CHINA ADVANCES TO GW-SCALE MASS PRODUCTION OF PEROVSKITE SOLAR CELLS

— AIMS TO EXCEED 30% CONVERSION EFFICIENCY WITH TANDEM CELLS —

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SUMMARY

- Perovskite solar cells are a promising next-generation solar cell technology because they are easy to manufacture, lightweight, and flexible. In addition, as they can convert a wider range of wavelengths of sunlight into electricity, tandem-type[1] cells combining different types of solar cells can achieve higher conversion efficiencies[2] that are not possible with crystalline silicon solar cells.
- China is leading the way in mass production of perovskite solar cells. Startups there began mass production at the 100 MW (thousand kW) scale in 2023, and there are efforts to establish GW-scale (million kW) production systems for large-area cells by the end of 2024.
- Major Chinese solar cell companies have secured an overwhelming market share in crystalline silicon solar cells. They are intensively developing tandem models that can achieve higher conversion efficiencies than those made from crystalline silicon.

1. PEROVSKITE SOLAR CELLS

Perovskite solar cell (PSC) is a new type of solar cell that uses a crystalline structure material known as perovskite,[3] which was invented in 2009 by Professor Riki Miyasaka at Toin University of Yokohama. PSC have high conversion efficiencies comparable to those of the currently mainstream crystalline silicon (c-Si) solar cells, which, combined with their low-cost production enabled by coating technology, makes them a promising next-generation solar power technology. Recently, companies developing PSC around the world have been successively breaking records in conversion efficiency. In January 2024, the MIT Technology Review named PSC as one of the "10 Breakthrough Technologies 2024," second only to AI. Japan has designated PSC as subject to the Green Innovation Fund, which provides long-term support for research, development, demonstration, and implementation of technologies necessary to achieve carbon neutrality by 2050, and is promoting research and development to achieve a power generation cost of 14 yen/kWh or less by 2030. Europe and the US are also engaged in joint public-private development projects. In China, policies such as the 14th Five-Year Plan for National Economic and Social Development are boosting the development of materials, manufacturing equipment, mass production and industrialization techniques for PSC and tandem solar cells. Furthermore, some startups are establishing GW-scale (million kW) production systems within

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[1] Tandem-type (multijunction) is a solar cell that can efficiently utilize sunlight by stacking solar cells with different absorption levels. (NEDO)
[2] The percentage of incident solar energy that can be converted into electrical power is expressed as the conversion efficiency (Source: National Institute of Advanced Industrial Science and Technology (AIST))
[3] Professor Miyasaka was the first in the world to apply perovskite crystals with the chemical formula $CH_3NH_3PbI_3$ to solar cells (Source: Japan Science and Technology Agency)

2024, positioning themselves at the forefront of PSC mass production.

2. CHARACTERISTICS OF PEROVSKITE SOLAR CELLS

Figure 1 shows the characteristics of PSC and a comparison with mainstream solar cells.

Figure 1 Comparison of key indicators for mainstream and perovskite solar cells

Key indicator	Crystalline silicon (c-Si)	Compound semiconductor (such as CIS)	Perovskite (PSC)
Main material	Silicon	Copper, indium, gallium, selenium	Lead, iodine
Absorption wavelength range	300 to 1,200 nm	400 to 1,300 nm	300 to 800 nm
★ Light absorption coefficient (*1)	Up to 10^4/cm	Up to 10^5/cm	Up to 10^5/cm
★ Photoelectric conversion layer thickness	50 to 300 μm	2 to 4 μm	1 μm
Highest conversion efficiency record	27.10%	23.60%	26.10%
★ Manufacturing process	3 days or longer	Approximately half that of crystalline silicon	A few tenths that of crystalline silicon
Manufacturing temperature	1,400°C or higher	400°C or higher	100℃
★ Lightness	×	△	○
★ Flexibility	△	△	○
Durability	○	○	×
Module price (actual in 2023)	Average USD0.12/W	Slightly below crystalline silicon	Projected to be 1/5 to 1/3 that of crystalline silicon
Market share (actual in 2022)	97.50%	Several percent (*2)	Under development

★: Indicator where PSC are considered to excel

*1 This measure indicates how much the intensity of light decreases as it travels 1 cm through a material. A higher value indicates stronger absorption.

*2 Specifically includes the total of thin-film types such as cadmium telluride (CdTe) and CIS based thin film systems

Source: Compiled by MGSSI based on NEDO, AIST, IEA, VDMA, and other publicly available information

Perovskite has an optical absorption coefficient an order of magnitude higher than that of c-Si, and the perovskite layer required for photoelectric conversion is tens to hundreds of times thinner, making PCSs both light and slim. PSC have been developed in both glass and film substrate types, with the film substrate type attracting attention in particular as a lightweight and flexible solar cell. The primary materials, lead and iodine, are relatively inexpensive. In addition, manufacturing methods through the coating technology using perovskite solution, such as inkjet processes, do not require the high-temperature processes necessary for c-Si solar cells and significantly reduce the number of steps involved, thus enabling reduced energy consumption during production and low-cost mass production. Moreover, perovskite has a high utilization rate in the visible range (wavelengths 360–800 nm), which, when layered with other types of solar cells that absorb different wavelength ranges, is expected to facilitate the development of tandem solar cells with higher conversion efficiencies. Particularly attracting attention is the development of tandem solar cells that use perovskite for the top layer and c-Si, which efficiently generates power at wavelengths above 800 nm, in the bottom layer.

On the other hand, the implementation and widespread adoption of PSC face challenges in the form of improving durability and establishing large-area cell manufacturing technology. Perovskite is susceptible to degradation by moisture, oxygen, and light, resulting in an outdoor lifespan of about 5 to 10 years, which is less than half that of c-Si solar cells. In addition, it remains technically challenging to successively manufacture large-area cells while forming a uniform perovskite layer.

Given these characteristics and challenges, it is expected that PSCs will initially be used in areas where their lightness and flexibility can be exploited, such as building roofs, exterior walls, and vehicle bodies. If the durability issue can be resolved, their application could expand to large power generation facilities such as mega solar plants.

3. CHINESE COMPANIES ENTERING GW-SCALE MASS PRODUCTION

Japanese companies have been leading in the research and development of PSC, particularly in developing products that feature lightness, flexibility, and high durability. For instance, Sekisui Chemical implemented the first film-type perovskite solar cell building material panel in Japan in its Osaka headquarters building in October 2023 and began operating it in July 2024. This panel is designed to withstand the wind load on the 12th story of the building for 20 years, aiming to achieve stable power generation performance and high durability.

On the other hand, in China, a latecomer to the development of PSC, mass production is accelerating, led by startups. As of 2023, some companies have already reached an annual production scale of 100 MW, and a few are advancing the establishment of GW-scale production lines within 2024, indicating significant movement toward market introduction (see Figure 2).

Figure 2 Mass production of perovskite solar cells by Chinese companies

		Production capacity (MW)			Mass production module			
Company	**Factory location**	**In operation**	**Under construction**	**In planning**	**Conversion efficiency (%)**	**Substrate type**	**Size (m)**	**Start of operation, etc.**
Wonder Solar	Ezhou, Hubei Province	200		1,800	n/a	Glass	Unknown	Plans to expand to 2,000 MW in the long term
	Fuyang, Anhui Province		1,200		n/a	Glass	Unknown	Scheduled to start operation by end of 2025
	Fuyang, Anhui Province			1,800	n/a	Glass	Unknown	Planned as the second phase of the above project under construction
Utmolight	Wuxi, Jiangsu Province	150			17%	Glass	1.2×0.6	Started operation in December 2022. Aiming for conversion efficiency of over 20% by end of 2024
	Wuxi, Jiangsu Province		1,000		18%	Glass	1.2×2.3	Construction scheduled to be completed in 3Q 2024, with production to begin sequentially. Conversion efficiency is target value
Renshine Solar	Suzhou, Jiangsu Province	150			18%	Glass	1.2×0.6	Started operation in January 2024. Aiming to achieve 20% conversion efficiency by end of 2024 Can produce both single junction and tandem types
GCL Optoelectronic Materials	Kunshan, Jiangsu Province	100			19%	Glass	1.0×2.0	Started operation in 2021. Achieved conversion efficiency of over 19.04% in April 2024
(*1)	Kunshan, Jiangsu Province		1,000		27%	Glass	1.2×2.4	Construction scheduled for completion in March 2025. Conversion efficiency is a target value of tandem type to be mass-produced
	Kunshan, Jiangsu Province			1,000	27%	Glass	1.2×2.4	Planned as the second phase of the above project under construction
Microquanta	Quzhou, Zhejiang Province	100			12%	Glass	1.2×0.6	Started operation from beginning of 2022
(*2)	Quzhou, Zhejiang Province		1,000		12%	Glass	1.2×0.6	Scheduled to start operation in the second half of 2024
HETE Photo Electricity	Hangzhou, Zhejiang Province	100			28%	Glass	Unknown	Has not been successful with tandem prototypes
DaZheng	Xiamen, Fujian Province		100		13 to 15%	Film	1.0×0.6	Projected to start operation from 2024 to 2025
Total		**800**	**4,300**	**4,600**				

*1 According to some reports, initially constructing a 500 MW facility, with plans to build an additional 500 MW once operations smoothly ramp up
*2 The company is developing flexible products using film substrates, but it appears that glass substrates will be employed for mass-produced cells
Source: Compiled by MGSSI based on various publicly available information and reports from different companies

In 2016, GCL Perovskite, under the major Chinese energy conglomerate the GCL Group, advanced significantly in developing high-efficiency large-area cells, with backing from major battery producer CATL and IT giant Tencent. The company plans to produce large-area tandem PSC with a target conversion efficiency of 27% and dimensions of 1.2 m x 2.4 m at a factory with an annual capacity of 1 GW currently under construction and scheduled for completion in March 2025. In April 2024, GCL Perovskite announced it would implement the world's first power generation demonstration project within the year, using tandem PSC in its own 2m^2 modules in collaboration with The Hong Kong and China Gas Company's energy solution company, Towngas Energy. Other companies, such as UtmoLight, also plan to start producing large-area PSC sequentially from 2024 to 2025.

Demand in China's domestic solar cell market is mainly for ground- and rooftop-mounted power generation projects, which require high conversion efficiency, and demand for film-substrate solar cells, which are limited to applications such as building facades, remains uncertain. As a result, most Chinese companies producing PSC use the glass substrate type, which is intended for use in power generation facilities. While few companies develop film substrate-type PSC, DaZeng, a leader in the field, is expanding its production capacity.

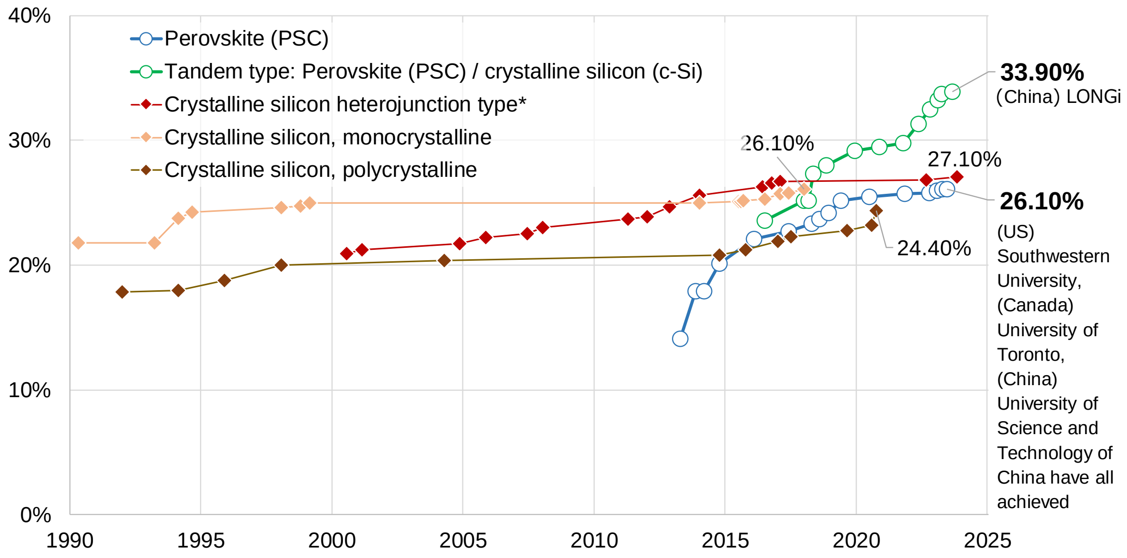
Positioning PSC as a critical technology for decarbonization, the Chinese government has included 50 MW or larger perovskite and tandem solar cells and other next-generation solar cell technologies in a national renewable energy model project starting in September 2023, with a focus on solving durability issues and other key challenges for future large-scale deployment. There may be potential for large-scale power generation demonstration projects using PSC in the future.

4. THE GOAL OF MAJOR CHINESE SOLAR CELL MANUFACTURERS: TANDEM SOLAR CELLS EXCEEDING 30% CONVERSION EFFICIENCY

In contrast to startups that are rapidly scaling up production, major Chinese solar cell manufacturers, which hold a dominant share of the c-Si solar cell market, are aiming to develop tandem solar cells combining c-Si and PSC that exceed 30% conversion efficiency.

Currently, c-Si solar cell technology has matured and is approaching the theoretical conversion efficiency limit of 30%. According to the latest data on laboratory conversion efficiency achievements (Figure 3), while the efficiency of c-Si solar cells has plateaued in recent years, the efficiency of PSC has increased rapidly since its invention. In particular, conversion efficiencies in tandem configurations with c-Si have exceeded 30%.

Figure 3 Change in highest conversion efficiency records for perovskite and crystalline silicon solar cells



*Heterojunction solar cells combine semiconductor materials with different physical properties to increase conversion efficiency.
Source: Compiled by MGSSI based on the National Renewable Energy Laboratory (NREL) "Best Research-Cell Efficiency Chart" (https://www.nrel.gov/pv/cell-efficiency.html) (last accessed: 15:00, May 22, 2024)

As illustrated in Figure 4, most major Chinese solar cell manufacturers have embarked on the development of tandem solar cells combining PSC and c-Si, which hold the potential to achieve conversion efficiencies exceeding the current c-Si limit of 30% and are well-poised for mass adoption. Several companies have already achieved in excess of a 30% conversion efficiency in their labs.

On November 3, 2023, LONGi Green Energy Technology's prototype PSC/c-Si tandem cell achieved a 33.9%

conversion efficiency, which was certified by NREL[4], marking it as the highest globally. Jinko Solar, the leader in global shipment volume, is targeting a conversion efficiency of 34% by 2026, while Trina Solar, ranked second, has been entrusted with multiple R&D projects by the government, including materials, manufacturing equipment and technology, and large-area cell manufacturing technology for PSC and tandem cells. Trina Solar aims to develop a tandem PSC/c-Si cell with a conversion efficiency of 31%.

For these leading Chinese solar cell manufacturers, successful development of high-conversion-efficiency PSC/c-Si tandem solar cells could open up opportunities for mass deployment in large-scale installations such as mega solar projects, while leveraging their existing c-Si solar cell production lines and expertise to advance next-generation solar cell technology—a strategic move that serves dual purposes.

In light of the accelerating R&D into PSC, the China Photovoltaic Industry Association is preparing to establish a committee on perovskite and tandem solar cells within 2024, which will advise on industrial policy, support technology development and demonstration projects, and help establish technical standards.

[4] NREL: National Renewable Energy Laboratory, USA

Figure 4 Tandem perovskite solar cells under development by major Chinese and global companies

Rank*	Country	Company	Conversion efficiency (%)	Cells/module Area (cm^2)	Combination	Progress in development and mass production
3	China	LONGi	33.90%	1.0	PSC/c-Si	Began research and development in 2021; mass production anticipated around 2030. Conversion efficiency of 34.6% was certified by European Solar Test Installation (ESTI) in June 2024
1	China	Jinko Solar	33.24%	n/a	PSC/c-Si	Aiming for over 34% conversion efficiency by 2026
	China	Auner	33.14% 25.45%	n/a 275.6	PSC/c-Si PSC/c-Si	A startup established in 2017. Advancing the development of large-area cells for commercialization and setting up a 100 MW pilot line
6	China	Tongwei	33.08% 23.84%	n/a 220.5	PSC/c-Si PSC/c-Si	Plans to launch a pilot line within 2024. Thinner cells, silver-free electrodes and other technologies under development
5	China	Canadian solar	31.50%	n/a	PSC/c-Si	Developed in collaboration with the Ningbo Institute of Materials Technology & Engineering, Chinese Academy of Sciences, where the conversion efficiency on the left was achieved in the laboratory. Prototyping of large-area cells planned in the future
6	China	Astronergy	31.14%	n/a	PSC/c-Si	Plans to launch a pilot line within 2024
	China	BOAMAX	29.65%	n/a	PSC/c-Si	Parent company Jiangsu Boamax, a publicly listed company specializing in crystalline silicon solar cells, is planning a pilot line
	Japan	KANEKA	29.20%	64.0	PSC/c-Si	Simulations indicate the possibility of achieving a conversion efficiency of 35%
	UK	Oxford PV	28.60%	258.1	PSC/c-Si	Has a mass production plant in Germany and is a leader in the development and mass production of tandem perovskite solar cells, with products using its own cells planned for release on the market by the end of 2024
2	China	Trina Solar	28.53%	16.0	PSC/c-Si	Engaged in several national R&D projects for materials, manufacturing equipment, and large-area cell manufacturing techniques for PSC and tandem solar cells, with the goal of achieving conversion efficiency of over 31%
	China	GCL	27.34% 26.36% 26.34%	2,050.0 17,100.0 2,048.0	PSC/c-Si PSC/c-Si PSC/c-Si	Furthest ahead in the development of large-area modules for commercialization, with plans to mass-produce products with 27% conversion efficiency from 2025. Parent company GCL SI under the GCL Group was ranked 10th globally in solar module shipments in 2023
	Japan	PXP	26.50%	n/a	PSC/CIS	Lightweight and flexible tandem cells combining perovskite and chalcopyrite. Pilot line planned to start operation by the end of 2024
	US	Tandem PV	26.00%	n/a	PSC/c-Si	Raised USD27 million from government support and venture capital by January 2024, and plans to build a manufacturing plant
	China	Renshine Solar	24.50%	20.0	PSC/PSC	The only company in China to develop an all-perovskite tandem type cell
4	China	JA Solar	n/a	n/a	PSC/c-Si	If development of perovskite technology and prototyping proceed smoothly, plans to develop a large-area tandem model with 30% conversion efficiency within 2-3 years
8	China	RISEN	n/a	n/a	PSC/c-Si	Plans to develop modules with 30% conversion efficiency and 850W output by 2027
29	China	HUASUN	n/a	n/a	PSC/c-Si	Advancing construction of a 50 MW-scale pilot line, with prototyping scheduled to begin in 2025

*Based on module shipments worldwide in 2023
Source: Compiled by MGSSI based on National Renewable Energy Laboratory (NREL) "Solar Cell Efficiency Tables (Version 63)" (https://www.nrel.gov/docs/fy24osti/87778.pdf) (last accessed: 15:00, May 22, 2024), SOLARBE GLOBAL "Top PV module companies by shipment volume in 2023" (https://www.solarbeglobal.com/top-pv-module-companies-by-shipment-volume-in-2023/) (last accessed: 15:00, May 22, 2024), and information released publicly by each company.

5. FUTURE PROSPECTS

In May 2024, Fuji Keizai forecasted that, due to the replacement of existing solar cells and the proliferation of high-efficiency PSC/c-Si tandem cells, PSC will enter full-scale mass production in the late 2020s, and the global market, which is dominated by glass substrate type, will grow to approximately 2.4 trillion yen by 2040. In contrast, the Japanese domestic market is expected to initially adopt film substrate types, but glass substrates will gradually become mainstream in the 2030s, with the market size projected to be around 2.33 billion yen by 2040, accounting for approximately 1% of the global total.

Unlike China, where solar applications are for ground and rooftop installations, Japan will focus on uses that leverage the lightness and flexibility of PSC while improving durability during the initial stages of PSC implementation. Chinese companies have a complete c-Si solar cell supply chain, and are in a favorable position to develop and mass-produce glass substrate and tandem type PSC. However, while Chinese companies are focusing on achieving high conversion efficiency, there are concerns that the durability of their cells has not been sufficiently verified, and continuous development and outdoor durability tests will be necessary. To approach the 20- to 30-year lifespan required for power generation projects, there will likely be increased demand for materials and processing technologies including high-quality perovskite materials that lead to improved durability, sealing materials, and coating technologies and facilities—areas in which Japanese companies lead. Over the long term, particularly for domestic companies in the relatively small Japanese market, early development of products and global strategies in anticipation of competition with companies from China and other countries will be necessary. In May 2024, the Ministry of Economy, Trade and Industry announced the convening of a public-private council to expand the introduction of next-generation solar cells and enhance industrial competitiveness, indicating its intention to work with industry in three areas: establishing mass production technologies for PSC, establishing production systems, and creating demand. In this way, the race to develop for the mass adoption phase of PSC is just beginning.