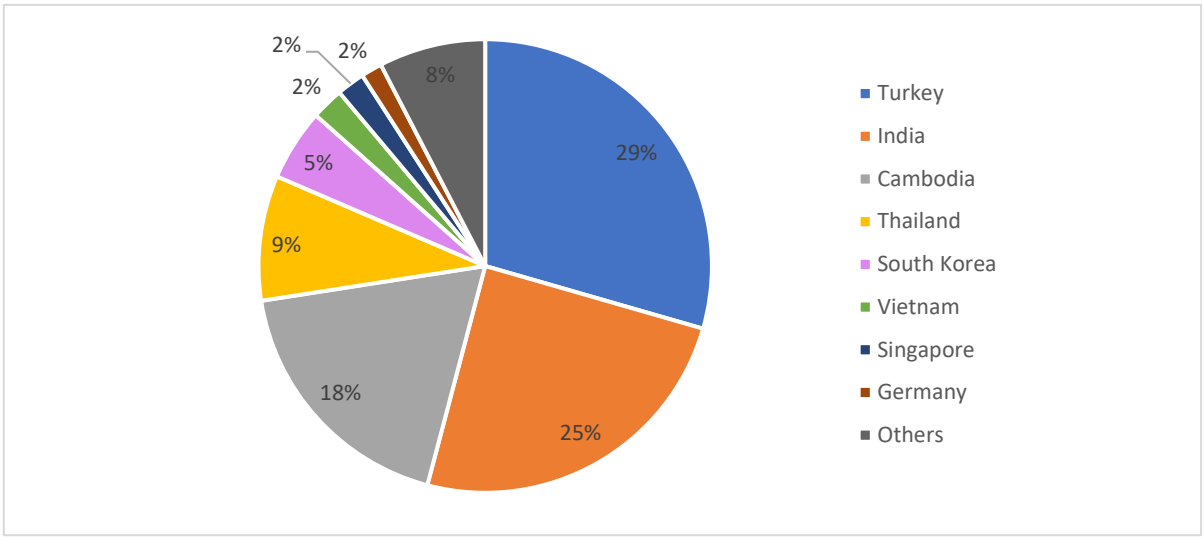
Table 7: Top 5 solar cell supplier by shipment volume, 2018-2023

	2018	2019	2020	2021	2022	2023
1	Tongwei	Tongwei	Tongwei	Tongwei	Tongwei	Tongwei
2	Aiko	Aiko	Aiko	Aiko	Aiko	Aiko
3	Uniex/Jietai	SolarSpace	Runergy	Runergy	Runergy	SolarSpace
4	URECO (Taiwan)	Uniex/Jietai	Lu'an	SolarSpace	SolarSpace	Jietai
5	Motech (Taiwan)	Runergy	SolarSpace	Lu'an	Jietai	Runergy

Source: PV Infolink

In 2023, China exported 39 GW of solar cells, up by 69.4% yoy. Export value increased by 5.2% yoy to US$3.94 billion. The top five export markets were Turkey, India, Cambodia, Thailand, and South Korea, which combined for 86.3% of China's cell exports (see Figure 12).

Figure 12: Major export markets of Chinese solar cells by export value, 2023



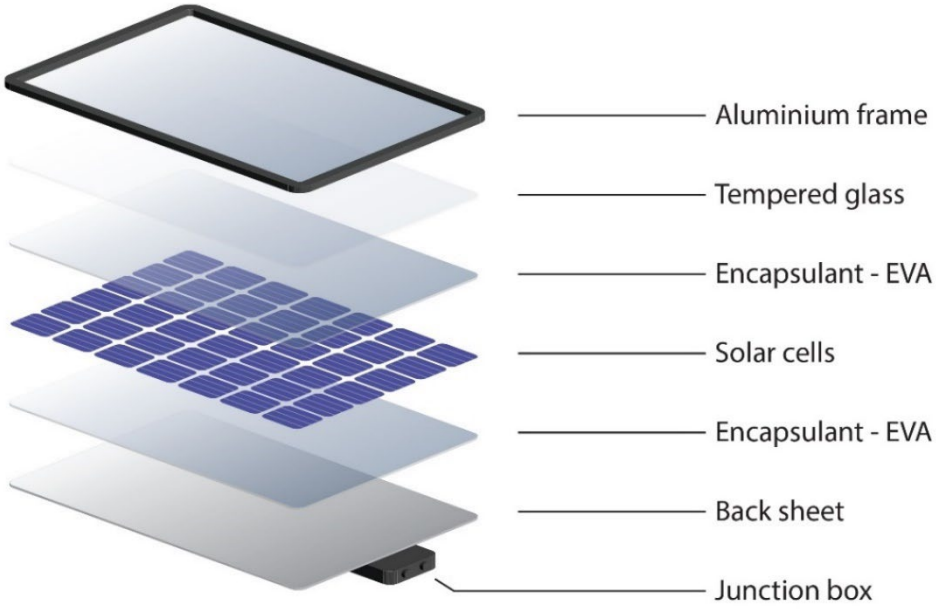
Source: China Chamber of Commerce for Import and Export of Machinery and Electronic Products

4. Solar panels

(a) Assembly of solar panels

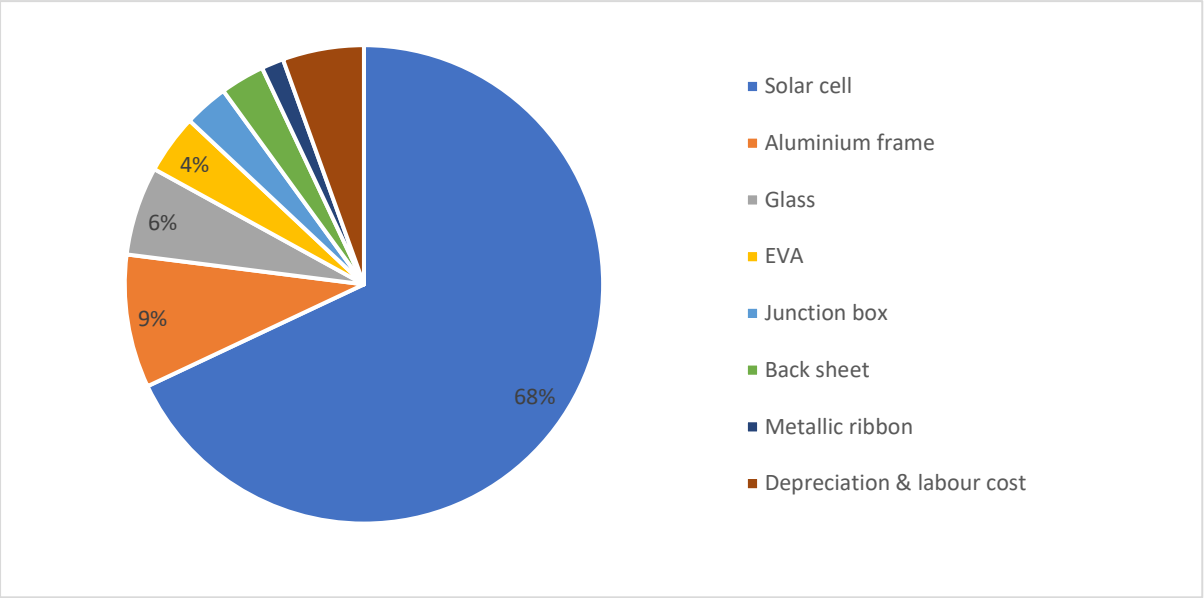
The process of solar panel assembly involves several steps. These include the connection of solar cells into strings, the organization of parallel cell strings into an array, connecting the strings with metallic ribbons, the mounting of the array onto a layer of encapsulant situated on top of a back sheet, and the lamination of a second sheet of encapsulant and front glass onto the entire assembly (see Figure 13).

Figure 13: Basic structure of a solar panel



The front glass sheet protects the cells from the weather. The ethylene vinyl acetate (EVA) film is a plastic layer used to encapsulate the cells and hold them in position. The aluminium frame protects the edge of the laminate section housing the cells while providing a solid structure to mount the solar panel in position. The back sheet, made of various polymers or plastics, is the rearmost layer of a standard solar panel and provides both mechanical protection and electrical insulation.

Figure 14: Cost structure of solar panel assembly, 2023



Source: Qianzhan Industrial Research Institute

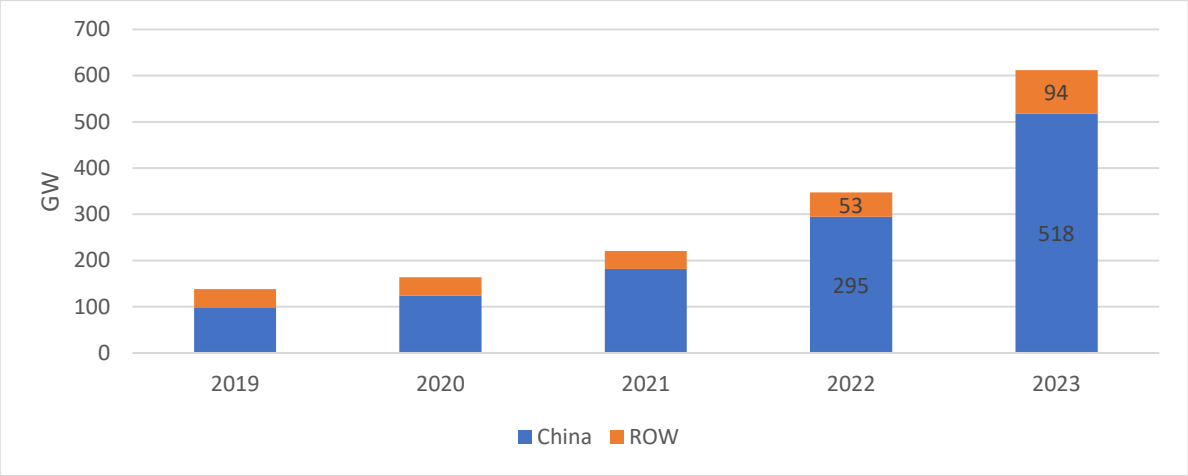
(b) Major producers of solar panels

Compared with the manufacturing of silicon wafers and solar cells, the assembly of solar panels is more geographically diversified due to the lower technical complexity of panel assembly as well as trade restrictions against Chinese-made solar panels, but China is still the absolute leader. China is also the main manufacturer of panel components including glass, EVA, back sheet and junction box.

From 2004 to 2023, the Chinese-manufactured share of global solar panel shipments surged from 1% to 85%. According to data released by China Photovoltaic Industry Association, the global production of solar panels was estimated to be 612 GW in 2023, of which China's production totalled 518 GW, ranking first in the world for 17 consecutive years (see Figure 15). Meanwhile, the global annual panel production capacity reached 1103 GW at the end of 2023, of which China's annual production capacity was 920 GW, accounting for 83% of the world's total.[17]

[17] China Photovoltaic Industry Association (2024 June). *2023-2024 nian zhongguo guangfu chanye niandu baogao* [2023-2024 China Photovoltaic Industry Annual Report].

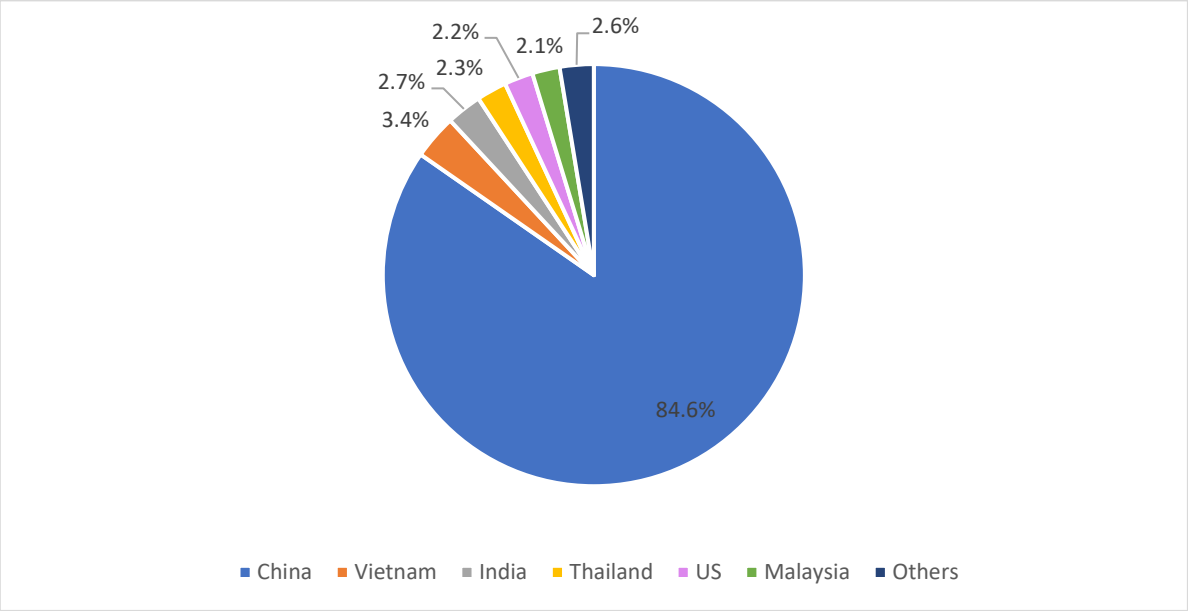
Figure 15: Global production of solar panels, 2019-2023



Source: China Photovoltaic Industry Association

Currently, outside of China, only a few Asian countries (Vietnam, India, Thailand, and Malaysia) and the US have meaningful solar panel manufacturing capabilities (see Figure 16).

Figure 16: Market shares of global production of solar panels by country, 2023



Source: The International Energy Agency Photovoltaic Power Systems Programme

The solar panel industry features high market concentration, with the top four producers accounting for over 40% of the global solar panel shipments in 2023. Among the top 10 producers worldwide, Canadian Solar is the only non-Chinese company, which is incorporated in Canada by a Canadian citizen with Chinese ancestry (see Table 8).

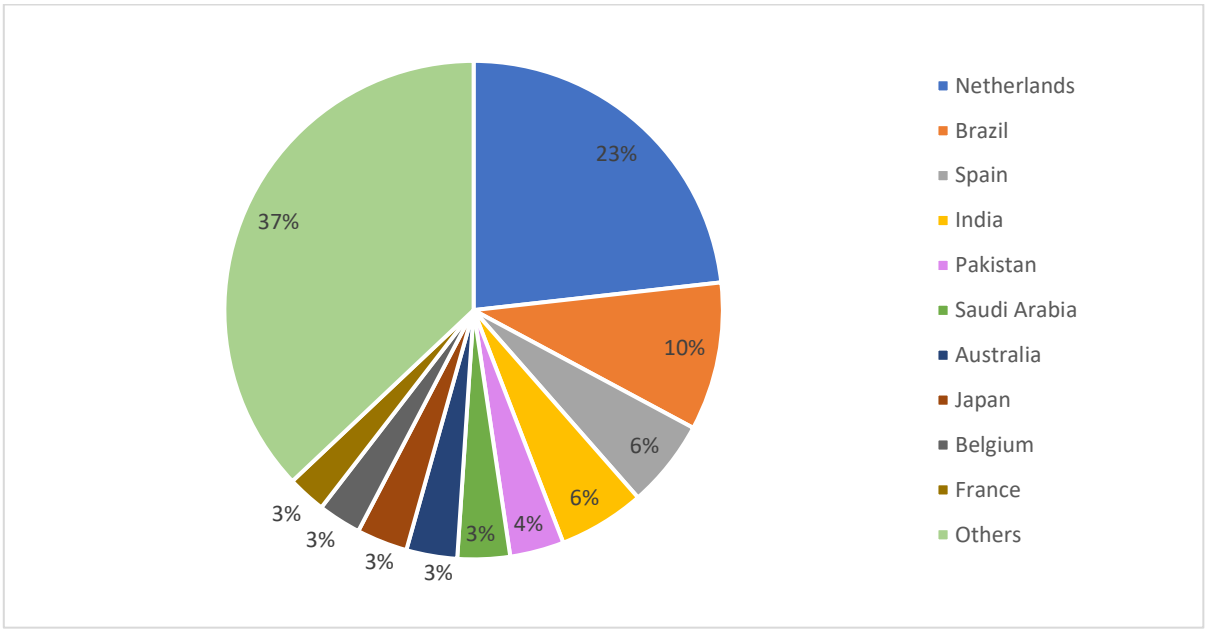
Table 8: Top 10 solar panel producers by shipment volume, 2023

	Company	Shipment volume (GW)
1	JinkoSolar	78.5
2	LONGi Green Energy	67.5
3	Trina Solar	65.2
4	JA Solar	53.1
5	Tongwei Solar	31.1
6	Canadian Solar	30.7
7	Astronergy	28.0
8	Risen	19.0
9	DAS Solar	18~20
10	GCL	16.4

Source: Compiled from company reports and public information

In 2023, China's exports of solar panels reached 211 GW, up by 36.6% yoy. Export value was US$38.8 billion, down by 5.8% yoy due to a plunge in panel prices. The Netherlands was the largest importer of China's solar panels, although around 60% of the panel imports are re-exported, mainly to other EU countries. Brazil, Spain, and India were also major markets for China's solar panels (see Figure 17).

Figure 17: Major export markets of Chinese solar panels by export value, 2023



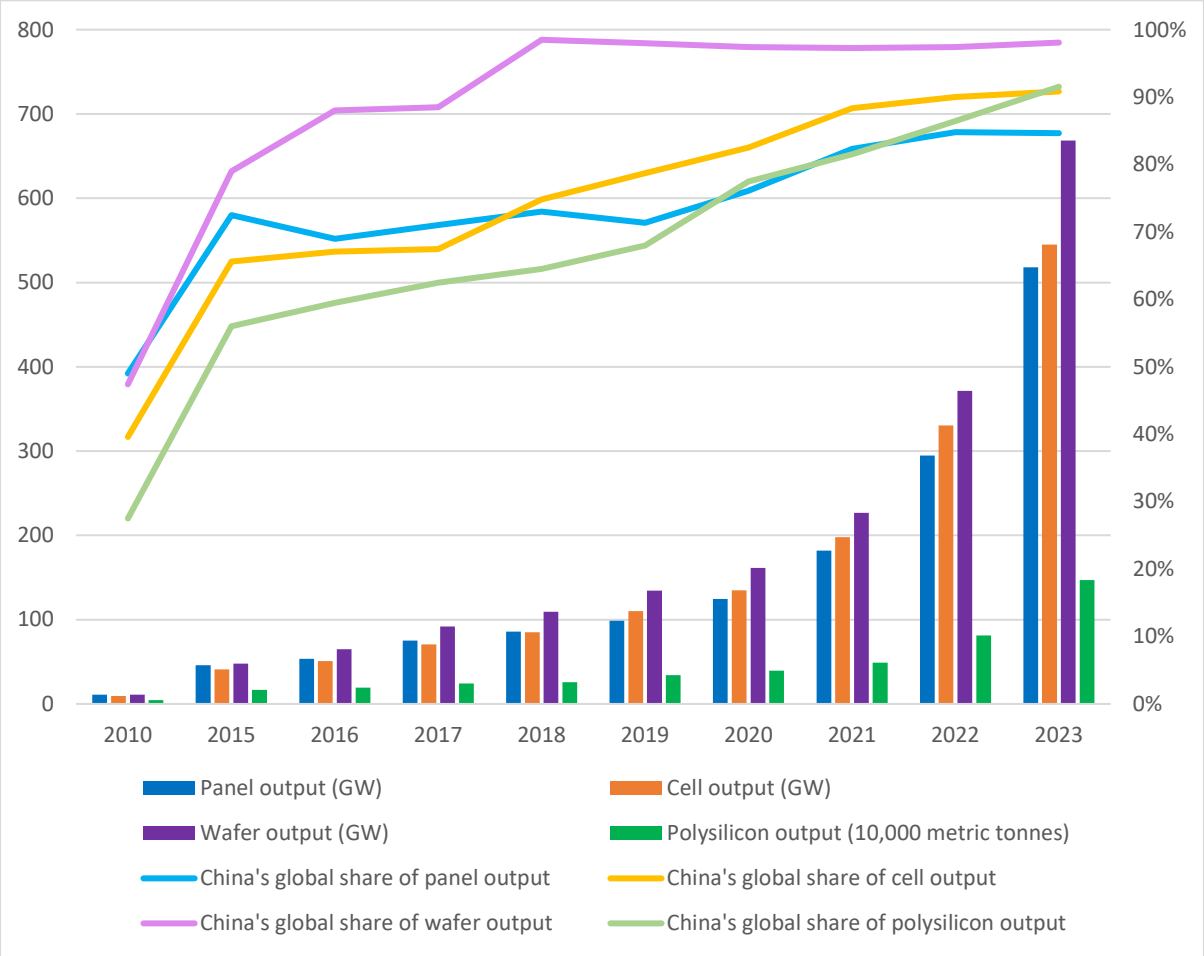
Source: China Chamber of Commerce for Import and Export of Machinery and Electronic Products

5. China's pivotal role in the global solar PV supply chain

Over the last 15 years or so, global solar PV manufacturing has increasingly migrated from Europe, the US, and developed Asian countries to China. In 2010, China's global share in the various manufacturing stages of the solar PV supply chain was around 40%; currently, this figure has more than doubled to 90% (see Figure 18).

As discussed in the previous section, China now controls over 90% of the global production of polysilicon, which is key to manufacturing ingots and wafers. Silicon wafers, which are processed to make solar cells, are almost entirely produced in China. China also controls over 90% of the global production of solar cells and over 80% of solar panel production.

Figure 18: China's production of and global share in manufacturing stages of the solar PV supply chain, 2010, 2015-2023



Source: China Photovoltaic Industry Association

IV. Forces Shaping the Future Global Solar Supply Chain Landscape

The future global solar supply chain landscape is being reshaped by a multitude of political, economic, social, environmental and technological forces. Some of these key forces include:

1. Geopolitics and trade protectionism

In an era marked by burgeoning geopolitical uncertainties, overdependence on energy products from a small number of countries poses significant risks in terms of energy security. Some countries consider China's supremacy in the solar supply chain as a source of risk and opt to raise trade barriers against Chinese solar products. Since 2011, the number of tariffs and anti-dumping and countervailing duties (AD/CVD) levied against imported solar products has been rising, especially those from China, pointing to heightened trade tensions in the solar industry (see Table 9).

Table 9: Trade policies on solar products in force in selected economies, January 2025

Country	Trade action	Duty rate
US	AD/CVD on solar cells and modules from the Chinese mainland and Taiwan	• Anti-dumping duty: 18.32%-249.96% • Countervailing duty: 14.78%-49.79%
	Section 201 tariffs on solar cells and modules from most countries	• 14.25% from 7 Feb 2024 through 6 Feb 2025 • 14% from 7 Feb 2025 through 6 Feb 2026
	Section 301 tariffs on solar cells and modules from the Chinese mainland	• Tariffs doubled from 25% to 50% since 27 Sep 2024
	Section 301 tariffs on solar wafers and polysilicon from the Chinese mainland	• Tariffs to be doubled from 25% to 50% since 1 Jan 2025
EU	AD/CVD on solar glass from the Chinese mainland, Taiwan, and Malaysia	• Anti-dumping duty: 17.5%-75.4% • Countervailing duty: 3.5%-17.1%
China	Anti-dumping duty on solar-grade polysilicon from the US and South Korea	• South Korea: 4.4%-113.8% • US: 30%-57%

	Trade action (cont.)	Duty rate (cont.)
India	Basics customs duty on solar cells and panels	• Solar cells: 25% • Solar panels: 40%
	Anti-dumping duty on EVA and the aluminium frames for solar panels from the Chinese mainland	• US$590-897 per metric ton for EVA • US$403-577 per metric ton for solar frames
Brazil	Import tariffs on solar modules	• Tariffs raised from 9.6% to 25% since 13 Nov 2024

Source: Compiled from public information

Against this backdrop, some solar companies move their manufacturing capabilities to unaffected countries to circumvent these duties. This could lead to the emergence of new solar manufacturing hubs, thus altering the global solar supply chain dynamics.

For example, the US has been targeting Chinese solar products over the past decade, leading to some shifts of solar production from the Chinese mainland to Taiwan, and then to Southeast Asian countries. In 2012, the Obama administration ruled that China had subsidized its solar producers and imposed AD/CVD on Chinese mainland producers of solar cells (whether or not assembled into modules), but Chinese mainland producers responded by shifting cell production to Taiwan.

In 2015, these duties were amended and expanded to cover Chinese mainland solar modules made from third-country-origin cells, and Taiwanese solar cells (whether or not assembled into modules) as well. In 2018, the Trump administration imposed an additional tariff of 25% on solar cells and modules from the Chinese mainland following a Section 301 investigation.

As a result of these protectionist duties, Chinese solar cells and panels have been almost completely phased out in the US market. Meanwhile, major Chinese solar producers have relocated US-oriented production to Southeast Asia. JinkoSolar, Trina Solar, LONGi, and JA Solar have all established integrated production capacity for silicon wafers, solar cells, and panels in Southeast Asia. As of end-March of 2024, more than a half of the panel production capacity and nearly two-thirds of the cell production capacity of Southeast Asian countries were actually established by Chinese companies (see Table 10).

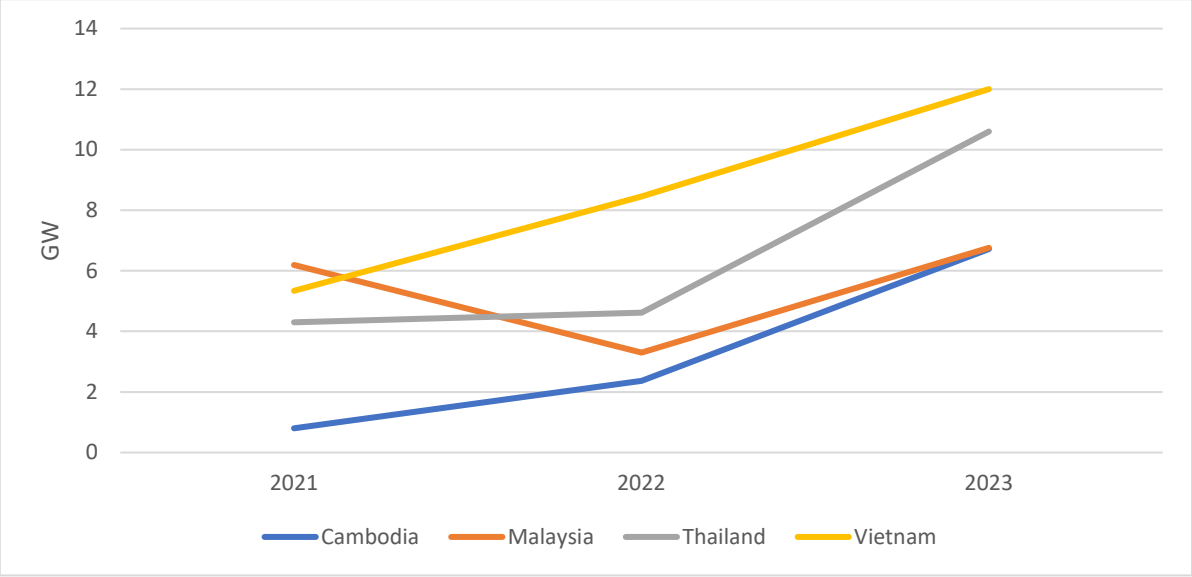
Table 10: Solar capacity of Southeast Asian countries, end-March of 2024

	Production capacity (GW/year)	Chinese-owned capacity (GW/year)	Example of Chinese operations
Solar panel	93.2	50.2	• Vietnam: 8 GW by JinkoSolar, 7 GW by LONGi, 5 GW by Trina Solar • Malaysia: 7 GW by JinkoSolar, 3 GW by LONGi • Thailand: 1.25 GW by Trina Solar
Solar cell	69.6	45.2	• Vietnam: 8 GW by JinkoSolar, 4.5 GW by Trina Solar, 3.35 GW by LONGi • Malaysia: 7 GW by JinkoSolar, 3 GW by LONGi, 1.5 GW by JA Solar • Thailand: 1.3 GW by Trina Solar
Silicon wafer	34.2	27.6	• Vietnam: 7 GW by JinkoSolar, 6.5 GW by Trina Solar • Malaysia: 4.1 GW by LONGi

Source: Solarbe.com

Vietnam, Thailand, Malaysia, and Cambodia, the four countries most benefitting from production shifts from China, combined to export 36.1 GW of solar panels to the US in 2023, accounting for two-thirds of all US solar panel imports (see Figure 19). In the first half of 2024, their combined share in the US imports increased further to 85.0%, reflecting a rush to stockpile solar panels from these countries to avoid potential retroactive AD/CVD by the US.

Figure 19: US solar panel imports from the four Southeast Asian countries, 2021-2023



Source: US Census Bureau

Going into 2025, a major concern is what a second Trump presidency will mean for US trade policy. US President Donald Trump has stated that he plans to impose at least a 10% tariff on all imports to the US and a 60% tariff on all Chinese imports. On 1 February, Trump signed an order to impose tariffs on all imports from Mexico, Canada and China starting on 4 February, but agreed to pause the tariffs on Mexico and Canada hours just before they were set to take effect. Still, the uncertainty surrounding US trade policy continues to cast a shadow over the global solar trade.

2. Domestic development policies

To expand domestic solar manufacturing and build more resilient supply chains, a lot of countries implement policies that prioritize the establishment of local solar manufacturing capabilities through low-cost loans and funding for research and development (R&D) in solar technology. Incentives such as tax credits, grants, or direct subsidies for solar manufacturing projects are also provided.

(a) China

Industrial policies of China have entirely changed the global solar supply chain landscape. In early 2000s, the Chinese government announced to expand the production of solar products and introduced various government incentives for the solar industry.[18] During the 2000s, an estimated US$50 billion (from both private and public funding sources) was invested in solar manufacturing in China, which enabled economies of scale in solar production and contributed to a significant cost decline in solar products. The plunge in solar prices also caused a raft of bankruptcies of US and European solar companies, which further increased the stronghold of China in the industry.

(b) The US

The US has one of the longest-lived and most-well-funded R&D programmes for solar energy in the world through its Solar Energy Technologies Office of the Department of Energy. Boosted by these government grants and loans, US companies have become major producers of cadmium telluride (CdTe) thin-film technology, holding nearly 80% of global capacity (including their plants in other countries).

Furthermore, the *Infrastructure Investment and Jobs Act* (IIJA), signed into law in November 2021, and the *Inflation Reduction Act* (IRA), in effect since August 2022, have provided historic grants, subsidies, and tax credits for the renewable energy sector. The IIJA allocated US$73 billion for grant programmes and initiatives to support energy infrastructure, including solar farms. Meanwhile, the IRA included over US$1 trillion in tax incentives over

[18] National subsidies for the solar industry have ceased since 2022.

10 years to produce and deploy clean energy technologies. It provides tax credits to solar companies based on their investment amount or product specifications, with credit rates reaching up to 30% of the investment. Solar raw materials, cells, panels, and supporting products are all eligible for tax credits (see Table 11).

Table 11: Tax credits for solar products under the IRA for 2022-2029

Eligible components	Credit amount
Solar-grade polysilicon	US$3 per kg
Solar wafer	US$12 per square metre
Solar cell	4 cents per watt
Polymeric back-sheet	40 cents per square metre
Solar panel	7 cents per watt

Source: IRA of the US

From the third quarter of 2021 to the second quarter of 2023, a whopping US$227 billion of public and private investments were announced in utility-scale solar projects, according to the analysis by Deloitte.[19] This underscores the significant boost to the solar sector provided by the two legislations.

However, the US government's support for solar energy is facing some uncertainty under the Trump administration, as Trump has shown an unfavorable attitude towards renewable energy. On his first day in office, Trump signed executive orders that withdraw the US from the landmark *Paris Agreement*, suspend offshore wind leasing from all areas of the US outer continental shelf, and revoke a Biden executive order aimed at ensuring half of all new vehicles sold in the US would be electric by 2030. He also put a 90-day freeze on the distribution of federal funds allocated through the IIJA and IRA for 90 days, which could impact many solar-related programmes. Nonetheless, Trump has also promised to bring manufacturing jobs back to the US, to which the solar sector could surely contribute. As of the time of writing, during the first month of Trump's presidency, it is still too early to tell how solar development will fare under the new administration.

(c) India

In March 2020, India introduced the Production Linked Incentive (PLI) Scheme to provide performance-linked incentives for selected manufacturing sectors, which was later expanded to cover the manufacturing of high-efficiency solar panels. Through the first two tranches of

[19] Deloitte Research Center for Energy & Industrials (2023, December 4). *2024 Renewable Energy Industry Outlook*. https://www2.deloitte.com/us/en/insights/industry/renewable-energy/renewable-energy-industry-outlook.html

the PLI Scheme, a total of 240 billion Indian rupees (equivalent to US$2.9 billion) have been allocated for 14 companies to build 48.3 GW of panel manufacturing capacity.

India has also reinstated the *Approved List of Models and Manufacturers* (ALMM) mandate from 1 April 2024. Only solar products and manufacturers on the ALMM are eligible for government-backed projects. By creating a non-tariff barrier for imported products, the ALMM mandate gives domestic solar manufacturers a significant advantage over foreign competitors.

(d) Turkey

Under the Renewable Energy Support Mechanism (YEKDEM), Turkey offers a purchase guarantee and feed-in tariffs for solar power systems and other renewable energy that are installed from July 2021 to December 2030. Additional remuneration is provided for the use of domestic components. Turkey also aims to install a minimum of 5 GW of new solar energy capacity annually to achieve its 2053 carbon neutrality target.

Amid these policies and duties on imported solar panels, Turkey has become the largest solar panel producer in Europe. It is also the largest importer of Chinese solar cells, which are mainly used in the assembly of solar panels in the country.

Furthermore, Turkey unveiled the High Technology Incentive Programme in July 2024, including US$2.5 billion earmarked to encourage investment in the domestic production of solar cells.

3. Supply of raw materials and critical components

For any product, the supply of raw materials and critical components plays a significant role in shaping the global supply chain. For the solar PV supply chain, silicon is the essential material. However, as the second most abundant element of the Earth's crust, silicon is not considered a bottleneck material for solar PV products.

However, China excels in all the manufacturing stages of solar panels (from polysilicon, wafers, to cells and panels). It is also the main producer of panel components including glass, EVA, back sheet and junction box. Therefore, non-Chinese producers of solar panels must rely on Chinese supply for wafers, cells and other panel components, which could leave their supply chains vulnerable to risks. This has prompted some countries to develop local production capabilities for solar inputs.

4. Sourcing capacity and costs

Due to the economies of scale and a highly integrated supply chain for solar components, China has become the most cost-competitive producer of all parts of the solar PV supply

chain. A solar panel made in China is 40% cheaper than that produced in India, 50% cheaper than in Europe and 65% cheaper than in the US, according to estimates.[20]

Although other countries have increased government support for their local solar manufacturing, achieving cost competitiveness comparable to China remains a challenge.

5. FTAs & trade preferences

Free trade agreements (FTAs) could lead to the reduction or elimination of tariffs on solar panel components and raw materials among the signatories. This allows companies to source solar inputs from other members within the trade bloc strictly based on cost considerations.

One important FTA for the global solar supply chain is the China ASEAN–Free Trade Area (ACFTA). Established in 2010, ACFTA is a free-trade area among China and the ten member states of the Association of Southeast Asian Nations (ASEAN)[21]. The ACFTA has lowered the overall costs for Southeast Asian solar manufacturers that rely on imported solar inputs from China, thus facilitating the expansion of solar manufacturing in Southeast Asia countries and strengthening the regional solar supply chain in the Asia-Pacific region since mid-2010s.

Meanwhile, the North American Free Trade Agreement (NAFTA), which came into force on 1 January 1994, promoted the nearshoring of solar production to Mexico. The NAFTA established a free trade zone among the US, Canada, and Mexico, which prompted some solar companies to set up factories in Mexico to take advantage of its lower production cost and zero-tariff treatment to the nearby US market. For example, Singapore-based Maxeon Solar Technologies established two panel manufacturing facilities in Mexico in 2011 and 2016 respectively for US-bound solar panels.[22]

6. Technology

Possessing or adopting the most-advanced solar cell technology is a must for any country aspiring to build its own solar supply chain and potential become a leader in the global solar

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[20] Wood Mackenzie (2023, October). *How will China's Expansion Affect Global Solar Module Supply Chains*. https://www.woodmac.com/news/opinion/how-will-chinas-expansion-affect-global-solar-module-supply-chains/

[21] The ten member countries of the ASEAN are Brunei, Cambodia, Indonesia, Laos, Malaysia, Myanmar, the Philippines, Singapore, Thailand, and Vietnam.

[22] In 2018, the Trump administration imposed Section 201 tariffs on all solar cells and modules from almost all countries, and neither Mexico nor Canada was exempt. After the *United States-Mexico-Canada Agreement* (USMCA) came into effect and replaced the NAFTA on 1 July 2020, these tariffs still applied to Mexico and Canada. On 4 February 2022, the Biden administration extended the Section 201 tariffs for an additional four years. On 15 February 2022, a USMCA panel ruled that US tariffs on Canadian solar products were in violation of the USMCA. On 7 July 2022, the US and Canada issued a *Joint Memorandum of Understanding*, under which the US has lifted its tariffs on Canadian solar imports. However, Mexico's negotiation with the US to pursue tariff exemption has stalled.

supply chain – in terms of both solar production and setting mainstream trends in solar technology.

Boosted by years of R&D investment, Chinese enterprises have emerged as global leaders in solar technology. China has filed 126,400 global patent applications for solar cells, ranking first in the world, according to data released by the National Intellectual Property Administration in late 2023.

Amid advancement in solar cell technology, a group of cell technologies has emerged as viable alternatives to the two commonly used technologies today (silicon cells and CdTe cells). Currently, Chinese solar companies are the global leaders in the R&D in these cutting-edge cell technologies. For example:

- On 19 November 2022, Chinese solar giant LONGi announced that its heterojunction (HJT) solar cells[23] have achieved a conversion efficiency at 26.81%, breaking the previous record of 26.7% set by a Japanese company.
- On 3 November 2023, LONGi announced that its crystalline silicon-perovskite tandem solar cells[24] have set a new record of 33.9% conversion efficiency, surpassing the previous record of 33.7% set by a Saudi university.

Chinese companies are also usually the first ones to adopt new solar technologies. While other countries are still expanding their production of PERC cells, China is already rapidly scaling up its production capacity in more advanced technologies such as TOPCon and HJT. According to estimates, China has announced a capacity expansion of over 1,000 GW for these new cell technologies, accounting for 95% of the world's total and 17 times more than the rest of the world combined.[25]

The rapid technology upgrade in China's solar industry is likely to make Chinese solar cells and panels even more competitive than those made overseas.

7. Environmental, social and governance considerations

Environmental, social, and governance (ESG) factors play a critical role in shaping the global solar supply chain landscape.

Awareness about greenhouse gas emissions and climate change has been growing in recent years. Many countries and regions have set ambitious targets for renewable energy

[23] HJT is a hybrid cell technology, combining aspects of conventional crystalline silicon solar cells with thin-film solar cells – an HJT cell is formed by adding thin layers of amorphous silicon to monocrystalline silicon.
[24] Crystalline silicon-perovskite tandem cells combine the high efficiency of perovskite with the long useful lifespan of silicon.
[25] Wood Mackenzie (2023, October). *How will China's Expansion Affect Global Solar Module Supply Chains*. https://www.woodmac.com/news/opinion/how-will-chinas-expansion-affect-global-solar-module-supply-chains/

adoption, with solar energy playing a central role in these plans. The resultant growing demand for solar energy could impact the domestic and global solar supply chain.

Take the EU for example. The EU once imposed anti-dumping duties on imports of solar panels, cells and wafers from China starting in June 2013. However, the EU did not extend the duties in September 2018, as it aimed to increase the supply of renewable energy. Furthermore, as part of its plan to accelerate the green transition and raise energy independence, the EU targets to scale up solar PV installed capacity from 260 GW in 2023 to almost 600 GW by 2030, as set out in its *Solar Energy Strategy* released in 2022. Given EU's limited manufacturing capacity of solar panels, this installed capacity expansion will most likely be based on solar panels imported from China, which supplies around 90% of solar panels used in the EU. As the policy priority of the EU is to facilitate a cost-effective expansion of solar power generation and to meet climate targets, the EU has ruled out trade measures against solar imports, despite repeated calls from European solar producers to impose anti-dumping duties against Chinese solar panels.

On the other hand, strict environmental requirements by European countries could also hurt the competitiveness of Chinese solar panels. For instance, the French government has imposed strict requirements on the carbon footprint[26] of solar panels and assumed that Chinese panel production incur a higher carbon footprint. This puts Chinese panel producers at a disadvantage in the bidding for solar PV projects in France. As a result, Chinese solar panels hold a market share of only 25% in the French market, much lower than the 90% share of Chinese solar panels in the overall EU market.

Furthermore, as the global solar supply chain operates in various countries with different labour laws, solar companies are scrutinized for their labour practices, including working conditions, wages, forced labour and child labour issues in the mining and manufacturing processes. The US government has accused China's Xinjiang autonomous region of 'forced labour'. The so-called *Uyghur Forced Labor Prevention Act* came into force in June 2022, which bans the import of goods that are mined, produced, or manufactured wholly or in part in Xinjiang, which accounts for nearly 40% of global polysilicon production.

Together with the existing duties on Chinese solar wafers and cells, this law makes US solar imports a lot less reliant on China – only solar modules made with non-Chinese wafers and cells and produced with non-Xinjiang polysilicon, can enter the US market without incurring substantial tariffs.

In April 2024, the EU also adopted a ban on products made with forced labour, and member states will have to implement the law within three years. The law is generally seen as a move

[26] Carbon footprint refers to the amount of carbon dioxide emissions associated with the activities of a person or an entity, or products throughout their entire lifecycles.

against China, which may impact the supply of solar inputs made in Xinjiang to the EU market.

All of these underscore the importance of ESG adherence for solar companies, which must now pay more attention to ESG concerns and integrate ESG practices into their operations.

V. Forecasts for the Global Solar Supply Chain Landscape

Considering the dynamics in geopolitics, government policies, technology, and market forces, we predict that global solar supply chain landscape will witness the following trends in the coming years:

1. China's will continue its leadership in solar PV supply chain

Thanks to its low production costs, advanced technology, and vertically integrated supply chain, China has cemented its position as the global leader in solar production over the past 15 years or so. We believe that these strengths will not weaken anytime soon, enabling China to maintain its leadership in the global solar supply chain.

In fact, China continues to ramp up the production capacity across all manufacturing stages of solar panels. According to industry sources, China added at least 31.65 GW of panel capacity, 33.6 GW of cell capacity, 44 GW of wafer capacity, and 300,000 metric tons of polysilicon capacity in the first half of 2024.[27] The rapid expansion in production capacity will reinforce China's stronghold in the global solar supply chain.

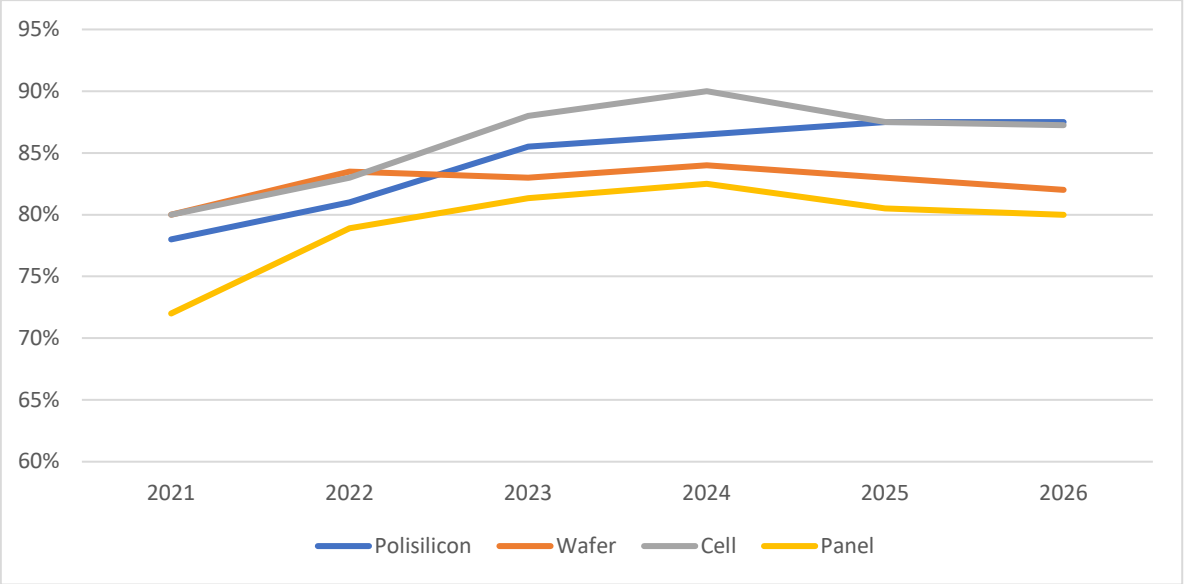
Even if some countries, including the US and India, do have considerable expansion plans in solar panel manufacturing, these countries will struggle to reduce their reliance on essential solar components from China over the next few years, given that China controls 98% of wafer productions and 90% of cell production globally. Therefore, the core of the solar PV supply chain – from the refining of polysilicon to the manufacturing of solar cells – will continue to take place in China.

According to estimates, China's share in global solar PV capacity would actually rise in 2024, and China will still hold more than 80% of the global manufacturing capacity of polysilicon, wafers, cells, and panels until at least 2026 (see Figure 20).[28]

[27] Da jiang su! 2024 Shangbannian guangfu kuochan 477GW [Big slowdown! PV capacity expands by 477GW in the first half of 2024]. https://guangfu.bjx.com.cn/news/20240708/1387428.shtml

[28] Wood Mackenzie (2023, October). *How will China's Expansion Affect Global Solar Module Supply Chains*. https://www.woodmac.com/news/opinion/how-will-chinas-expansion-affect-global-solar-module-supply-chains/

Figure 20: China's share in global production capacity in solar PV supply chain, 2021-2026



Source: Wood Mackenzie

2. Chinese solar investment will be made across continents

China's stronghold in the solar PV supply chain is also reflected in the outward investment made by Chinese solar companies on a global scale. As trade barriers continue to mount, it is anticipated that Chinese solar enterprises will accelerate their expansion of overseas capacities, and their investment destinations will also diversify from the four major solar production countries in Southeast Asia to other emerging markets and even the US.

Since 2014, Chinese solar makers have been establishing production bases in Southeast Asian countries to circumvent the US duties imposed on Chinese solar cells and modules. However, in August 2023, the US Department of Commerce determined that Chinese solar cell producers were working in Cambodia, Malaysia, Thailand and Vietnam to circumvent these duties. On 1 October 2024, it announced preliminary anti-subsidy countervailing duties on solar cells imported from these countries, but a final order will only be made in April 2025. Certain Chinese solar subsidiaries in these countries receive a duty rate of as high as 292.61% (see Table 12). On 29 November 2024, the US Department of Commerce also announced preliminary anti-dumping rates on solar cells from these countries (see Table 13), but a final order will only be made in June 2025.

Table 12: US preliminary anti-subsidy countervailing duty rates on Southeast Asian solar cells

Country	General dumping rate	Dumping rate for individual companies
Cambodia	8.25%	8.25%-68.45%
Malaysia	9.13%	3.47%-123.94%
Thailand	23.06%	0.14%-34.52%
Vietnam	2.85%	0.81%-292.61%

Source: The US Department of Commerce

Table 13: US preliminary anti-dumping rates on Southeast Asian solar cells

Country	General duty rate	Duty rate for individual companies
Cambodia	125.37%	125.37%
Malaysia	21.31%	0%-81.24%
Thailand	77.85%	77.85%-154.68%
Vietnam	271.28%	53.30%-56.51%

Source: The US Department of Commerce

Amid these investigations and duties by the US, Chinese solar companies are exploring new production bases outside these four Southeast Asian countries for US-oriented production. It is noteworthy that Southeast Asia remains the top choice for production shifts due to its relatively low costs and proximity to China. For example, Trina Solar started the construction of a solar cell and panel manufacturing plant with an annual production capacity of 1 GW in Indonesia in 2023, which began operations in November 2024. SolarSpace launched the first phase of a cell factory with an annual production capacity of 5 GW in Laos in September 2023, and it is also building other manufacturing facilities for solar cells (4 GW/year) and panels (3 GW/year) in the country.

The Middle East, with its abundant sunlight and rapidly growing domestic solar market, has also emerged as a popular destination for Chinese solar investments. Trina Solar announced in October 2023 its plans to invest in an integrated solar manufacturing facility in the United Arab Emirates (UAE) with annual production capacity of 50,000 tons of high-purity silicon, 30 GW of silicon wafers, and 5 GW of solar cells and panels. In July 2024, JinkoSolar announced that it will establish a joint venture in Saudi Arabia to build a solar PV manufacturing facility. With an annual production capacity of 10 GW for each of high-efficiency solar cells and

panels, the project will be the largest overseas cell and panel factory established by a Chinese solar company.

Other emerging markets such as Bangladesh, Latin America, and Africa have also been mentioned as potential destinations for Chinese solar investments. For instance, SJEF Solar has announced its plan to build a solar cell factory in the state of Puebla of Mexico. Meanwhile, in partnership with UAE-based Global South Utilities, JA Solar has signed a memorandum of understanding to establish two solar factories in Egypt – one for the production of solar cells and the other for the assembly of solar panels.

Notably, leading Chinese solar makers are also building solar panel manufacturing capacity in the US to circumvent its imports duties, and to take advantage of its high-margin domestic market[29] and the financial incentives offered by the US government (see Table 14). By the end of 2025, Chinese-based solar companies are expected to own around 30% of the panel manufacturing capacity of the US.

Table 14: Solar panel manufacturing facilities in the US established by Chinese companies

Company	Annual capacity	Location	Status
Hounen Solar	1 GW	Orangeburg, South Carolina	Operational since Oct 2023
LONGi[30]	5 GW	Pataskala, Ohio	Operational since Feb 2024
JinkoSolar[31]	2 GW	Jacksonville, Florida	Operational since 2Q24
Runergy	2 GW	Huntsville, Alabama	Operational since Oct 2024
Trina Solar[32]	5 GW	Wilmer, Texas	Operational since Nov 2024
JA Solar	2 GW	Phoenix, Arizona	To be completed by end-2024
Boviet Solar	2 GW	Greenville, North Carolina	To be operational in 1Q25
TCL Zhonghuan[33]	2 GW	Albuquerque, New Mexico	To be operational in early 2026

Source: Compiled from company announcements and public information

[29] The US market provides higher gross margins for solar panel makers than other markets do. Take Trina Solar for example. Its gross margin in the US market was 34.24% in 2023, which is significantly higher than that in China (12.17%), Europe (16.47%), and Japan (20.48%).

[30] The project is conducted through a newly formed company called Illuminate USA, a joint venture with Invenergy, a US renewable developer.

[31] Established in November 2017, the JinkoSolar factory in Florida had an annual capacity of 0.4 GW. In 2023, JinkoSolar invested US$52 million to expand its annual capacity to 2 GW.

[32] On 6 November 2024, Trina Solar announced that it has entered into an agreement with Freyr Battery, a US clean energy solutions provider, to sell its solar module manufacturing facility in Texas for US$340 million. The transaction is expected to close around the end of 2024.

[33] The project is done through TCL Zhonghuan's newly acquired subsidiary Maxeon, which is headquartered in Singapore.

3. Onshoring/reshoring to the US will accelerate on the back of government policies

Although the intersection of energy, industrial and trade policies under a Trump administration creates uncertainty for the solar sector, the trend of localization of solar manufacturing in the US is expected to continue.

By imposing high tariffs on solar imports and offering substantial tax credits through the IRA, the US is aiming to enhance the competitiveness of manufacturing solar panels domestically and attract companies to establish solar manufacturing facilities in the country. According to industry practitioners, the tax credits provided by the US government can offset the cost differences between Southeast Asia and the US, giving solar makers significant incentives to produce in the US.[34]

Since the IRA passed, more than 40 companies – including major Chinese solar manufacturers, which are also eligible for the same tax credits – have announced plans for new factories or capacity expansions in the US (see Tables 14 & 15).[35] For example, First Solar, the largest solar manufacturer in the US, is expanding its manufacturing capacity in the US. In late September 2024, First Solar inaugurated a new fully vertically integrated, thin-film solar manufacturing facility in Alabama, which has 3.5 GW of solar capacity and covers the whole production process from semiconductor to wafer to cell to module. It is also building a 3.5 GW solar facility in Louisiana, slated for operation in the second half of 2025.

Since the IRA passed, more than 370 GW of new production capacity had been announced across the solar PV supply chain in the US as of September 2024, including 163 GW of solar modules, 36 GW of module parts, 80 GW of solar cells, 30 GW of silicon wafers, and 25 GW of polysilicon.[36] Not all these announced expansion plans will come to fruition. However, even if only half of the expansion plans for panel manufacturing materialize, the total panel production capacity (including existing capacity) of the US will still be double the domestic demand in 2027.

[34] Yang Z. (2024, April 23). This Solar Giant is Moving Manufacturing back to the US. *MIT Technology Review*. https://www.technologyreview.com/2024/04/23/1091665/canadian-solar-ira-manufacturing-us/

[35] Sinovoltaics (2024, June 1). *Sinovoltaics Supply Chain Map – North America (Q2 2024)*. https://sinovoltaics.com/sinovoltaics-us-solar-market-supply-chain-map-north-america/

[36] National Renewable Energy Laboratory *(2024, October 20). Fall 2024: Solar Industry Update*. https://www.nrel.gov/docs/fy25osti/92257.pdf

Table 15: Major planned new solar capacity / capacity expansions in the US by non-Chinese companies

Company	Company HQ	Solar panel (GW/year)	Solar cell (GW/year)	Silicon wafer (GW/year)	Polysilicon (metric ton/year)
First Solar	US	7.9			
Warree	India	6	3		
SEG Solar	US	5.5	2		
Canadian Solar	Canada	5	5		
Qcells	South Korea	3.3	3.3		
Enel/3Sun	Italy	3	3		
Convalt	US	2.3	10		
Vikram Solar	India		4	4	
NorSun	Norway			5	
Wacker	Germany				80,000
Hemlock	US				35,000

Source: Sinovoltaics Supply Chain Map – North America (Q2 2024)

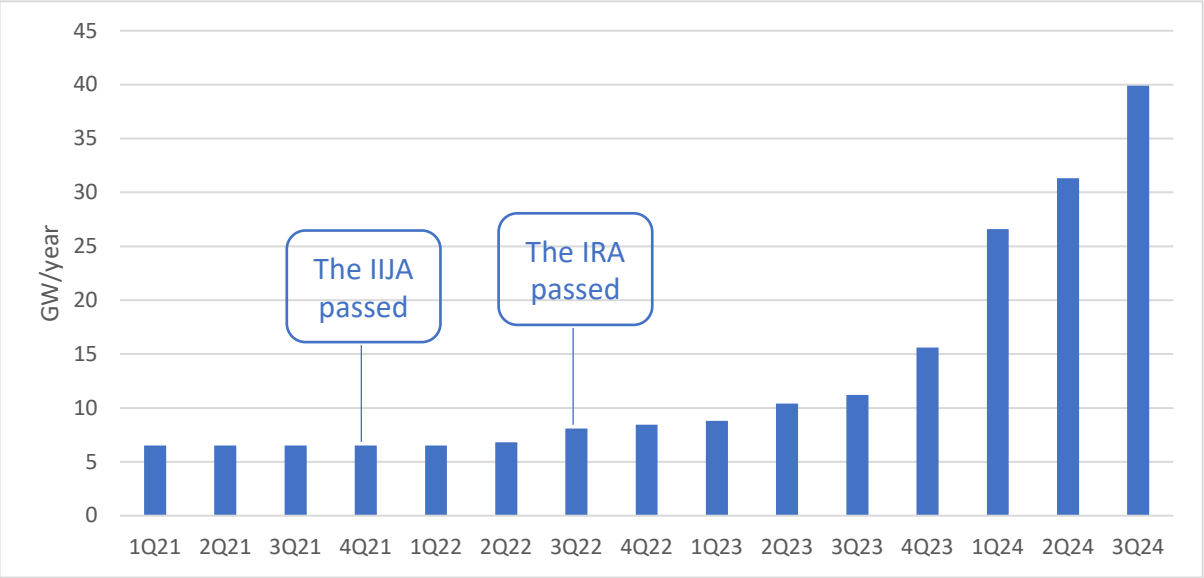
In fact, the solar panel manufacturing capacity of the US already reached almost 40 GW per year as of September 2024 (see Figure 21).[37] If all these production facilities become fully utilized, the US will be able to achieve self-sufficiency in terms of solar panel deployment, as it installs just 40 GW of solar PV capacity annually.

In addition, the US has started to produce solar cells recently, as US solar company Suniva opened a cell manufacturing facility in the third quarter of 2024, marking the return of solar cell production to the US for the first time since 2019. The US will also begin to produce silicon wafers in 2025, after an integrated solar manufacturing facility built by South Korean Hanwha Qcells located in Cartersville, Geogia becomes fully operational.[38] Moreover, the US Department of the Treasury ruled on 22 October 2024 that solar ingot and wafer production facilities and equipment also qualify for the 25% investment tax credit under the *CHIPS and Science Act of 2022*, which is likely to boost investment in domestic ingot and wafer facilities.

[37] Wood Mackenzie and Solar Energy Industries Association (2024, December 4). *US Solar Market Insight Q4 2024*. https://seia.org/research-resources/solar-market-insight-report-q4-2024/

[38] Once the integrated facility is fully operational, Hanwha Qcells will be the only company in North America to produce all the key components across the solar supply chain.

Figure 21: US solar panel production capacity, 1Q21-3Q24



Source: US Solar Market Insight (various issues), Wood Mackenzie and Solar Energy Industries Association

However, we expect that the US will still be highly dependent on imported wafers and cells in the foreseeable future, as there are few announced investment plans for new wafer and cell facilities, and most of these plans are not likely to be realized due to huge investment costs and fierce price competition.[39] US solar panel makers will also continue to rely on imports for panel components such as solar glass and back sheets. As a matter of fact, a significant portion of the planned expansion in US solar manufacturing capacity involves only the assembly of solar panels from solar cells and panel components made in China or Southeast Asia (and many solar factories there are owned by Chinese solar companies). Building a fully integrated solar supply chain within the US will take a very long time, in our view.

4. India will replace Southeast Asian countries as the second-largest panel production country

As the solar cell and panel exports of the four major panel producing countries in Southeast Asia (i.e., Cambodia, Malaysia, Thailand and Vietnam) will soon be subject to AD/CVD when exporting to the US, their solar production and exports will be severely hampered. Industry sources even indicated that, due to concerns about possible retroactive duties by the US,

[39] In February 2024, CubicPV, a wafer manufacturer backed by Bill Gates' Breakthrough Energy Ventures, cancelled plans to build a 10 GW wafer factory in the US, citing a collapse in wafer prices and a rise in construction costs.

many Chinese-owned solar manufacturing facilities in Vietnam have suspended production since May 2024 when the US first announced the initiation of AD/CVD investigations.

Meanwhile, India has implemented a two-pronged strategy – supportive industrial policies and duties on imported solar cells and panels – to promote the domestic solar industry. This has fueled the expansion of the country's solar manufacturing capacity. In the first half of 2024 alone, India's annual panel production capacity increased by 11.3 GW to 77.2 GW; annual solar capacity also added 2 GW to 7.6 GW.

Going forward, India is poised to overtake Southeast Asian countries to become the second-largest panel production region in the world.

VI. Concluding Remarks

The solar supply chain stands as a vital pillar in the renewable energy landscape. As we have explored, the global aspect of this supply chain encompasses a complex network that not only includes the production and distribution of solar panels but also reflects broader trends in geopolitics, domestic policies, market forces, technology, and sustainability.

The leadership of China in solar manufacturing has been a defining feature of the global solar supply chain over the past decade. However, the landscape is shifting. With a rise in global geopolitical tensions, trade protectionism, and government support in other countries, among other changes, the geographical landscape of the solar supply chain is being reshaped. Countries like the US and India are beginning to assert themselves as viable alternatives in solar manufacturing. This diversification is crucial for these countries and even for the world as a whole, as it mitigates the risks associated with over-reliance on a single country and fosters a more resilient global solar supply chain.

All in all, the global solar supply chain is at a transformative juncture. As we move towards a more sustainable energy future, understanding the complex dynamics at play and both challenges and opportunities that lie ahead will be essential for all stakeholders in the solar industry.

Our Global Supply Chain Analysis by Industry

Electric Vehicle

Charged Up: The Rise of Electric Vehicles and the Race for Critical Minerals and Components

View

Solar PV

Chasing the Sun: Will the Global Solar Supply Chain Find New Horizons?

View

Apparel

Beyond Borders: The Global Landscape of Apparel Supply Chains and China's Evolving Role

View

Medical Device

Embracing Multipolarity: Post-COVID Evolution of Global Medical Device Supply Chain

View

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