自然エネルギー財団
RENEWABLE ENERGY INSTITUTE

Progress in Diversifying the Global Solar PV Supply Chain

December 2024

Author

Romain Zissler, Senior Researcher, Renewable Energy Institute.

Editor

Masaya Ishida, Director, Renewable Energy Institute.

Suggested Citation: Renewable Energy Institute, Progress in Diversifying the Global Solar PV Supply Chain (Tokyo, 2024), 41 pp.

www.renewable-ei.org/en/

Renewable Energy Institute

Renewable Energy Institute is a non-profit organization which aims to build a sustainable, rich society based on renewable energy. It was established in August 2011, in the aftermath of the Fukushima Daiichi Nuclear Power Plant accident, by its founder Mr. Masayoshi Son, Chairman & CEO of SoftBank Corp., with his own private resources. The Institute is engaged in activities such as: Research-based analyses on renewable energy, policy recommendations, building a platform for discussions among stakeholders, and facilitating knowledge exchange and joint action with international and domestic partners.

Table of Contents

List of Charts

List of Tables

Introduction

Solar photovoltaic (PV) has become the leading electricity generating technology. On a global scale, both in 2022 and 2023, the annual growth in electricity generation from solar PV outpaced the growth of any other technology.[1] By 2030-2035, the International Energy Agency projects that solar PV will be the world's largest source of electricity generation.[2]

The success of solar PV is first and foremost based on its excellent cost competitiveness. With an average power generation cost of only $0.04/kWh across the world in the second half of 2023, solar PV was only rivalled by onshore wind.[3]

Moreover, as a decarbonized technology, solar PV delivers environmental benefits against global warming. And as it does not require any imported fuel to generate electricity, solar PV strengthens energy security.

Therefore, it is not exaggerated to affirm that solar PV is the trump card of the energy transition. As such, the robustness of the solar PV supply chain is of critical importance, and China's current domination over it is problematic.

Based on up-to-date data and information, this report explores the progress in diversifying the global solar PV supply chain through four sections.

Section 1 provides an overview of the global solar PV supply chain. It presents crystalline silicon modules as the undisputed solar PV technology, points out silicon, silver, aluminum, and copper as the four most valuable minerals for crystalline silicon modules, and stresses the concentration of solar PV manufacturing capacity in China and by Chinese manufacturers.

Section 2 analyses the key factors and issues behind China's domination. It highlights economies of scale and vertical integration as reasons for competitiveness, shows that geographic concentration within China comes with pros and cons, raises criticisms against the Chinese solar PV industry, and explains the consequences of solar PV oversupply.

Section 3 covers the different counteractions led in the United States, Europe, and Asia. The United States advances complementary subsidies and protectionist measures. Europe, despite being aware of the risk of excessively depending on China, prioritizes demand over domestic supply. Japan puts the emphasis on a new promising technology, perovskite cells. And Southeast Asia and India are recognized as underrated actors of diversification.

Section 4 identifies recycling and perovskite cells as potential alternative solutions to Chinese crystalline silicon modules. It notes that improvements are taking place for recycling to become less technically challenging and more affordable. And it briefly describes the global landscape of perovskite cells nascent manufacturing.

Key Findings

<u>This page summarizes the ten key findings of this report for busy readers</u>:

- As of September 2024, 99% of the world's solar PV modules manufacturing capacity was based on crystalline silicon because this technology is inexpensive, performant, and durable. Approximately three-fourths of the economic value of crystalline silicon modules come from four minerals: silicon, silver, aluminum, and copper, which productions are generally not excessively geographically concentrated.
- Throughout the entire solar PV supply chain (i.e., polysilicon, ingots, wafers, cells, and modules), the shares of China and Chinese manufacturers often largely exceeded 80% and they were sometimes close to 100%. It is undesirable for any supply chain to be so dependent on a single country. This is the reason why diversification efforts are led across the world (e.g., United States, Europe, Japan, Southeast Asia and India).
- The Chinese industry dominates the solar PV supply chain because it has managed to maximize economies of scale and because it is well-organized around vertically integrated companies. Moreover, the Chinese solar PV industry is innovative and effectively supported by its government. Also, it benefits from affordable electricity prices, which is critical as solar PV manufacturing is electricity intensive.
- The Chinese solar PV industry is confronted with harsh criticisms due to human rights violations, unfair trade practices, and environmental pollution due to its reliance on coal power. Furthermore, China's aggressive export strategy is blamed for solar PV products oversupply resulting in rock-bottom prices and economic losses.
- In the United States, a combination of subsidies (i.e., tax credits) and protectionist measures have been implemented. Many new projects have been announced, they now need to be realized.
- Europe tries to balance its own interests between increasing its manufacturing capacity and taking advantage of cheap Chinese imports. So far, priority has been given to demand over domestic supply as reducing electricity prices and greenhouse gas emissions are deemed more urgent issues.
- Japan puts the emphasis on perovskite cells, a promising technology that is not fully ready for commercial deployment yet. This strategy should, however, not be used as an excuse for not more proactively installing crystalline silicon. Affordable and rapid decarbonization does not need to wait for perovskite to become mainstream.
- Despite catching less attention, Southeast Asia and India significantly contribute to the diversification of the solar PV supply chain. In Southeast Asia, labor costs are low, and energy is subsidized. In India domestic-content requirements and customs duties have been implemented.
- In addition to these efforts, solar PV recycling and new technologies, like perovskite, hold the potential to be alternatives to Chinese crystalline silicon modules in the 2030s. To take off, these solutions need more governmental support.
- China will retain some domination over the global solar PV supply chain, but worldwide progress in diversifying manufacturing capacity makes the global solar PV supply chain more robust.

Section 1: Overview of the Global Solar PV Supply Chain

1. Crystalline silicon modules, currently the undisputed leading technology

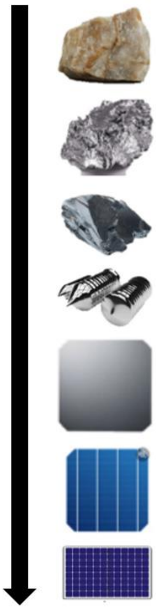
As of September 2024, 99% of the world's solar PV modules manufacturing capacity (i.e., actual production data being unavailable, manufacturing capacity is instead used as the indicator for supply throughout this report) was based on crystalline silicon (the remainder was thin film).[4] Crystalline silicon is the leading technology for solar PV modules because it is inexpensive, performant, and durable.

More precisely: in September 2024, the total cost of Chinese crystalline silicon modules was only $0.11 per watt (/W).[5] At the end of 2023, the conversion efficiency of typical crystalline silicon modules was 22% (up from 16% in 2012).[6] And crystalline silicon modules are designed to last 25 years or more.

Moreover, the availability of silicon is excellent. Silicon is the world's second most abundant element in the Earth's crust: 28%, behind oxygen 46%.[7]

To understand the specificities of the supply chain of crystalline silicon modules, their manufacturing process is illustrated (Chart 1) and supported by detailed step-by-step explanations.

Chart 1: Simplified Manufacturing Process of Crystalline Silicon Modules



Step 1: mineral extraction
input – **silica** in quartzite, quartz pebble, quartz vein
Step 2: carbothermic reduction, removal of silica impurities
output – **silicon metal**
Step 3: further purification processes (e.g., Siemens chlorination)
output – **polysilicon**
Step 4: crystallization (i.e., Czochralski process) or casting
output – **ingots**
Step 5: sawing and slicing
output – **wafers**
Step 6: cleaning, texturing, doping, etching, antireflective coating deposition, contact printing and sintering, testing
output – **cells**
Step 7: backsheet, contacts, encapsulation, glass and frame assembly and sealing, junction box connection, testing
output – **modules**

Source: International Energy Agency, Special Report on Solar PV Global Supply Chains (July 2022).

This manufacturing process starts by extracting silica (i.e., a chemical compound composed of silicon and oxygen) which is found in nature as quartz [Step 1].

Then, silica impurities are removed by carbothermic reduction to obtain silicon metal (i.e., quartz silica is melted in an electric arc furnace at around 1,700 degrees Celsius) [Step 2].

This step is followed by another purification process, most often the Siemens chlorination process, allowing to transform silicon metal into polysilicon [Step 3].

Next, polysilicon is either crystallized into monocrystalline ingots, through the Czochralski process, or cast into multicrystalline ingots (as of September 2024, 97% of the world's ingots manufacturing capacity was based on monocrystalline) [Step 4].[8]

Ingots are then sliced very thinly and cleaned to form wafers [Step 5].

Following steps including texturing, cleaning, doping, etching, and printing silver paste metal connections, wafers are transformed into cells [Step 6].

Cells are then arranged on a backsheet, connected, and laminated with an encapsulating plastic material. Modules are usually completed with the addition of front glass, a junction box, and an aluminum frame [Step 7].

To be connected to the grid and start generating electricity, modules require a mounting structure, cables, and inverters.

2. The four most valuable minerals: silicon, silver, aluminum, and copper

About three-fourths of the economic value of crystalline silicon modules come from four minerals: silicon, silver, aluminum, and copper (the rest mainly comes from glass and polymers).[9]

The main uses of these four minerals in crystalline silicon solar PV systems are summarized in Table 1 below:

Table 1: Uses of Silicon, Silver, Aluminum, and Copper in Crystalline Silicon Solar PV Systems

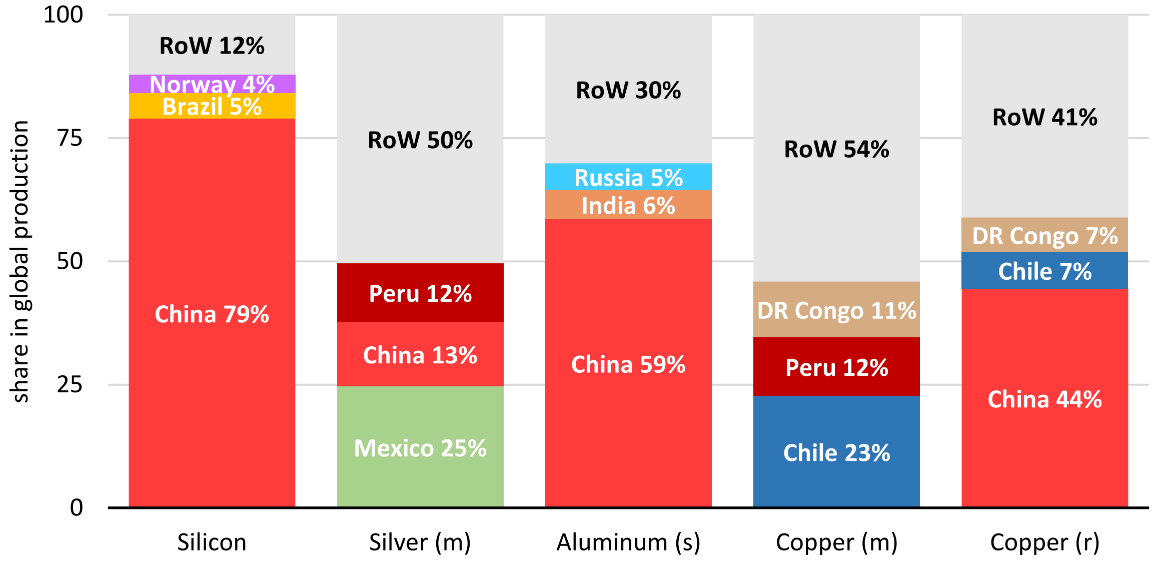
Mineral	Main uses
Silicon	Crystalline silicon wafers (in the form of high-purity quartz)
Silver	Electronic contacts: silver paste, busbars, and soldering
Aluminum	Module frame, mounting structure, connectors, back contact, inverters
Copper	Cables, wires, ribbons, inverters

Source: International Energy Agency, Special Report on Solar PV Global Supply Chains (July 2022).

From an energy security perspective, it is important that the productions of silicon, silver, aluminum, and copper are geographically diversified. Otherwise, it would make the supply chain of crystalline silicon solar PV systems vulnerable.

Among these four minerals, the production of silicon is the one that is the most concentrated geographically (Chart 2). In 2023, China produced 79% of the world's silicon. To a lesser extent, the production of aluminum is also somewhat concentrated, with China occupying the leading position again (59% of the world's production). Neither the production of silver nor that of copper suffers from excessive concentration.

Chart 2: Main Producing Countries of Silicon, Silver, Aluminum, and Copper 2023



Notes: "Silicon" refers to "silicon metal". (m) means "mine", (s) "smelter", and (r) "refinery". "RoW" is an abbreviation standing for "Rest of the World" and "DR Congo" for "Democratic Republic of the Congo".

Source: United States Department of the Interior – United States Geological Survey, Mineral Commodity Summaries 2024 (January 2024).

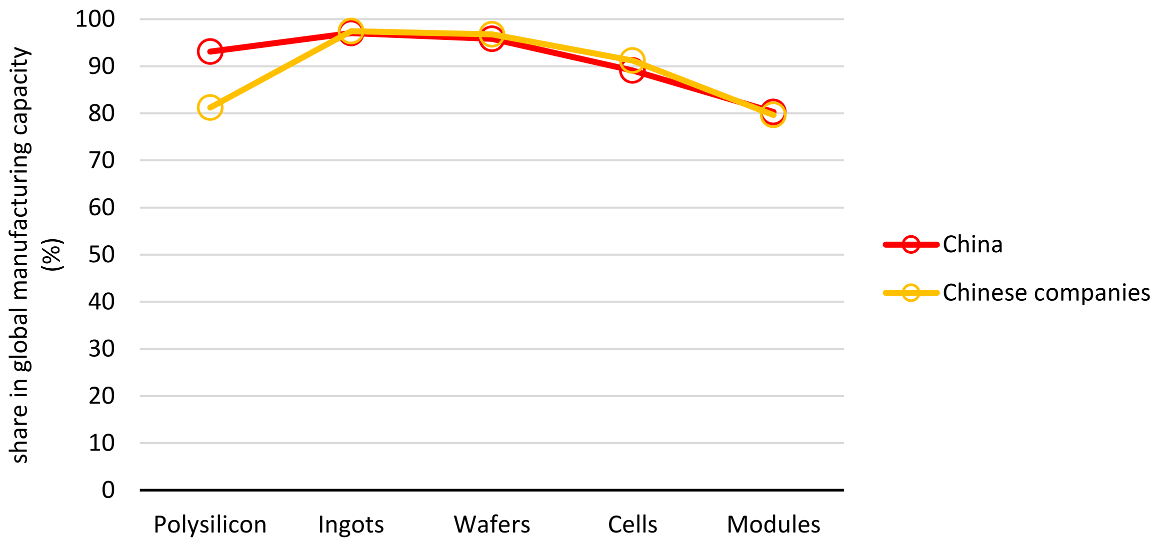
Therefore, in terms of minerals, the supply chain of solar PV systems is overall rather well-balanced.

3. Concentration of manufacturing capacity in China and by Chinese manufacturers

The main energy security issue for the solar PV supply chain is not the concentration of minerals, but of manufacturing capacity in China and in the hands of Chinese manufacturers.

As of September 2024, considering all the five main segments of the global solar PV supply chain: polysilicon, ingots, wafers, cells, and modules, the shares of China and Chinese manufacturers often largely exceeded 80% and they were sometimes close to 100% (i.e., ingots and wafers) (Chart 3).

Chart 3: Shares of China (location) and Chinese Companies in Manufacturing Capacity, as of Sep. 2024

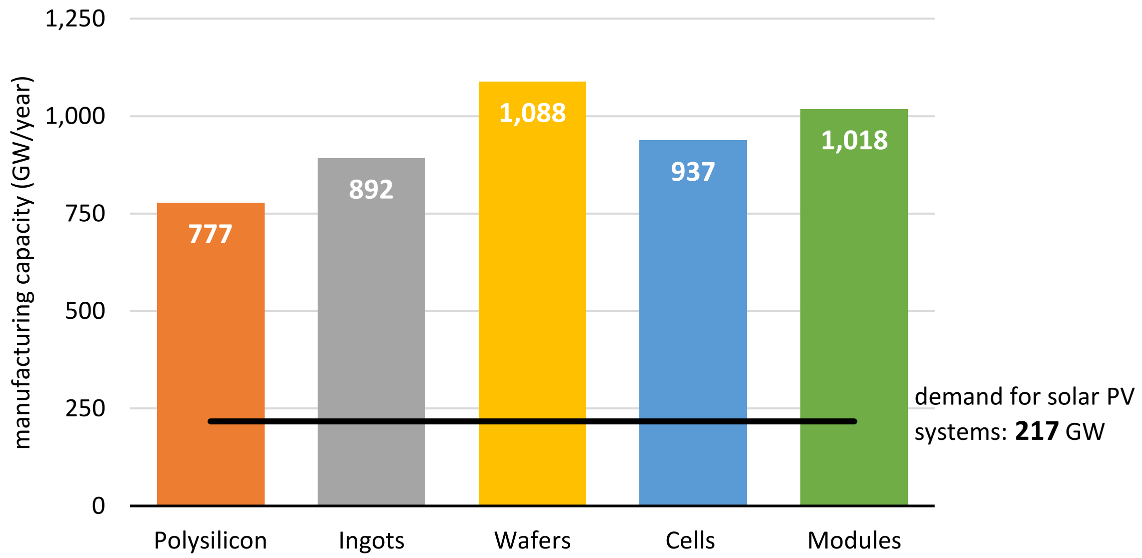


Note: for companies, excluding international co-ownership because the shareholder structure could not be identified.

Source: BloombergNEF, Equipment Manufacturers: PV – updated September 24, 2024 (accessed October 9, 2024) [subscription required].

In China in 2023, solar PV manufacturing capacity surpassed domestic demand by 4-5 times, depending on segments (Chart 4). One of the reasons for this oversupply is that in the early 2000s, the Chinese government selected solar PV as a key industry to enrich its economy and exports.

Chart 4: China – Manufacturing Capacity by Segment and Solar PV System Demand 2023

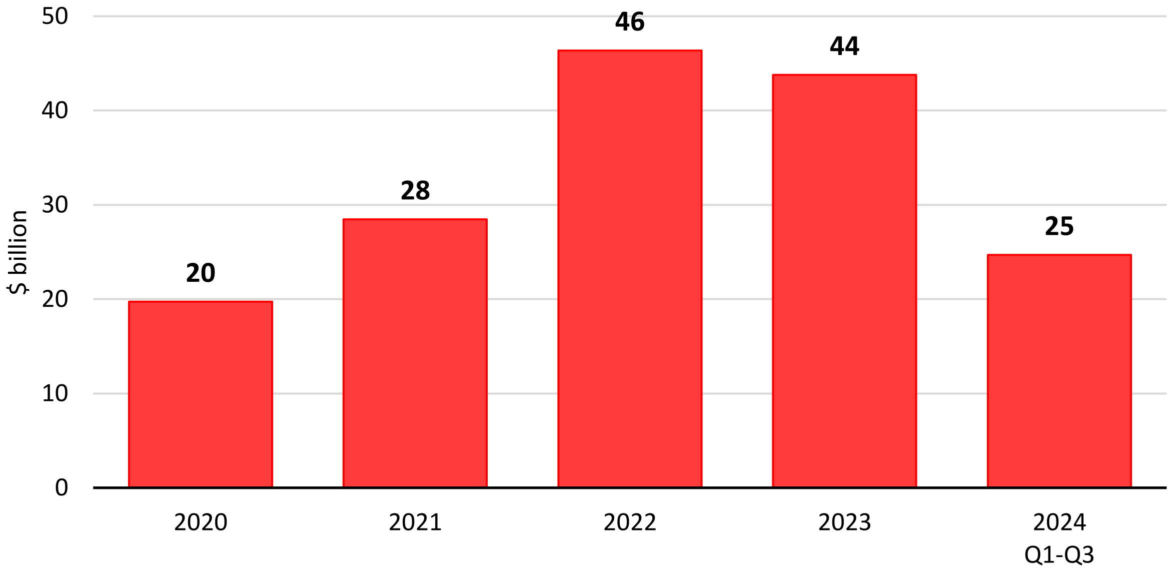


Note: for polysilicon, it is assumed that 3,000 tons is equivalent to 1 GW.

Sources: manufacturing capacity, from BloombergNEF, Equipment Manufacturers: PV – updated September 24, 2024 (accessed October 9, 2024) [subscription required]. And demand for solar PV systems, from International Renewable Energy Agency, Renewable Energy Statistics 2024 (July 2024).

China’s solar PV export strategy is crowned with success. For instance, between January 2020 and September 2024, China’s exports of solar PV cells and modules were worth $163 billion (Chart 5).

Chart 5: China – Export Value of Solar PV Cells and Modules 2020-2024 Q1-Q3



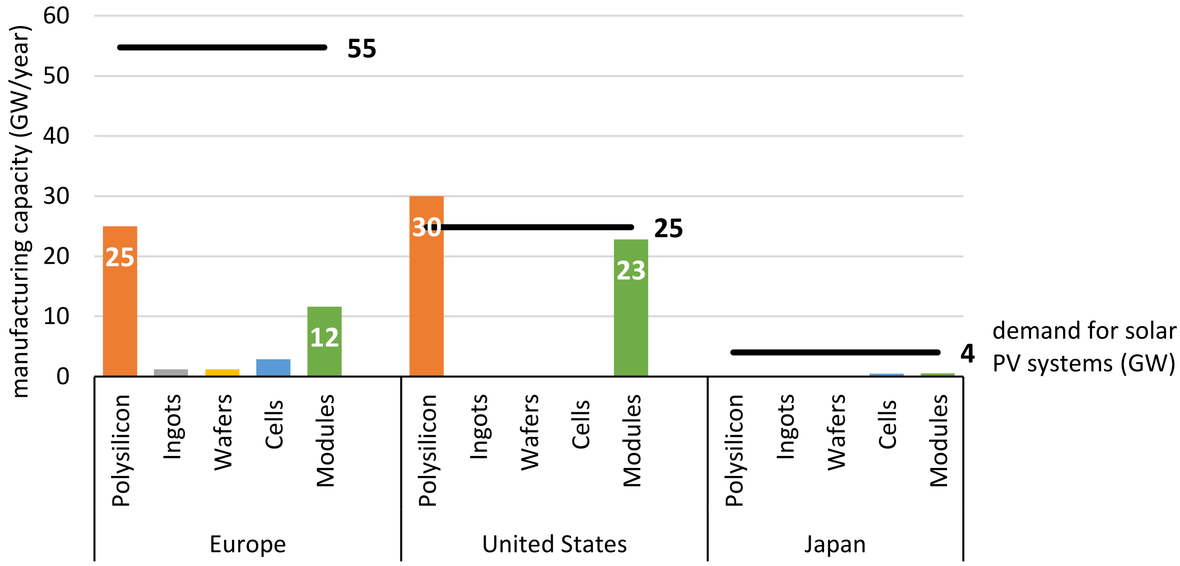
Source: BloombergNEF, Equipment Manufacturers: PV Exports and Imports – updated October 21, 2024 (accessed November 7, 2024) [subscription required].

China’s situation is in stark contrast with that of major developed power systems: Europe, the United States, and Japan.

In 2023, the solar PV manufacturing capacity of these three power systems was largely insufficient to meet their own needs (Chart 6).

Europe had some manufacturing capacity throughout the entire solar PV supply chain, but in no segment, it could meet half of its annual demand (55 gigawatts (GW)). The United States’ manufacturing capacity for polysilicon (30 GW/year) and modules (23 GW/year) were roughly on par with its annual demand (25 GW), but it had no ingots, wafers, and cells manufacturing capacity. And Japan only had few cells and modules manufacturing capacity (i.e., 0.5 GW/year each).

Chart 6: Europe, United States, and Japan – Manufacturing Capacity by Segment and Solar PV System Demand 2023



Notes: for polysilicon, it is assumed that 3,000 tons is equivalent to 1 GW. For readability purposes, manufacturing capacity < 3 GW is not displayed.

Sources: manufacturing capacity, from BloombergNEF, Equipment Manufacturers: PV – updated September 24, 2024 (accessed October 9, 2024) [subscription required]. And demand for solar PV systems, from International Renewable Energy Agency, Renewable Energy Statistics 2024 (July 2024).

Furthermore, except for a polysilicon company (i.e., Wacker Chemie – Germany) and a module maker (i.e., First Solar – United States), European, American, and Japanese manufacturers are minor actors of the global solar PV industry (Table 2). As of September 2024, with a manufacturing capacity of 17 GW, First Solar, was the world leading company for thin film non silicon modules, but this was insufficient to be among the Top10 module manufacturers because of crystalline silicon supremacy.

Table 2: Top10 Companies by Solar PV Manufacturing Segment, as of Sep. 2024

Ranking	Segment				
	Polysilicon	**Ingots**	**Wafers**	**Cells**	**Modules**
1	East Hope (China) – 103 GW	TCL Zhonghuan (China) – 183 GW	TCL Zhonghuan (China) – 180 GW	Trina Solar (China) – 105 GW	JinkoSolar (China) – 120 GW
2	Xinte Energy (China) – 100 GW	LONGi (China) – 148 GW	LONGi (China) – 173 GW	JinkoSolar (China) – 100 GW	LONGi (China) – 118 GW
3	Tongwei (China) – 90 GW	JinkoSolar (China) – 94 GW	JinkoSolar (China) – 99 GW	LONGi (China) – 85 GW	Trina Solar (China) – 112 GW
4	Daqo New Energy (China) – 68 GW	JA Solar (China) – 85 GW	JA Solar (China) – 86 GW	JA Solar (China) – 82 GW	JA Solar (China) – 95 GW
5	GCL Technology (China) – 67 GW	Zhenjiang Huantai Silicon Science & Technology (China) – 56 GW	Gokin Solar (China) – 75 GW	Tongwei (China) – 78 GW	Tongwei (China) – 80 GW
6	Wacker Chemie (Germany) – 32 GW	Trina Solar (China) – 55.5 GW	GCL Technology (China) – 59 GW	Suzhou Runergy PV Technology (China) – 63 GW	Canadian Solar (Canada) – 56 GW
7	Asia Silicon (China) – 30 GW	Gokin Solar (China) – 55 GW	Trina Solar (China) – 57 GW	Solarspace Technology (China) – 58 GW	Chint Solar ZheJiang (China) – 39 GW
8	Wuhan Dongli and Xinjiang Goens Energy Technology (both China) each 20 GW	Yuze Semiconductor (China) – 43 GW	Zhenjiang Huantai Silicon Science & Technology (China) – 48 GW	Canadian Solar (Canada) – 51 GW	Risen Energy (China) – 36 GW
9		Shuangliang Eco-Energy Systems (China) – 40 GW	Shuangliang Eco-Energy Systems (China) – 40 GW	Guangdong Aiko Solar Energy Technology (China) – 46 GW	DAS Solar (China) – 30 GW
10	Hoshine Silicon Industry, Ningxia Baofeng Energy, Qinghai Lihao Semiconductor Material, Suzhou Runergy PV Technology, Trina Solar, and Xinjiang Jingnuo New Energy Development (all China) each 17 GW	Hoyuan Green Energy (China) – 35 GW	Qingdao Gaoce Technology (China) – 38 GW	Shanghai Aiko Solar Energy Technology (China) – 44 GW	GCL System Integration Technology (China) – 29.5 GW

Notes: excluding co-ownership because the shareholder structure could not be identified. For polysilicon, it is assumed that 3,000 tons is equivalent to 1 GW.

Source: BloombergNEF, Equipment Manufacturers: PV – updated September 24, 2024 (accessed October 9, 2024) [subscription required].

Thus, in Europe, Japan, and the United States, there is a clear imbalance between the supply and demand of solar PV products. This imbalance results in a significant dependence towards foreign countries and manufacturers.

Europe’s solar PV cells and modules imports are now almost all coming from China (i.e., 98% on a value basis in the first half of 2024).[10] Japan also heavily relies on China for its solar PV cells and modules imports (i.e., 78% between January and August 2024).[11]

Because of various trade policies to protect the American solar PV industry against products made in China, the United States' imports of cells and modules originate from other countries, mainly Southeast Asian countries (i.e., especially Malaysia, Thailand, and Vietnam, where most manufacturing capacity is owned by Chinese companies), but also South Korea (cells) and India (modules).[12]

From an economic point of view, imports mean an outflow of money. In the case of Europe, imports of Chinese cells and modules reached $71 billion between January 2020 and September 2024.[13] In other words, solar PV imports contribute to worsening Europe's persistent trade deficit with China, which is a source geopolitical concern.

Section 2: Key Factors and Issues behind China's Domination

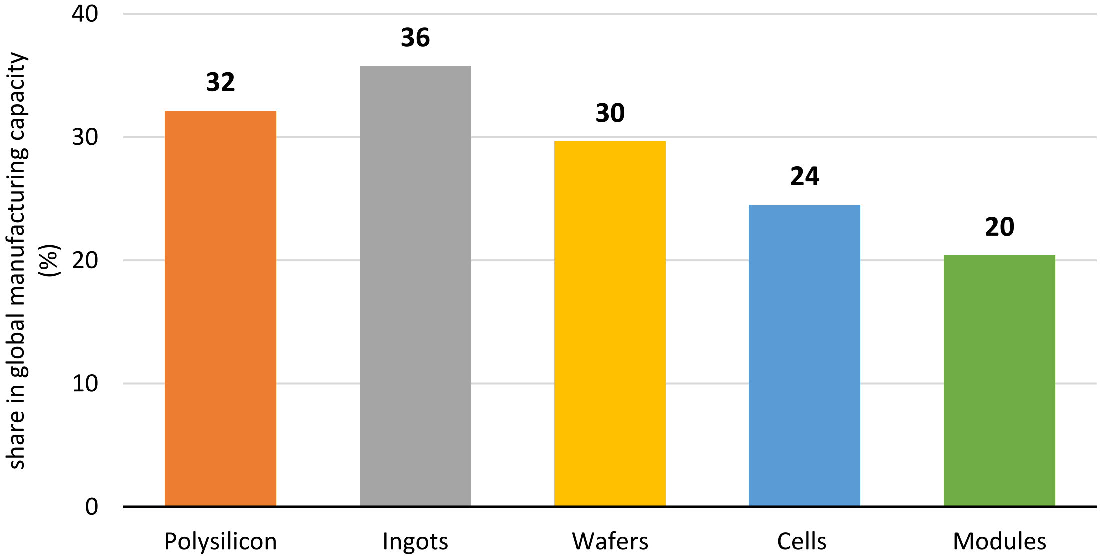
1. Economies of scale and vertical integration give competitive edge

China's competitive edge in solar PV manufacturing over other countries comes from four key factors: economies of scale, supply chain vertical integration, technological innovation, and government support. In this list, economies of scale and supply chain vertical integration are the two most important factors.

Compared to other electricity generating technologies, solar PV is characterized by its simplicity and reproducibility, making it well-suited for mass production. Mass production enables economies of scale. China managed better than any other country to reap these economies of scale.

The recipe to maximize economies of scale is straightforward: the bigger, the better. For each segment, China built all the world's largest factories (i.e., these factories are located in China and are owned by Chinese manufacturers). Some of these facilities are enormous (i.e., with manufacturing capacity of dozens of gigawatts per year) and concentrate substantial shares of the world's solar PV manufacturing capacity (Chart 7). For example, as of September 2024, 36% of the world's ingots manufacturing capacity was concentrated in just five Chinese plants.

Chart 7: Share of Top5 Largest Plants in Global Manufacturing Capacity, as of Sep. 2024

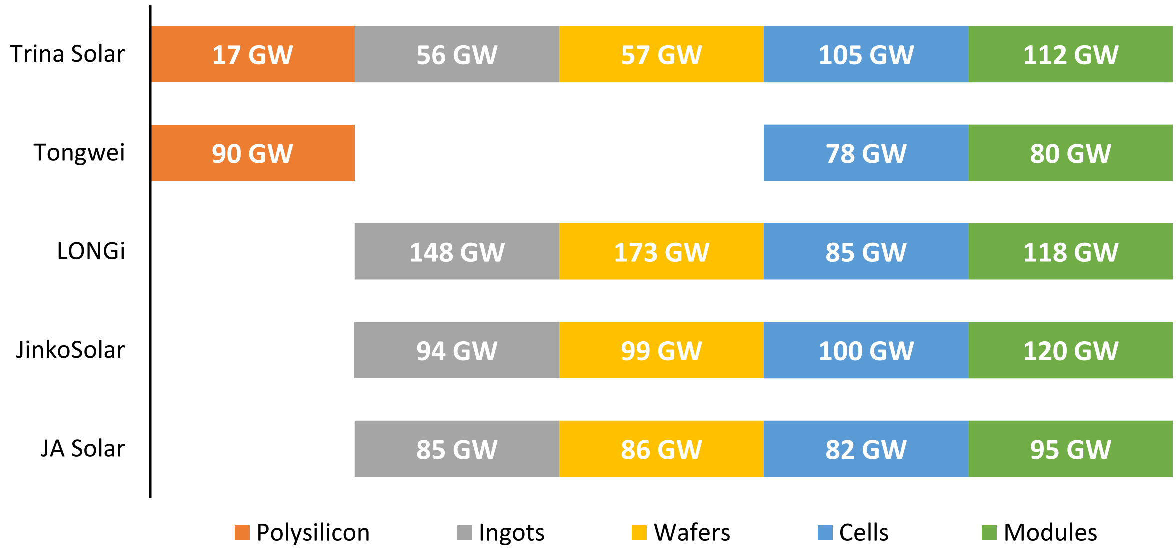


Source: BloombergNEF, Equipment Manufacturers: PV – updated September 24, 2024 (accessed October 9, 2024) [subscription required].

In a very competitive environment such as that of the solar PV industry, vertically integrated companies (i.e., companies active in several segments of the supply chain) have consistently outperformed pure-play companies (i.e., companies active in only one specific segment) financially.[14] On the one hand, integrated manufacturing processes are more cost efficient. On the other hand, vertically integrated companies can compensate for losses in one segment through profits in another.

Examples of fully or partially vertically integrated companies include JA Solar, JinkoSolar, LONGi, Tongwei, and Trina Solar, which are well-known for being the world's five largest manufacturers of cells and modules (Chart 8).

Chart 8: Examples of Chinese Vertically Integrated Companies, as of Sep. 2024



Notes: excluding co-ownership because the shareholder structure could not be identified. For polysilicon, it is assumed that 3,000 tons is equivalent to 1 GW.

Source: BloombergNEF, Equipment Manufacturers: PV – updated September 24, 2024 (accessed October 9, 2024) [subscription required].

In addition to economies of scale and supply chain vertical integration, technological innovation and government support also helped China assert its domination over the solar PV supply chain.

Regarding technological innovation, thanks to research and development (R&D), continuous improvements in solar PV manufacturing could be achieved resulting in higher conversion efficiency (from 16% in 2012 to 22% in 2023) and lower raw material use (e.g., silicon and silver), thereby reducing costs.[15] Likewise, automation of processes by using machines increased productivity and decreased the need for manual labor, offering cost efficiency gains (Chart 9).

Chart 9: Trina Solar – Module Assembly Line

Source: PV Tech, [Trina Solar supplies 488MW n-type TOPCon modules to power station in China](#) – September 8, 2023 (accessed October 15, 2024).

As for government support, a mix of incentives targeting both supply and demand has been implemented in favor of solar PV manufacturing in China.[16] On the supply side, grants and low-cost loans from state banks have been made available from the mid-2000s. On the demand side, feed-in tariffs and auctions for solar PV have been introduced in 2011 and 2019, respectively. The goal of demand side measures was to create sustainable demand accompanying the growth of the country's manufacturing capacity.

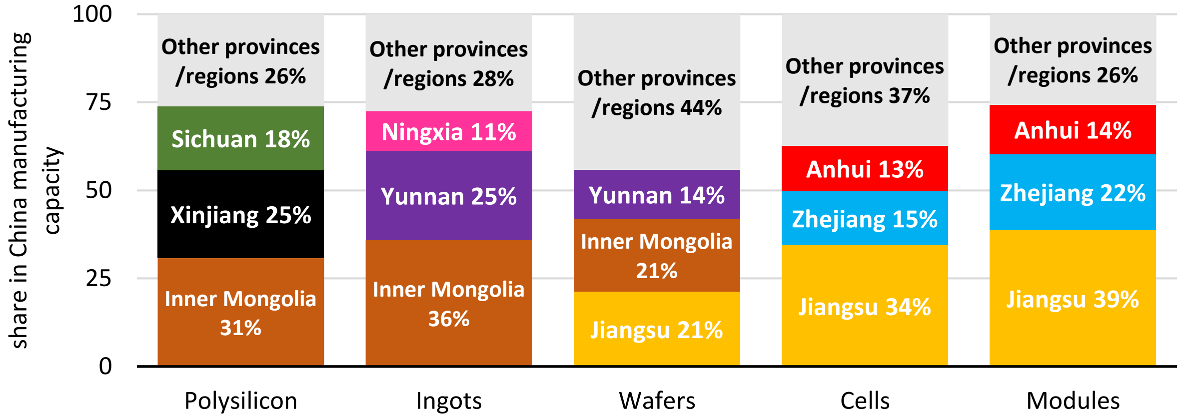
Finally, it may also be noted that the Chinese solar PV industry benefits from affordable electricity prices. In 2023, electricity prices for large industrial customers in energy-intensive industries were around $0.07 per kilowatt-hour (/kWh) in China. This was slightly higher than in the United States ($0.06/kWh), but much lower than in the European Union ($0.11/kWh).[17] Affordable electricity prices are critical because solar PV manufacturing is electricity-intensive, in particular polysilicon manufacturing due to high temperature requirements.[18]

2. Geographic concentration within China comes with advantages and drawbacks

In China, solar PV manufacturing capacity is concentrated in a few provinces and autonomous regions (i.e., regions granted a degree of self-governance from an external authority). Geographic concentration of large manufacturing plants presents advantages in terms of cost minimization.

Into more details, upstream, polysilicon and ingots manufacturing capacity are mostly located in the center (from north to south: Inner Mongolia, Ningxia, Sichuan, and Yunnan) and the northwest of the country (Xinjiang) where electricity prices are low thanks to cheap electricity generated from coal and hydro. Downstream, cells and modules manufacturing capacity are mostly located in three eastern provinces (from north to south: Jiangsu, Anhui, and Zhejiang) near or along the East China Sea, where products can be exported by maritime shipping on container vessels (Charts 10 & 11).

Chart 10: China – Concentration of Solar PV Manufacturing Capacity by Area, as of Sep. 2024



Source: BloombergNEF, Equipment Manufacturers: PV – updated September 24, 2024 (accessed October 9, 2024) [subscription required].

Chart 11: China – Map Highlighting Main Provinces and Regions for Solar PV Manufacturing

Source: created by Renewable Energy Institute based on BloombergNEF, Equipment Manufacturers: PV – updated September 24, 2024 (accessed October 9, 2024) [subscription required].

On the downside, geographic concentration exposes the supply chain to some drawbacks. The potential disruption risks associated with this type of concentration include natural hazards such as earthquakes and fires, and extreme weather events such as drought and flooding.[19]

For instance, in 2020 and 2022, the global production of polysilicon was reduced because of flooding and fire issues at a handful of Chinese plants.[20]

The incidents that occurred in 2020 led to an estimated 4% decline in annual polysilicon production, contributing to the near tripling of polysilicon prices between 2020 and 2021.[21] Because of higher polysilicon prices, and disruptions due to the COVID-19 pandemic (e.g., congested shipping ports increasing freight prices), the prices of modules rose for the first time in 2021 (around +20% compared to 2020), even if more modules manufacturing capacity became operational. Thanks to polysilicon manufacturing capacity expansion and lower freight prices, modules prices resumed their downward trajectory from 2022.[22]

3. Criticisms against the Chinese solar PV industry

Despite its accomplishments the Chinese solar PV industry faces harsh criticisms because of human rights violations, unfair trade practices, and environmental pollution.

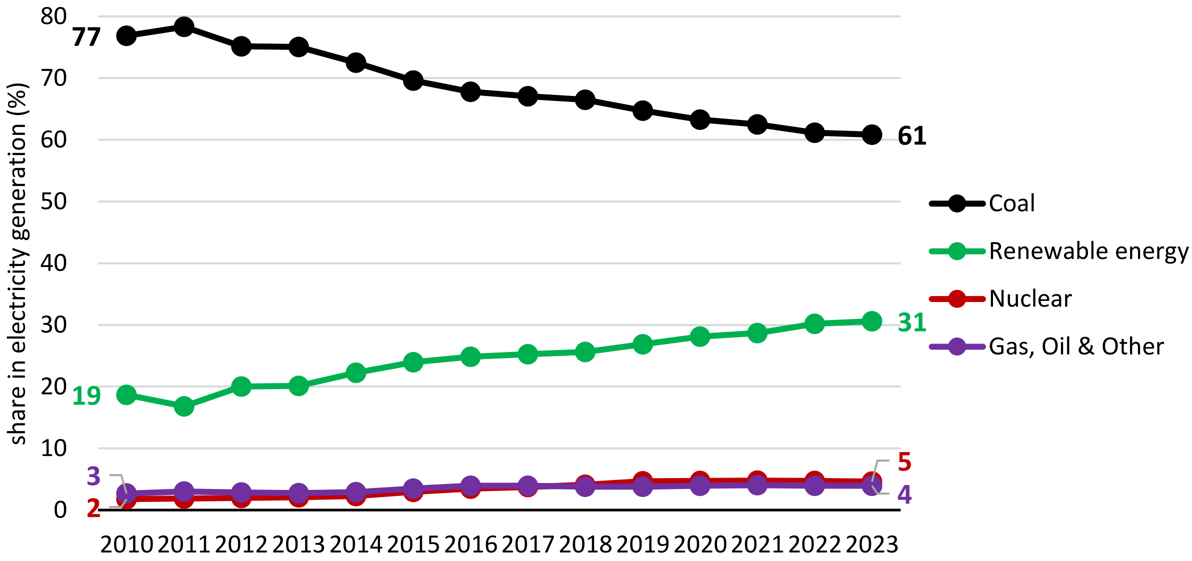
First, in May 2021, the Sheffield Hallam University, United Kingdom revealed that millions of indigenous Uyghur and Kazakh citizens from the Xinjiang autonomous region were placed into state-imposed forced labor programs (i.e., to work in farms and factories).[23] Investigations concluded that forced labor was used in polysilicon manufacturing. Violating human rights is obviously always condemnable, and it logically caused public outrage.

In an update published in November 2023, the Sheffield Hallam University negatively stated that: "At the same time as scrutiny of solar supply chains has increased, transparency has decreased in the solar industry […]."[24] And it added that: "The lack of transparency has made it increasingly difficult to verify whether supply chains are free from risk of Uyghur forced labor and reduces trust in the solar industry."[25] This is unsatisfying.

Second, from 2012 onward, the United States started applying antidumping and countervailing duties (AD/CVDs) (i.e., duties imposed to offset subsidies or dumping on imported goods) to solar cells originating in China because it found that Chinese manufacturers sold subsidized cells at dumping margins in the United States.[26] Additional American sanctions for unfair trade practices followed since then (see page 20). To avoid these sanctions Chinese companies established manufacturing plants in Southeast Asia, where sometimes only minor processing is completed (i.e., unsubstantial transformation of products leaving their identity intact).[27] This trick is controversial, to say the least.

Third, solar PV manufacturing is electricity-intensive, and 61% of China's electricity was still generated from dirty coal power in 2023. On a more positive note, however, this share decreased by 16 percentage points since 2010, primarily thanks to the expansion of renewable energy (mainly on- & off-shore wind, solar PV, and hydro) (Chart 12).

Chart 12: China – Electricity Generation Mix 2010-2023



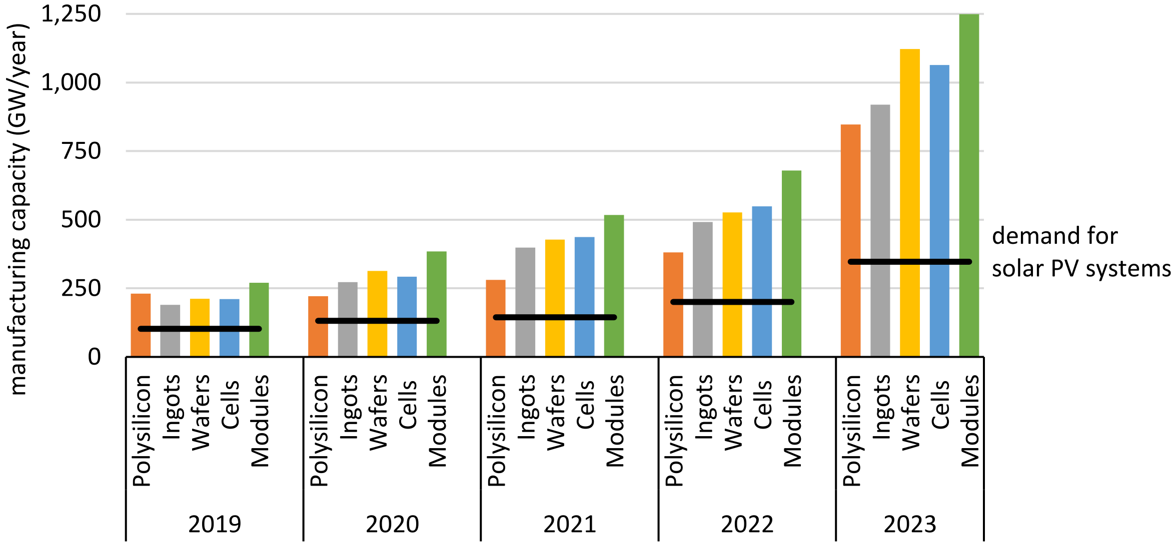
Notes: "Renewable energy" includes hydro, wind, solar, biomass, and geothermal. "Other" includes non-renewable waste, pumped storage hydro, and unspecified.

Source: Energy Institute, Statistical Review of World Energy 2024 (June 2024).

4. Solar PV oversupply means fierce competition, rock-bottom prices, and losses

Without minimizing the previous criticisms against the Chinese solar PV industry, another major issue is China's aggressive export strategy, which is to blame for global oversupply. As a result of continued oversized growth in China in the past few years, the world's solar PV manufacturing capacity exceeded demand by 2-4 times, depending on segments, in 2023 (Chart 13).

Chart 13: World – Manufacturing Capacity by Segment and Solar PV System Demand 2019-2023



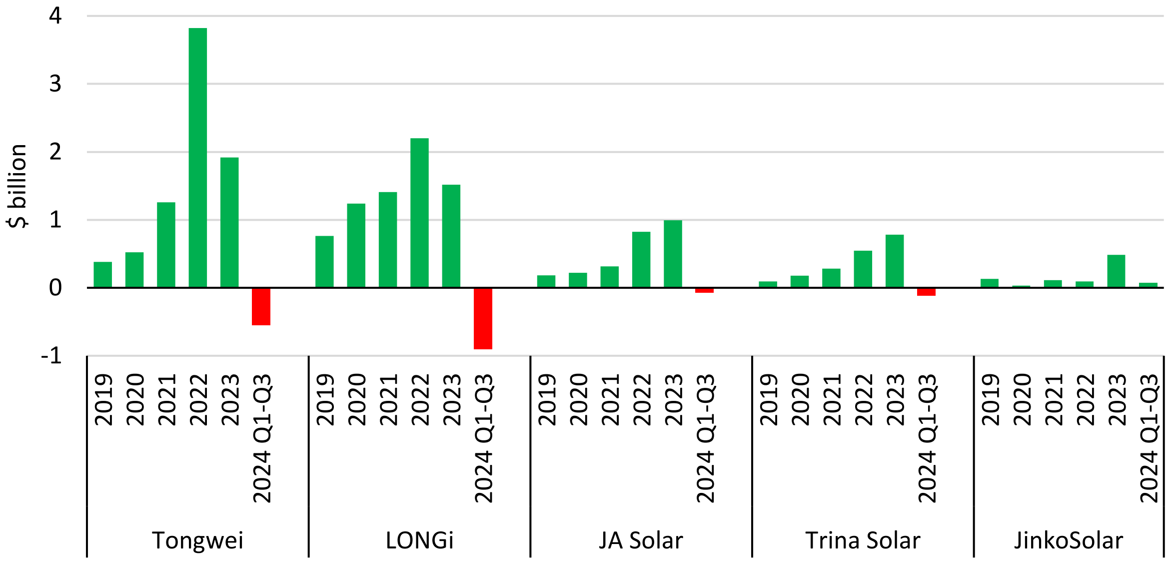
Note: for polysilicon, it is assumed that 3,000 tons is equivalent to 1 GW.

Sources: manufacturing capacity, from BloombergNEF, Equipment Manufacturers: PV – updated September 24, 2024 (accessed October 9, 2024) [subscription required]. And demand for solar PV systems, from International Renewable Energy Agency, Renewable Energy Statistics 2024 (July 2024).

Oversupply makes competition among manufacturers fierce. In the solar PV industry today, price, not differentiation (i.e., the unique qualities of a product), is the decisive factor to outcompete rivals. To maintain their market shares, manufacturers sell at prices below production costs (e.g., in September 2024, Chinese crystalline silicon modules were sold at prices around $0.10/W while their costs were $0.11/W).[28]

Rock-bottom prices of solar PV products accelerate global decarbonization by making it economically very attractive to invest in the installation of solar PV. Nevertheless, given that many solar PV manufacturers, including almost all the top ones, are now confronted with losses, the current situation cannot indefinitely continue (Chart 14).

Chart 14: Top Solar PV Manufacturers Net Income 2019-2024 Q1-Q3



Source: The Wall Street Journal, Markets: Tongwei, LONGi, JA Solar, Trina Solar, and JinkoSolar (all accessed November 26, 2024).

In this context, existing manufacturers may be forced into bankruptcy or restructuring, and it becomes difficult for new entrants to join the market despite worthwhile counteractions in the United States, Europe, and Asia.

Section 3: Counteractions in the United States, Europe, and Asia

1. United States: complementarity of subsidies and protectionism

In August 2022, President Joseph Biden (Democratic) signed the Inflation Reduction Act (IRA) into law, marking the most significant action the American Congress has taken on clean energy and climate change in the history of the country.[29] [For more information, read *Renewable Energy Institute, United States Carbon Free Power Sector by 2035: Economics and Technology Propel Renewables (September 2024)*.]

In the framework of the IRA, two federal tax credits stimulate domestic solar PV manufacturing: the advanced manufacturing production credit (tax code: §45X) and the advanced energy project "(investment)" credit (§48C). These tax credits are not stackable. The tax credit to be chosen depends on forecasted profits.

Beginning in 2023, the manufacturing production credit introduces new production tax credits (PTCs) for the manufacture of solar PV components (Table 3). The funds to be allocated are uncapped. Credits are fully available from 2023 to 2029 and are then phased down from 2030 to 2032 (i.e., 75% in 2030, 50% in 2031, and 25% in 2032). No credit is available after 2032.

Table 3: United States – Main PTCs for Domestic Solar PV Manufacturing

Component	Credit amount [US component cost, when available]
Polysilicon	$3 per kilogram [N/A]
Wafers	$12 per square meter [N/A]
Cells	$0.04/W [$0.10/W]
Modules	$0.07/W [$0.15/W]

Sources: credits, from Environmental Defense Fund and Deloitte, IRA Activation Guide: Advanced Manufacturing (May 2023). And costs, from BloombergNEF, 'Made in US' Solar Ambitions Can't Shake China's Influence (March 2024) [subscription required].

The energy project credit provides an investment tax credit (ITC) of 6% (or 30%, if prevailing wage and apprenticeship requirements are met) for re-equipping, expanding, or establishing a facility to manufacture solar PV components.[30]

Unlike in the manufacturing production credit scheme, the funds to be allocated in the energy project credit scheme are capped: $10 billion, to be awarded via two competitive processes which are technology neutral (i.e., other clean energy technologies are also eligible to this ITC).[31]

In March 2024, the recipients of the first $4 billion were selected.[32] In January 2025, the recipients of the second $6 billion will be selected.[33] Because only some recipients voluntarily chose to self-disclose the result of their successful application, it is not possible to analyze how the funds are awarded among the different eligible technologies.

Though these tax credits are generous, they are insufficient to close the manufacturing cost gap with China. For example, the total cost of manufacturing solar PV benefitting from the cells and modules PTCs (and assuming polysilicon, ingots, and wafers are imported at $0.04/W) is $0.18/W in the United States, against $0.11/W in China.[34]

For over a decade, American federal and government organizations have found evidence that China's cost advantage is partly due to unfair trade practices. In retaliation, they have implemented a set of trade sanctions against the Chinese solar PV industry throughout the years (Table 4).

Table 4: United States – Trade Sanctions against the Chinese Solar PV Industry

Policy	Type	Product scope	Geographic scope	Rate	Timeline
AD/CVD – solar 1	AD/CVD orders; anticircumvention orders	Solar cells	China; anticircumvention orders apply to Cambodia, Malaysia, Thailand, and Vietnam	Varies by company and by year (AD range: 0-239%, CVD range: 3-526%)	2012 onward (AD/CVD) 2022 onward (anticircumvention)
AD/CVD – solar 2	AD/CVD orders	Solar modules	China	Varies by company and by year	2015 onward
Section 301	Import tariff	Hundreds of products including solar cells	China	25% then 50% (from 2024)	2018 onward
Uyghur Forced Labor Prevention Act	Import ban	All products; polysilicon and products made with polysilicon are a priority sector	Global imports suspected of having inputs from Xinjiang or made using forced labor	N/A	2022 onward

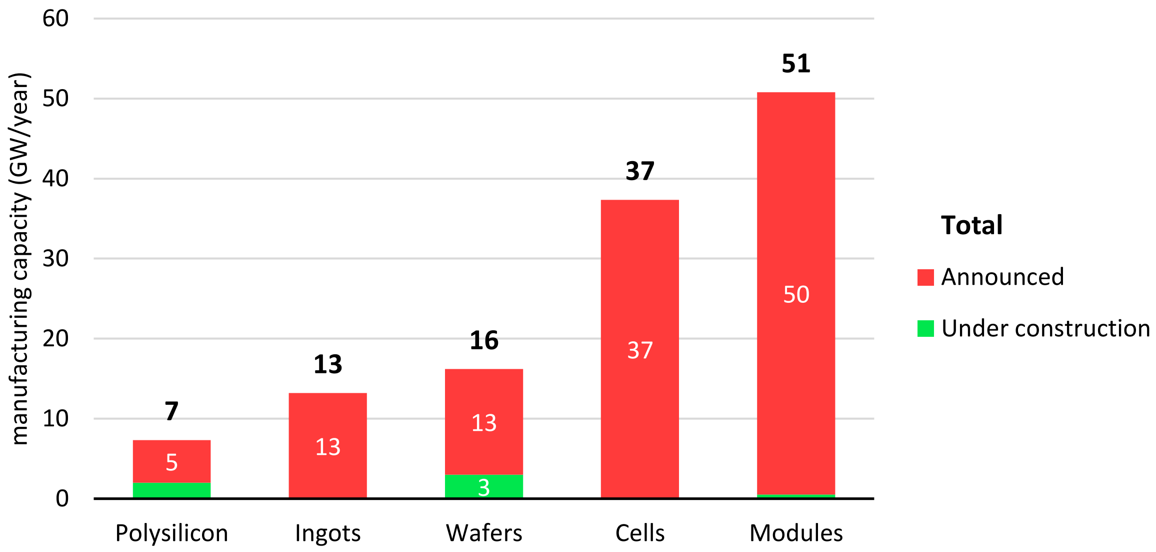
Source: PV Magazine, Solar Panel Import Tariffs Increase US Module Prices by up to 286% – June 10, 2024 (accessed October 21, 2024).

Among these sanctions, it is interesting to stress the anticircumvention orders applying to Cambodia, Malaysia, Thailand, and Vietnam. These were decided because some Chinese manufacturers were shipping solar cells through these four Southeast Asian countries for minor processing in an attempt to avoid paying AD/CVDs.

President Biden suspended the implementation of this decision for a period of two years (between June 2022 and June 2024) to bolster the installation of solar PV and accelerate the decarbonization of the country's power sector. The United States aims for 100% carbon free electricity by 2035. This presidential arbitrage divided the American solar PV industry with the installers welcoming it, but not the manufacturers.

As of September 2024, with this combination of subsidies and protectionism, numerous solar PV manufacturing projects had been announced, but few had started construction (Chart 15). This shows the difficulty of realizing these plans in the context of global oversupply and low prices.

Chart 15: United States – Solar PV Manufacturing Capacity in the Pipeline, as of Sep. 2024



Notes: for polysilicon, it is assumed that 3,000 tons is equivalent to 1 GW. For readability purposes, manufacturing capacity < 3 GW is not displayed.

Source: BloombergNEF, Equipment Manufacturers: PV – updated September 24, 2024 (accessed October 9, 2024) [subscription required].

Donald Trump (Republican) was elected for a second presidential term on November 5, 2024. Its inauguration is scheduled to take place on January 20, 2025. Thus, the exact policies his government will implement are unknown yet.

In the meantime, President-elect Trump's climate skepticism is raising concerns about possible negative changes in terms of federal support for clean energy technologies. As for domestic solar PV manufacturing, these worries could be unfounded.

A full repeal of the tax credits supporting domestic solar PV manufacturing is unlikely as traditional Republican states like Texas, Indiana, South Carolina, Alabama, and Oklahoma are planned to host new solar PV manufacturing projects which realization depends on the benefits of these tax credits.[35] The representatives of these states are pragmatic and should therefore oppose policy changes that would reduce investments contributing to the economic attractiveness of their territory (i.e., factories create fiscal revenue end employment).

Regarding protectionist measures, these are unlikely to be softened. This is because import tariffs of 25% against Chinese solar cells were introduced during the first presidential term of Trump (i.e., "Section 301" in 2018), and because President-elect Trump repeatedly pledged for increased trade barriers moving forward.

2. European Union: risk awareness, but demand prioritized over domestic supply

In May 2022, the European Union (EU) announced its Solar Energy Strategy, as part of the REPowerEU Plan – the EU initiative to put an end to its dependency from Russian fossil fuels by massively and rapidly deploying renewable energy.[36]

The EU Solar Energy Strategy aims to bring online over 320 GW of solar PV by 2025 and almost 600 GW by 2030[37] (cumulative installed solar PV capacity reached 255 GW in the EU in 2023)[38].

These ambitious targets were set by highlighting solar PV as a cost-effective decarbonized technology.

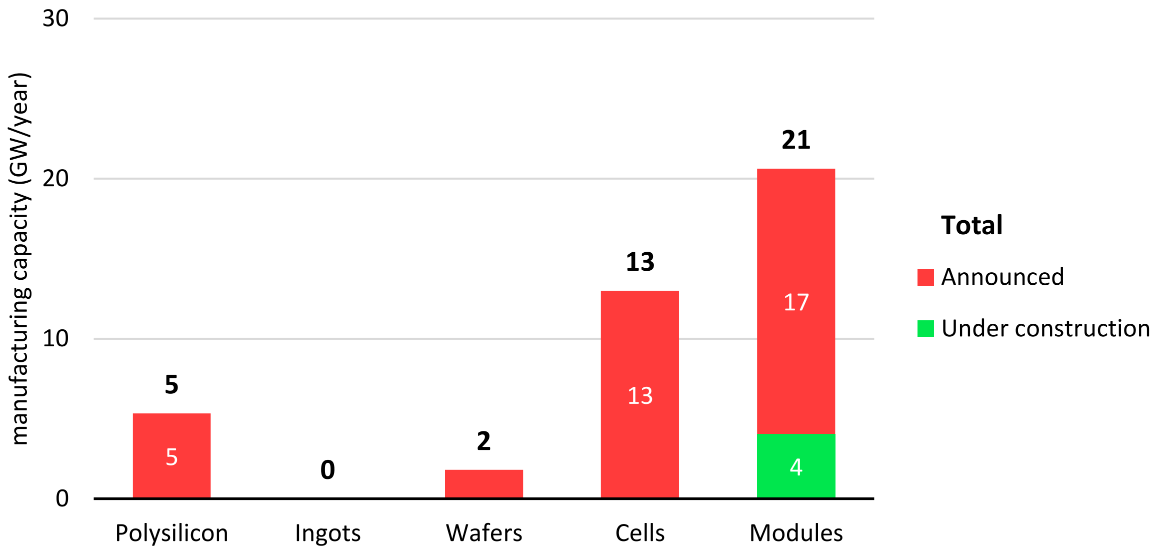
At that time, this expansion of solar PV was also seen as an opportunity for the EU to reinforce its industrial leadership. To this end, the decision to launch a European Solar PV Industry Alliance was made.

The role of this Alliance is to create the right conditions for investment in solar PV manufacturing capacity in Europe.[39] It has the objective to develop an industry with a production capacity of 30 GW by 2025 along the whole supply chain (which entails significant efforts except for polysilicon).

The Alliance leads four actions: (1) mobilizing financing for European solar PV manufacturing projects, (2) ensuring a sustainable level playing field, (3) swiftly implementing eco-design requirements, and (4) anticipating the skills requirements of the industry.

As of September 2024, considering the moderate pipeline of solar PV manufacturing projects under construction and announced in Europe, the EU strategy somewhat disappointed (Chart 16). In particular, ingots and wafers manufacturing capacity were not taking off, jeopardizing the European Solar PV Industry Alliance's objective of production capacity of 30 GW by 2025 along the entire supply chain.

Chart 16: Europe – Solar PV Manufacturing Capacity in the Pipeline, as of Sep. 2024



Notes: for polysilicon, it is assumed that 3,000 tons is equivalent to 1 GW. For readability purposes, manufacturing capacity < 3 GW is not displayed.

Source: BloombergNEF, Equipment Manufacturers: PV – updated September 24, 2024 (accessed October 9, 2024) [subscription required].

It is likely that European solar PV manufacturing capacity will not dramatically increase soon, and that Europe remain dependent towards the Chinese industry. Europe is aware of this problematic reliance, but it prioritizes solar PV demand over domestic solar PV supply to decrease its electricity prices and reduce its greenhouse gas emissions, which are deemed more urgent issues.

In this regard, the address by Mr. Draghi, former European Central Bank President, during the presentation of his landmark report on the future of European competitiveness at the European Parliament, on September 17, 2024, was unequivocal: "There are some technologies, like solar panels, where foreign producers are too far ahead and attempting to capture production in Europe will only set back decarbonization. Even if those countries are using subsidies, we should let foreign taxpayers finance cheaper installation of clean energy in Europe."[40] No other statement could better have expressed this mindset.

3. Japan: crystalline silicon potential underestimated, promising perovskite emphasized

Japan's strategy to strengthening its solar PV supply chain is very different from that of the United States and the EU. Japan only has little manufacturing capacity based on crystalline silicon and there is no plan to expand the production of this technology in the country. Instead, Japan is putting the emphasis on an innovative technology: perovskite, invented by Professor Tsutomu Miyasaka, Toin University of Yokohama in 2009.

The Japanese government claims that there is a "scarcity of suitable terrain" for the installation of solar PV based on crystalline silicon, which faces space constraints due to weight issues, making its expansion difficult in the country.[41] This claim is incorrect as the potential for crystalline silicon remains largely untapped in Japan (e.g., rooftops and unused farmlands).

Sticking to this erroneous narrative, the Japanese government promotes thin, light and flexible perovskite cells. These characteristics allow perovskite to be introduced in spaces where it is hard to install crystalline silicon (e.g., building walls and factory roofs with a small tolerable load).

Another advantage of perovskite over crystalline silicon for Japan is that the primary material for producing perovskite cells is iodine. With a share of 30% in 2023, Japan was the world's second largest producer of iodine (behind Chile which produced 63% of global iodine).[42]

Despite these advantages, perovskite is not a mature technology yet. To reach commercialization, perovskite will need to overcome a number of challenges, among which: achieve anticipated cost reduction and improve cell durability to extend short lifespan (i.e., ten years currently).

Perovskite solar cells can be produced with the materials painted or printed on a film. Therefore, they can be mass-produced in a small number of production processes. Moreover, perovskite can unleash conversion efficiency gains. Under laboratory conditions, both perovskite and crystalline silicon recorded conversion efficiencies of 27%, and the tandem perovskite-crystalline silicon recorded a 35% efficiency (all these records have been realized by Chinese organizations).[43]

For perovskite, the Japanese government aims to achieve a power generation cost as low as ¥14/kWh in 2030 and ¥10/kWh in 2040.[44] In comparison, according to BloombergNEF, the power generation cost of solar PV based on crystalline silicon was ¥10/kWh in 2023, and it is projected to be ¥7/kWh in 2030.[45]

In October 2021, the Japanese government established the Project for Developing Next-Generation Solar Cells with a budget of ¥49.8 billion (around $320 million) to support companies' efforts for developing perovskite and is aiming for its public implementation by 2030.[46]

Several private companies are taking advantage of this support measure. These companies include Aisin, EneCoat, Kaneka, Sekisui Chemical, Toshiba.[47]

For instance, Sekisui Chemical has created a 30-centimeter-wide roll-to-roll manufacturing process that enables continuous production (Chart 17). In this manufacturing process, printing or application is conducted while multiple drum rolls convey the products.

Chart 17: Sekisui Chemical – Roll-to-Roll Manufacturing Process

Source: Japan – Ministry of Economy, Trade and Industry, Perovskite Solar Cells: The Key to the Future Expansion of Renewable Energy in Japan. Part 2: Efforts toward Early Public Implementation – February 16, 2024 (accessed October 29, 2024).

In August 2023, observing the intensification of the global competition to develop perovskite, the Japanese government decided to increase the budget of the Project for Developing Next-Generation Solar Cells to ¥64.8 billion (around $420 million), a 30% increase from the original plan in 2021.[48]

For Japan to succeed in beating the global competition, it will be critical to excel in going from R&D to industrialization. This necessitates building a gigawatt-scale domestic supply chain and fostering initial demand via targets and incentives (e.g., feed-in tariffs) at an early stage.

In November 2024, the Japanese government published its Next-Generation Solar Cell Strategy in which it announced the aim of introducing at least 20 GW of perovskite in Japan by 2040.[49] This target is useful as it offers a clear vision for the industry to adequately and timely scale up its manufacturing activities.

Putting the emphasis on perovskite should, however, not be used as an excuse for not more proactively installing crystalline silicon in Japan. Affordable and rapid decarbonization does not need to wait for perovskite to become mainstream. Just like the EU, Japan should take advantage of cheap crystalline silicon imports, preferably not only from China, but also from Southeast Asia and India for diversification purposes.

Not only Japan is actively developing perovskite. China is the other leading country pursuing this technology, with already some progress made towards mass production (see pages 31-32).

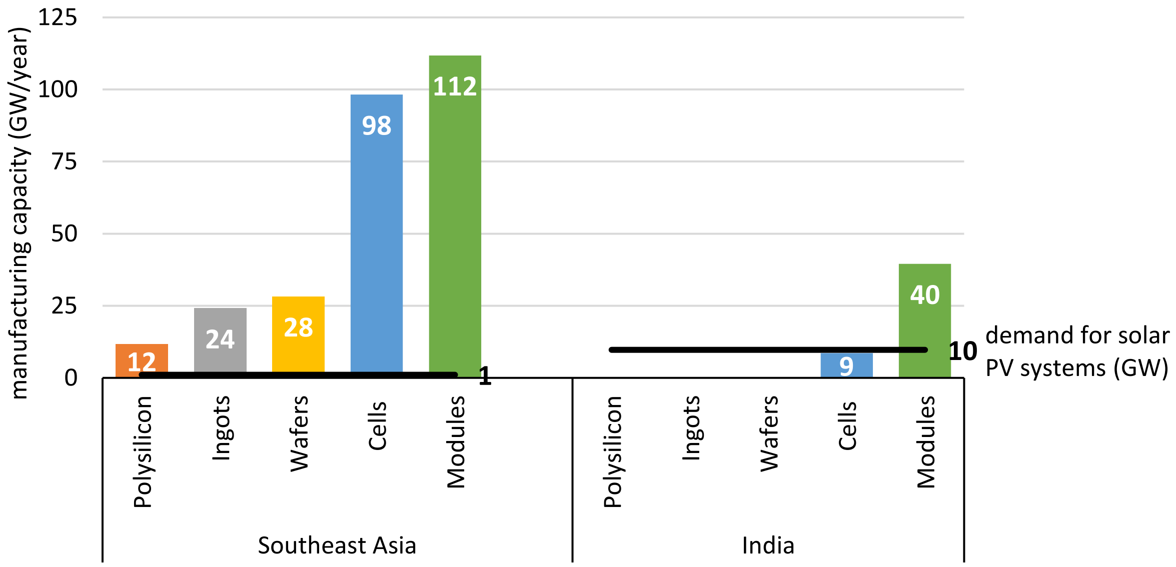
4. Southeast Asia and India: underrated actors of diversification

Southeast Asian countries (i.e., Cambodia, Indonesia, Laos, Malaysia, Philippines, Singapore, Thailand, and Vietnam) and India are also increasing their domestic solar PV manufacturing capacity, contributing to the diversification of the global supply chain away from China.

As of 2023, Southeast Asian countries were active across the whole solar PV supply chain with rather significant manufacturing capacity in each segment, and especially in cells and modules (Chart 18). Vietnam, Thailand, and Malaysia were the regional leaders. Behind, Indonesia started to catch up this trio with the commissioning of new modules manufacturing capacity.

India only had cells and modules manufacturing capacity. This manufacturing capacity was smaller than that of Southeast Asian countries, but bigger than those of Europe, Japan, and the United States.

Chart 18: Southeast Asia and India – Manufacturing Capacity by Segment and Solar PV System Demand 2023



Note: for polysilicon, it is assumed that 3,000 tons is equivalent to 1 GW.

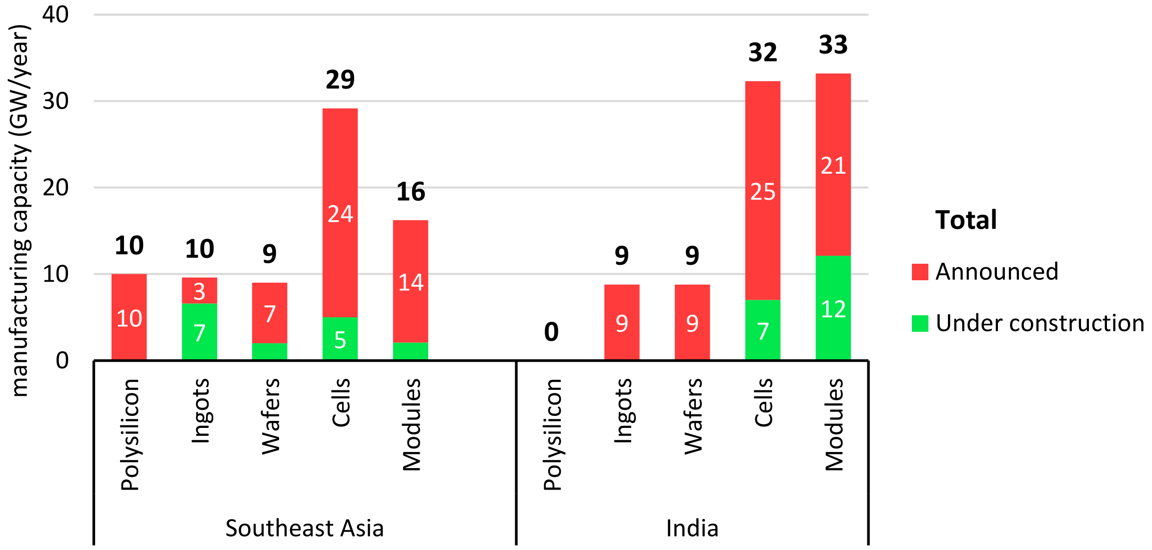
Sources: manufacturing capacity, from BloombergNEF, Equipment Manufacturers: PV – updated September 24, 2024 (accessed October 9, 2024) [subscription required]. And demand for solar PV systems, from International Renewable Energy Agency, Renewable Energy Statistics 2024 (July 2024).

In Southeast Asia, most of manufacturing capacity is owned by Chinese companies. However, non-Chinese companies also own meaningful manufacturing capacity. For example, non-Chinese companies include Southeast Asian companies Vietnam Sunergy (Vietnam) and New East Solar Energy (Cambodia) as well as foreign companies such as Canadian Solar (Canada), First Solar (United States), and Hanwha Q CELLS (South Korea). Southeast Asian countries manage to attract foreign investments thanks to low labor costs and energy subsidies.[50]

Moving forward, based on the pipeline of projects under construction and announced, the growth of solar PV manufacturing capacity in India and Southeast Asia is expected to be similar (Chart 19).

In India in the 2010s, domestic-content requirements were introduced by several government purchasing programs (e.g., 50% of capacity auctioned reserved for projects that use domestically manufactured solar cells and modules).[51] And from 2022, customs duties of 25% on cells and 40% on modules started to be imposed on imports.[52] This strategy helps bridge the gap with Southeast Asia and enables the emergence of Indian companies like Waaree Energies, Adani Enterprises, and Premier Energies.

Chart 19: Southeast Asia and India – Solar PV Manufacturing Capacity in the Pipeline, as of Sep. 2024



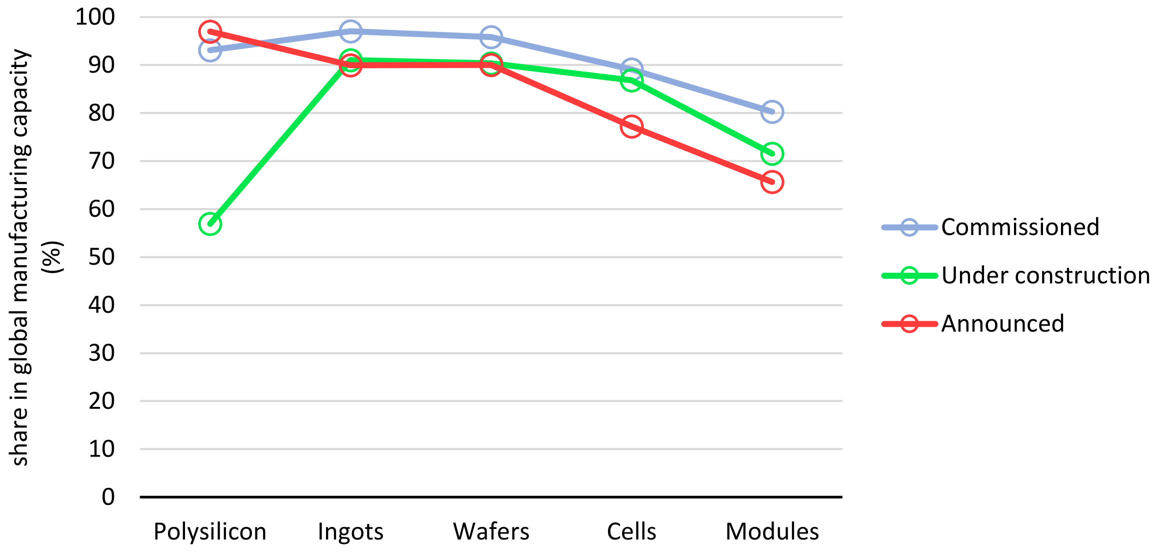
Notes: for polysilicon, it is assumed that 3,000 tons is equivalent to 1 GW. For readability purposes, manufacturing capacity < 3 GW is not displayed.

Source: BloombergNEF, Equipment Manufacturers: PV – updated September 24, 2024 (accessed October 9, 2024) [subscription required].

In the foreseeable future, China will retain some domination over the global solar PV supply chain (Chart 20). Nonetheless, thanks to the pipeline of projects in progress in the United States, Europe, Japan, Southeast Asia, and India, the supply chain will be more diversified.

It may be noted that more progress is being made in the diversification of cells and modules than in polysilicon, ingots, and wafers. This is because building cells and modules manufacturing capacity requires lower investments costs and shorter lead times.

Chart 20: Share of China (location) in Solar PV Manufacturing Capacity by Project Status, as of Sep. 2024



Source: BloombergNEF, Equipment Manufacturers: PV – updated September 24, 2024 (accessed October 9, 2024) [subscription required].

Section 4: Recycling and Perovskite as Alternative Solutions

1. Improving recycling to become less technically challenging and more affordable

Global cumulative installed solar PV capacity amounted to 1,411 GW in 2023, and deployment will strongly accelerate over the next decades.[53] For instance, in its latest *World Energy Outlook* published in October 2024, the International Energy Agency projected that global cumulative installed solar PV capacity will be between approximately 16,000 GW and 22,000 GW in 2050.[54]

With the scale-up of the solar PV industry, the volume of defective, damaged, and spent modules will expand rapidly in the decades ahead.[55]

Development and optimization of collection, triage, repair, refurbishment, reuse, and recycling pathways are needed to convert solar PV materials into assets that contribute to the circular economy and improve environmental responsibility, rather than creating new waste streams.[56]

Furthermore, recycling solar PV helps relieving pressure resource constraints (e.g., copper) and can strengthen energy security by recovering materials which are not domestically produced.[57]

Modules that cannot be repaired or refurbished have reached end of life and can often be recycled.[58] However, solar PV recycling is still technically complex and insufficiently profitable.

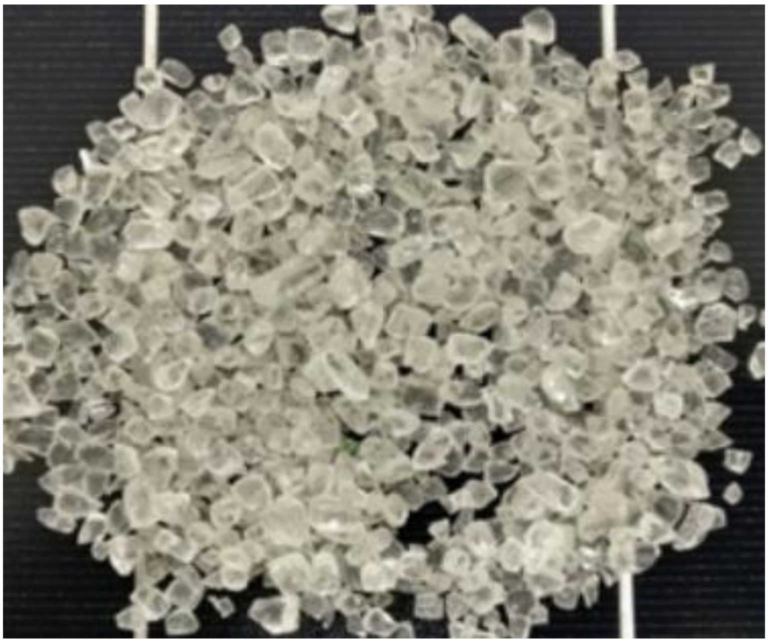
All solar PV modules are not homogeneous in size, technology, composition or condition.[59] Moreover, existing solar PV panels were not designed to be recycled: durability and performance requirements have led to sandwich-like, sealed and encapsulated structures, making the separation of constituent materials difficult.

The recycling of modules generally starts with manual removal of the cables, junction box and frame, from which copper and aluminum can be recovered easily.[60] Then, to separate the module's other constituents (e.g., glass, silicon, and silver – for modules based on crystalline silicon) three different treatments exist: mechanical, thermal, and chemical – each coming with their advantages and drawbacks.

Mechanical treatment consists of shredding solar panels, followed by milling and sorting.[61] It is the most common approach because existing shredding facilities can be easily adapted to recycle PV modules.[62] However, the outputs of mechanical processing are usually not very pure (i.e., entailing lower economic value).

For crystalline silicon modules, the mechanical treatment of the German company Reiling represents a fully commercial, best available technology that sets a benchmark for maturity, cost, and low energy consumption.[63] This treatment allows the recovery of glass (Chart 21), but not of silicon and silver.

Chart 21: Reiling – Glass Product Obtained by Mechanical Treatment



Source: International Energy Agency Photovoltaic Power Systems Program, Advances in Photovoltaic Module Recycling Literature Review and Update to Empirical Life Cycle Inventory Data and Patent Review (June 2024).

In the thermal treatment, solar panels are subject to pyrolysis at temperatures ranging from 300 to 650 degrees to separate constituents.[64] This is an effective method to recover valuable elements such as silicon and silver, but it requires a lot of energy and generates toxic fumes.

Chemical treatment uses organic solvents and inorganic acids to separate constituents.[65] This is also an effective method to recover valuable elements, but it is costly, and chemical waste requires a complex treatment process.

The medium-term future of solar PV recycling should be brighter. Until now, developments in solar PV recycling have been limited because the current waste stream was too small to justify significant investments in dedicated recycling technologies.[66]

In anticipation of a market with a desirable size, recyclers are ramping up their efforts pursuing innovative solutions. In advanced recycling processes at pilot stage, different treatments are combined to improve the quality of recovered materials.[67] This progress should lead to the start of operation of the first commercial plants for module recycling in the years to come.

The efforts of the business sector are increasingly accompanied by governmental regulations. Historically, governments across the world have prioritized solar PV installation, and to a lesser extent solar PV manufacturing. Solar PV recycling is starting to get more attention.

The EU was the first jurisdiction to adopt a PV-specific waste regulation mandating the recycling of all solar PV modules, under the revision of the Waste Electrical and Electronic Equipment Directive in 2012.[68] In this framework, producers or sellers who put modules on the EU market are liable for the costs of collection, handling and treatment of their products.

In the United States, solar PV recyclers can participate in the energy project credit scheme.[69] Under this scheme, in April 2024, the American company SOLARCYCLE announced that it is the recipient of $64 million to build a solar glass plant manufacturing glass in addition to recycling solar panels.[70] The plant is scheduled to begin construction in 2024 and will be operational in 2026.

In China, the National Development and Reform Commission aims to mature solar PV recycling by 2030, including the establishment of a dedicated industrial cluster.[71] In the meantime, solar PV manufacturers are required to handle retired equipment and are not allowed to dump decommissioned equipment in landfill sites.

And in Japan, legislation to require recycling of solar panels that have reached the end of their useful lives is being explored.[72] The parliament is expected to receive a proposal as soon as 2025. A few Japanese companies such as NPC (mechanical treatment) and Shinryo (thermal treatment) are already conducting recycling activities.

These advances are encouraging signs that recycling will more and more contribute to the diversification of the global solar PV supply chain.

2. Global landscape of perovskite cells nascent manufacturing

As the global solar PV supply chain is currently overwhelmingly dominated by crystalline silicon, and with China being by far the major supplier of this technology, the arrival of promising perovskite offers the possibility of diversifying solar PV manufacturing capacity. This will, however, necessitates that other countries than China take the lead in perovskite manufacturing.

To date, China leads the way in mass production of perovskite solar cells. In China in 2023, startups began mass production at the 100-megawatt (MW) scale.[73] And there are efforts to establish GW-scale production systems in the country by the end of 2024 (Table 5). The fact that China was a latecomer to the development of perovskite makes this achievement remarkable.

Most Chinese companies producing perovskite solar cells use a glass substrate type, which is intended for power generation facilities.[74] This is due the demand for solar PV in China which focuses more on ground-mounted projects than on building façade projects.

Conversely, in Japan it is expected that perovskite solar cells using a film substrate type will initially be adopted.[75] This is because the country focuses on uses that leverage the lightness and flexibility of perovskite.

Thus, for the time being, the competition between China and Japan is somewhat indirect.

Table 5: Chinese Companies Mass Production of Perovskite Solar Cells

Company	Commissioned (MW/year)	Under Construction – start year (MW/year)	Announced (MW/year)	Substrate type
Wonder Solar	200	1,200 (2025)	3,600	Glass
UtmoLight	150	1,000 (2024)	0	Glass
Renshine Solar	150	0	0	Glass
GCL Optoelectronic Materials	100	1,000 (2025)	1,000	Glass
Microquanta	100	1,000 (2024)	0	Glass
HETE Photo Electricity	100	0	0	Glass
DaZheng	0	100 (2024-25)	0	Film
Total	800	4,300	4,600	N/A

Source: Mitsui & Co. Global Strategic Studies Institute, China Advances to GW-Scale Mass Production of Perovskite Solar Cells — Aims to Exceed 30% Conversion Efficiency with Tandem Cells (July 2024).

While China and Japan near perovskite mass production, Europe and the United States appear to be at an earlier development stage due to a lack of public funding to scale up activities (it is difficult to find comprehensive information about perovskite in Europe and the United States).

Nevertheless, it may be mentioned that in Europe, Oxford PV, a British company, developed a perovskite solar cell factory with a production capacity of 50 MW/year in Germany.[76] In September 2024, the company announced the first commercial sale of its products, to a customer based in the United States.[77]

In June 2024, it was reported that the American startup Swift Solar is planning to build a 100 MW/year perovskite solar cell factory in the United States in the next two-three years.[78] In October 2024, the United States Manufacturing of Advanced Perovskites, a consortium formed by the National Renewable Energy Laboratory and American universities promoting an acceleration of domestic commercialization of perovskite technologies, warned that urgent action is required in favor of perovskite in the United States for the country not to lose against foreign competition (i.e., China and Japan).[79]

Conclusion

Until the end of this decade, China and Chinese manufacturers will retain some domination over the global solar PV chain. However, the global solar PV supply chain is becoming more robust thanks to the diversification of crystalline silicon modules manufacturing capacity in the United States, Europe, Southeast Asia, and India.

In the 2030s, improvements in solar PV recycling and the widespread adoption of new technologies like perovskite cells, which development is led by China (glass substrate) and Japan (film substrate), will provide new opportunities to further diversify the global solar PV supply chain.

This progress will strengthen worldwide energy security and facilitate the much-needed acceleration of the energy transition.

From a Japanese perspective, the strategy of the government that underestimates the huge potential for crystalline silicon and puts the emphasis on perovskite should be revised. This is because there is no reason for Japan not to take advantage of its still largely untapped potential for crystalline silicon, while waiting for perovskite to become mature.

Even if crystalline silicon products are not manufactured in Japan or by Japanese companies, cheap imports, not only from China but also from Southeast Asia and India, would reduce electricity prices and greenhouse gas emissions and reinforce the country’s energy security.

List of Abbreviations

AD/CVD: antidumping and countervailing duty
EU: European Union
GW: gigawatt
IRA: Inflation Reduction Act
ITC: investment tax credit
kWh: kilowatt-hour
MW: megawatt
PTC: production tax credit
PV: photovoltaic
R&D: research and development
W: watt

Endnotes

[1] Energy Institute, Statistical Review of World Energy 2024 (June 2024).
[2] International Energy Agency, World Energy Outlook 2024 (October 2024).
[3] BloombergNEF, Levelized Cost of Electricity 2023-H2 (December 2023) [subscription required].
[4] BloombergNEF, Equipment Manufacturers: PV – updated September 24, 2024 (accessed October 9, 2024) [subscription required].
[5] BloombergNEF, Solar Supply Chain Index, September 2024: Negative-Sum Game (October 2024) [subscription required].
[6] BloombergNEF, Solar Cell and Module Efficiency Improves Steadily (October 2023) [subscription required].
[7] The World Economic Forum, Visualizing the Abundance of Elements in the Earth's Crust – December 14, 2021 (accessed October 8, 2024).
[8] BloombergNEF, op. cit. note 4.
[9] International Energy Agency, Special Report on Solar PV Global Supply Chains (July 2022).
[10] BloombergNEF, op. cit. note 5.
[11] Ibid.
[12] Ibid.
[13] BloombergNEF, Equipment Manufacturers: PV Exports and Imports – updated October 21, 2024 (accessed November 7, 2024) [subscription required].
[14] International Energy Agency, op. cit. note 9.
[15] Ibid.
[16] Ibid.
[17] International Energy Agency, Electricity 2024: Analysis and Forecast to 2026 (January 2024).
[18] International Energy Agency, op. cit. note 9.
[19] Ibid.
[20] Ibid.
[21] Ibid.
[22] BloombergNEF, Bimonthly PV Index November 2023: Every Cent Counts (November 2023) [subscription required].
[23] Sheffield Hallam University, In Broad Daylight: Uyghur Forced Labor and Global Solar Supply Chains (May 2021).
[24] Sheffield Hallam University, Over-Exposed (November 2023).
[25] Ibid.
[26] PV Magazine, Solar Panel Import Tariffs Increase US Module Prices by up to 286% – June 10, 2024 (accessed October 17, 2024).
[27] United States Department of Commerce, Department of Commerce Issues Final Determination of Circumvention Inquiries of Solar Cells and Modules from China – August 18, 2023 (accessed October 17, 2024)
[28] BloombergNEF, op. cit. note 5.
[29] The White House, Building a Clean Energy Economy: A Guidebook to the Inflation Reduction Act's Investments in Clean Energy and Climate Action (January 2023).
[30] Environmental Defense Fund and Deloitte, IRA Activation Guide: Advanced Manufacturing (May 2023).
[31] Ibid.
[32] United States Department of Energy, Federal Tax Credits for Solar Manufacturers (accessed October 21, 2024).
[33] Ibid.
[34] BloombergNEF, 'Made in US' Solar Ambitions Can't Shake China's Influence (March 2024) [subscription required].
[35] BloombergNEF, op. cit. note 4.
[36] European Commission, EU Solar Energy Strategy (May 2022).
[37] Ibid.
[38] International Renewable Energy Agency, Renewable Energy Statistics 2024 (July 2024).
[39] European Solar PV Industry Alliance, Homepage (accessed October 22, 2024).
[40] Mr. Draghi, Presentation of the Report on the Future of European Competitiveness – September 17, 2024 (accessed October 22, 2024).
[41] Japan – Ministry of Economy, Trade and Industry, Perovskite Solar Cells: The Key to the Future Expansion of Renewable Energy in Japan. Part 1: Differences from Conventional Solar Cells – February 9, 2024 (accessed October 28, 2024).

[42] United States Department of the Interior – United States Geological Survey, Mineral Commodity Summaries 2024 (January 2024).
[43] United States – National Renewable Energy Laboratory, Interactive Best Research-Cell Efficiency Chart – updated October 29, 2024 (accessed October 29, 2024).
[44] Japan – Ministry of Economy, Trade and Industry, Next-Generation Solar Cell Strategy (November 2024) (in Japanese).
[45] BloombergNEF, op. cit. note 3.
[46] Japan – Ministry of Economy, Trade and Industry, R&D and Social Implementation Plan Formulated for "Next-Generation Solar Cell Development" Projects (October 2021).
[47] Japan – Ministry of Economy, Trade and Industry, Perovskite Solar Cells: The Key to the Future Expansion of Renewable Energy in Japan. Part 2: Efforts toward Early Public Implementation – February 16, 2024 (accessed October 29, 2024).
[48] Ibid.
[49] Japan – Ministry of Economy, Trade and Industry, op. cit. note 44.
[50] International Energy Agency, op. cit. note 9.
[51] Ibid.
[52] Ibid.
[53] International Renewable Energy Agency, op. cit. note 38.
[54] International Energy Agency, op. cit. note 2.
[55] International Energy Agency Photovoltaic Power Systems Program, Advances in Photovoltaic Module Recycling Literature Review and Update to Empirical Life Cycle Inventory Data and Patent Review (June 2024).
[56] Ibid.
[57] International Energy Agency, op. cit. note 2.
[58] International Energy Agency Photovoltaic Power Systems Program, op. cit. note 55.
[59] International Energy Agency, op. cit. note 9.
[60] Ibid.
[61] American Chemical Society, How to Improve Solar Panel Recycling – October 18, 2024 (accessed November 8, 2024).
[62] International Energy Agency Photovoltaic Power Systems Program, op. cit. note 55.
[63] Ibid.
[64] American Chemical Society, op. cit. note 61.
[65] Ibid.
[66] International Energy Agency Photovoltaic Power Systems Program, op. cit. note 55.
[67] Ibid.
[68] International Energy Agency, op. cit. note 9.
[69] The White House, op. cit. note 29.
[70] SOLARCYCLE, SOLARCYCLE Receives Clean Energy Investments from Biden Administration's Inflation Reduction Act – April 19, 2024 (accessed November 11, 2024).
[71] PV Tech, China to Build Solar Recycling System by 2025 – August 21, 2023 (accessed November 11, 2024).
[72] Nikkei Asia, Japan Eyes Recycling Mandate for Solar Panels – June 12, 2024 (accessed November 11, 2024).
[73] Mitsui & Co. Global Strategic Studies Institute, China Advances to GW-Scale Mass Production of Perovskite Solar Cells — Aims to Exceed 30% Conversion Efficiency with Tandem Cells (July 2024).
[74] Ibid.
[75] Ibid.
[76] SolarPower Europe, #MakeSolarEU: Oxford PV's Role in Reshoring Solar Manufacturing to Europe – February 2, 2024 (accessed November 12, 2024).
[77] Oxford PV, 20% More Powerful Tandem Solar Panels Enter Commercial Use for the First Time in the US – September 5, 2024 (accessed November 12, 2024).
[78] BloombergNEF, US Startup Seeks to Build Next-Gen Solar Factory in Two Years (2) – June 13, 2024 (accessed November 12, 2024) [subscription required].
[79] United States Manufacturing of Advanced Perovskites, Statement on Perovskite PV Ecosystem Needs (October 2024).

Progress in Diversifying the Global Solar PV Supply Chain

December 2024

Renewable Energy Institute
11F, KDX Toranomon 1-Chome Bldg., 1-10-5 Toranomon, Minato-ku, Tokyo 105-0001 JAPAN
TEL：+81(0)3-6866-1020
info@renewable-ei.org
www.renewable-ei.org/en