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Harnessing Perovskite Solar Cells from Japan for Global Renewable Energy Transformation

Shuhei Muramatsu, Hiroki Umetsu

Economic & Industrial Research Department

Executive Summary

- Perovskite solar cells (PSCs) are attracting attention as next-generation technology that contributes to expansion of both renewable energy introduction and industrial competitiveness in Japan. Despite competition from overseas companies, Japanese companies have the potential to be competitive across the entire supply chain, from material procurement to manufacturing.
- PSCs, with their advantages of being lightweight, flexible, transparent, and highly efficient in conversion, are expected to be deployed in a wide range of installation sites. However, to realize their implementation, it is necessary to reduce manufacturing costs, extend their lifespan, and improve conversion efficiency through enhanced R&D and mass production.
- For their widespread adoption, it is essential to deepen the development and demonstration of use cases in collaboration with manufacturers and users, and to ensure policy-driven demand in the early stages. Furthermore, to secure the continuous and stable demand required for manufacturers' investment decision-making in mass production, active expansion into the global market should also be pursued.

In pursuit of the Japanese government's goal of achieving green transformation, expectations are rising for perovskite solar cells (PSCs), which have features that contribute to the further expansion of renewable energy introduction, and in which Japanese companies possess high technological capabilities, including in materials and components. In our DBJ Research No.420 "Innovative Technologies Paving New Possibilities for the Power System" report (August 9, 2024), PSCs, along with energy storage systems such as batteries, long-duration energy storage (LDES) and demand response (DR), were identified as notable innovative technologies in the power sector. This article organizes the current technological and policy trends related to PSCs and outlines the direction for the widespread adoption of PSCs in Japan and the rest of the world from the perspectives of R&D, mass production, and demand-side factors.

1-1. Expectation of Solar Power Generation

Solar power generation is one of the most rapidly expanding renewable energy sources both domestically and internationally, due to its relative ease of implementation and low levelized cost of electricity (LCOE). Further expansion is expected. The International Energy Agency (IEA) estimates that achieving carbon neutrality by 2050 will require solar power generation capacity to be five times greater by 2030 and fifteen times greater by 2050 compared with 2022 levels. This means that solar power would account for more than 40% of the total power generation mix by 2050. In Japan, the 6th Strategic Energy Plan sets a target of introducing approximately 110GW of solar power by 2030, necessitating an additional 40GW of solar power generation over the next five years.

1-2. Challenges of Silicon-Based Solar Cells

On the other hand, the currently dominant silicon-based solar cells face several challenges, including the decreasing availability of installation sites, increasing grid congestion, and a heavy reliance on a single country for the manufacturing supply chain. Approximately three-quarters of Japan's land area is covered by forested mountains, and the amount of solar panel installations per unit of flat land is already the highest among major countries, leaving little room for additional installations. Moreover, the installation of solar cells on steep slopes has led to issues such as landslides and the deterioration of scenic views, presenting challenges for regional coexistence.

Additionally, the widespread installation of solar power plants in areas with underdeveloped transmission and distribution networks, facilitated by subsidies and off-site power purchase agreements, has necessitated strengthening these networks to connect solar power plants with demand centers, increasing integration costs. While installing panels at electricity consumption sites to expand self-generation and consumption is an effective way to alleviate grid congestion, suitable rooftops that can support the weight of conventional silicon-based panels are limited.

Furthermore, the supply chain for conventional silicon-based cells is highly dependent on a single country, China, particularly for silicon procurement, wafer manufacturing, and panel assembly, with respective dependency rates of 70%, 90%, and 70%, according to the IEA. This reliance poses a global challenge to the resilience of the solar panel supply chain. In addition, conventional silicon-based cells have a high proportion of silicon costs in their overall manufacturing cost, leaving little room for cost reduction through technological innovation or improvements in the manufacturing process. This presents another challenge for their further expansion.

1-3. Expectation for PSCs

Challenges are addressed by the PSCs, which utilize a compound with a crystal structure known as "perovskite" (Figure 1). Compared with conventional silicon-based solar cells, PSCs offer superior flexibility, lightweight properties, and transparency, and theoretically, they have a higher conversion efficiency. These attributes make it possible to install PSCs in locations where weight-bearing capacity or shape has previously made the installation of silicon-based solar cells difficult.

Particularly, if PSCs are installed on the roofs, walls, and windows of residential, office, and factory buildings—where power consumption is high—and self-consumption of electricity increases, this can help alleviate grid congestion and reduce overall integration costs. Self-consumption is also beneficial for consumers, as it eliminates transmission charges and renewable energy surcharges that arise from using the transmission and distribution network, thereby lowering electricity costs.

Furthermore, Japan possesses competitive technologies in PSCs and in the production of iodine, a major component, leading to reduced dependency on a single region in the supply chain. In addition, in the medium to long term, the manufacturing costs of PSCs are expected to decrease compared with single-junction silicon-based solar cells. PSCs require less material, and the material costs are estimated to be about half that of conventional silicon-based cells. The manufacturing process of PSCs primarily involves coating and printing materials, making it easier to achieve economies of scale. Furthermore, while the production of conventional silicon-based cells requires heating to around 1,700℃ to extract high-purity silicon from silica, the manufacturing of PSCs only requires heating to about 150℃. As a result, the energy consumption during production is less than one-tenth of that for conventional silicon-based cells, leading to potential reductions in both manufacturing costs and greenhouse gas emissions.

Figure 1 Challenges of Conventional Silicon-Based Solar Cells and Expectations for Perovskite Solar Cells

Reduced Installation Capacity	Grid Congestion	Fragile Supply Chain	High Manufacturing Cost
Current Challenges			
・Leaving little room for additional installations of solar panels in Japan	・Grid congestion and output suppression caused by solar installations in remote areas, increasing the need for grid upgrades	・Heavy reliance on one country for the whole supply chain	・Little room for cost reduction, given the high silicon content in manufacturing costs
Solution	Solution	Solution	Solution
a			
・PSCs' characteristics allow for installation on roofs and windows where conventional silicon-based cells struggle.	・Installing PSCs at consumption sites can reduce grid stress and avoid costly upgrades.	・Japanese companies are competitive in PSCs, and Japan is a top global producer of iodine, a key component.	・PSCs use fewer materials and energy, potentially halving the material cost compared with conventional silicon-based cells.

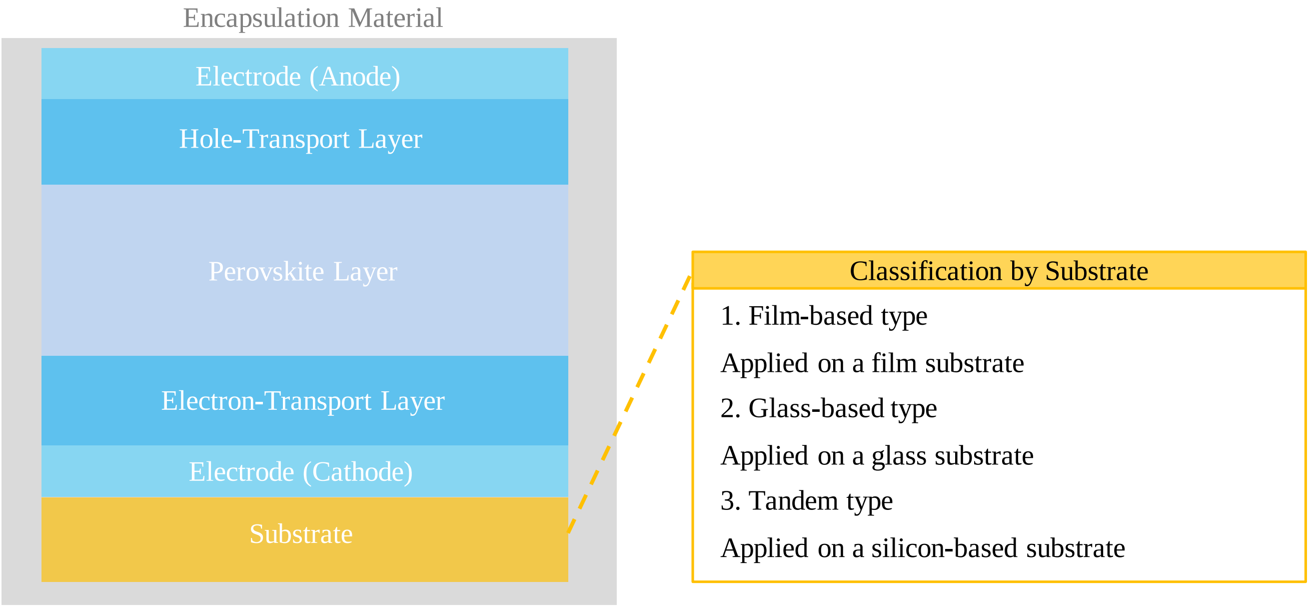
(Note) Created by DBJ.

Given the importance of PSCs in achieving carbon neutrality by 2050, the Japanese government is also developing a framework for policy support. In 2023, Prime Minister Kishida announced plans to establish a gigawatt-scale mass production system for PSCs before 2030. In response, the Ministry of Economy, Trade, and Industry (METI) outlined a policy to build a domestic supply chain and implement PSCs in society through R&D, mass production, and demand creation. Specifically, on the production side, the Green Innovation Fund (GI Fund), is providing support for the technological development of PSCs. Additionally, the "GX Supply Chain Development Support Program" is planned to support capital investment in the development of mass production systems. Regarding demand creation, the establishment of a new category for PSCs under the current feed-in tariff (FIT) and feed-in premium (FIP) schemes is being considered. As a reference, the FIT scheme ensures that electricity generated from renewable sources is purchased at a fixed price over a long term, while the FIP scheme provides a premium on top of the market price, incentivizing renewable energy producers.

2. Structure, Classification, and Corporate Trends of PSCs

PSCs are manufactured by applying a very thin perovskite layer, approximately 1μm (0.001mm) thick, along with electrodes, a hole-transport layer, and an electron-transport layer, onto a substrate, and then coating it with an encapsulation material. Depending on the substrate material, there are three types: (1) film-based, (2) glass-based, and (3) a tandem type that uses an existing silicon-based substrate (Figure 2).

Figure 2 Structure of PSCs



(Note) Created by DBJ.

1. **Film-based type**: The film-based type has relative difficulty ensuring durability and mass production, but its light weight and flexibility allow for a wider range of installation sites and lower costs related to transportation, installation, and removal.
2. **Glass-based type**: In contrast, the glass-based type is heavier and lacks flexibility compared with the film-based type, but ensuring durability and mass production is easier.
3. **Tandem type**: The tandem type uses an existing silicon-based substrate onto which the components of the perovskite solar cell are applied. While this type has higher manufacturing costs and loses characteristics such as light weight, flexibility, and transparency, it achieves higher conversion efficiency by absorbing a wider range of wavelengths.

Looking at corporate development trends, Japanese companies mainly focus on the film-based type (e.g., EneCoat Technologies, Sekisui Chemical, Toshiba) and the glass-based type (e.g., Aisin, Kaneka, Panasonic), while Chinese and European companies are primarily concentrating on the tandem type. In addition, many Japanese companies are also developing related components. For example, Canon is working on coating materials for PSCs, Toray on encapsulation materials, Nippon Sheet Glass and AGC on glass substrates, and Nissan Chemical on hole-transport materials. Moreover, Chiba Prefecture’s and Niigata Prefecture’s combined production of iodine, the primary raw material for the perovskite layer, makes Japan the second-largest producer in the world after Chile.

3. Potential Installation Sites for PSCs

For the widespread adoption of PSCs, two primary directions are envisioned: (1) utilizing the characteristics of light weight, flexibility, and transparency to install PSCs in locations where conventional silicon-based solar cells are difficult to install, focusing on film-based and glass-based types, and (2) replacing existing silicon-based installations with PSCs that offer higher conversion efficiency, particularly focusing on the tandem type.

3-1. Lightweight and Flexible Installations

Potential candidates for primary direction (1) above include roofs of prefabricated buildings, gymnasiums, and older wooden houses with low load-bearing capacity. Additionally, while there are concerns about limited sunlight exposure compared with rooftop installations, the installation of glass-based PSCs on building windows and film-based PSCs on walls is also promising. In such cases, considering the difficulty and cost of installation, maintenance and removal, it is expected that low-rise buildings such as houses will be prioritized, followed by high-rise buildings. The introduction of PSCs in these buildings will play an important role in achieving net zero energy houses and buildings (ZEH and ZEB) for residential and office buildings. Beyond buildings, other promising applications include installations over roads, carports, and sound barriers along highways.

Additionally, agrivoltaics (dual use of land), which contributes to the expansion of renewable energy in Japan where flat land is limited, is also a promising application. In agrivoltaics, farmland-sited solar panels are installed above ground level, supported by columns. However, the use of silicon-based cells has faced challenges such as the need for strong supports and mounts to withstand the load, and the reduction of sunlight leading to limited crop varieties and decreased yields. The lightweight and transparent characteristics of PSCs could address these challenges. Moreover, installation on vehicle bodies and windows could initially focus on large, simple-shaped vehicles like trucks and buses, and later extend to passenger cars, supporting the power supply for electric vehicles (EVs).

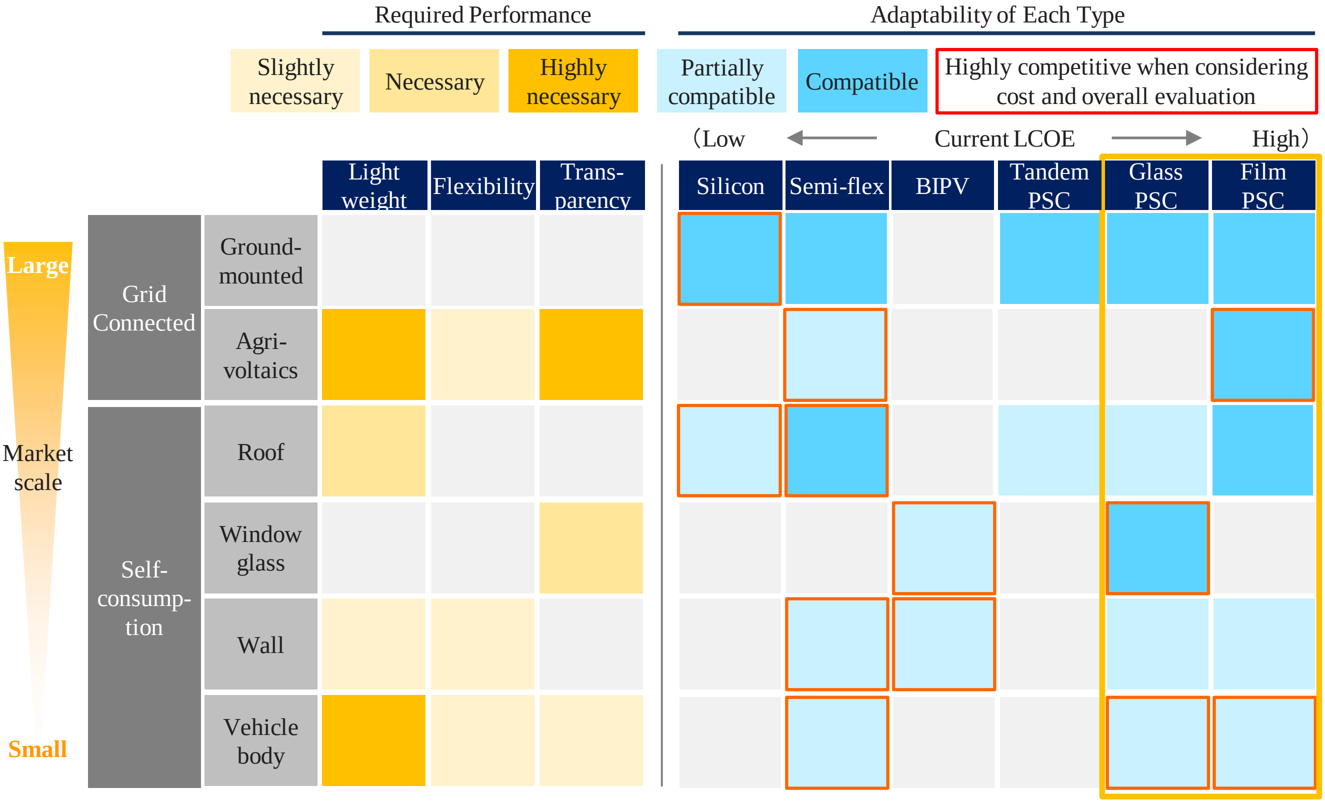
3-2. Replacing Existing Installations

As for primary direction (2) above, potential installation sites include open land and roofs with sufficient load-bearing capacity. Considering solar panels' approximately 20-year lifespan, many large-scale solar installations introduced after policy support by Japan in 2009 will reach the end of their operational life around 2030, presenting significant opportunity for replacement with PSCs.

3-3. Competition in the Adoption of PSCs

However, the above are merely potential installation sites for PSCs. To achieve widespread adoption, it is essential to secure cost competitiveness through further technological development. Currently, the LCOE is already being reduced for semi-flexible silicon-based cells, which are lightweight and can be bent to some extent without using glass or aluminum frames, as well as for building-integrated photovoltaics (BIPV) that offer good aesthetics and maintain a certain degree of transparency by arranging the cells strategically. This suggests a high possibility of competition between perovskite solar cells and these alternatives in various applications (Figure 3-1).

Figure 3-1 Competitiveness of Solar Cell Types by Installation Site

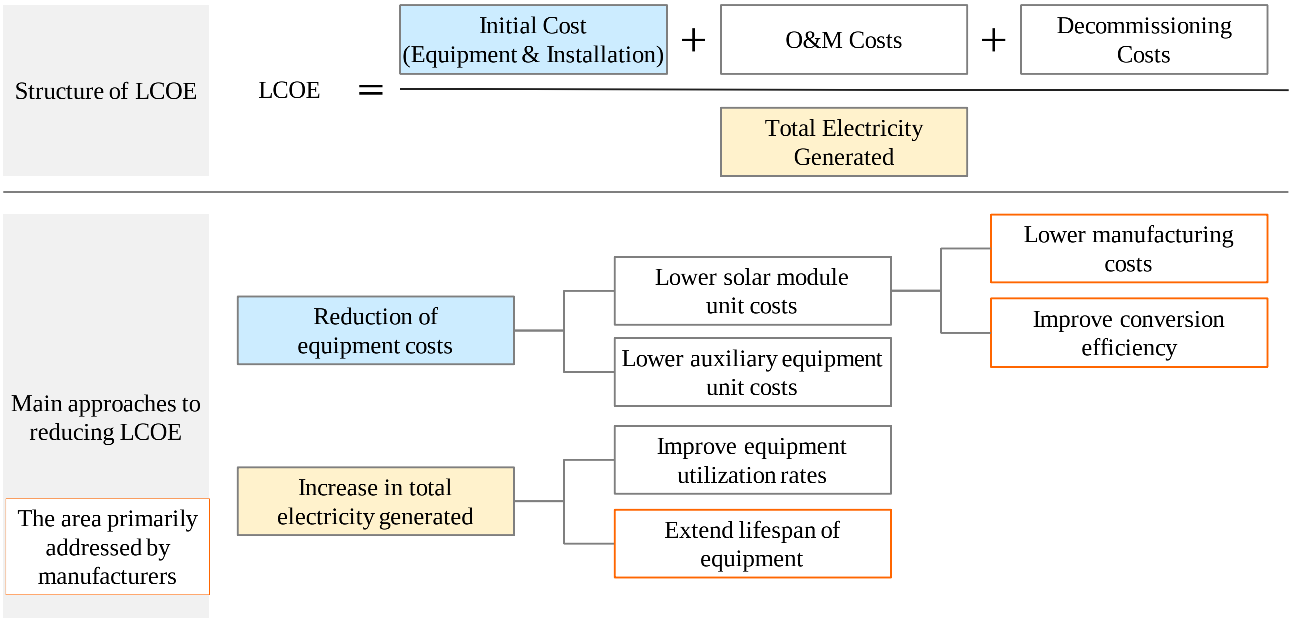


(Note) Created by DBJ.

Specifically, regarding the film-based type, while its characteristics of light weight, flexibility, and transparency are strengths, semi-flexible silicon-based cells have also achieved a certain level of performance in terms of weight and flexibility, potentially competing when it comes to installation on roofs and walls. Additionally, although the glass-based type boasts high transparency, it may face competition from building-integrated photovoltaics (BIPV) that also offer adequate transparency when installed on window glass. In any case, for PSCs to outperform conventional silicon-based cells and expand their market, it is essential to reduce the LCOE.

The LCOE is calculated by dividing the total costs by the total amount of electricity generated and is generally used for analyzing electricity generation costs. Effective approaches to reducing LCOE include lowering manufacturing costs, improving conversion efficiency to reduce equipment costs, and increasing the total amount of electricity generated by enhancing durability (extending the lifespan). Therefore, it is crucial for PSC manufacturers to strengthen R&D and focus on mass production to achieve these three approaches (Figure 3-2).

Figure 3-2 Structure and Approaches to Reducing LCOE



(Notes)
1. Created by DBJ.
2. The structure of LCOE is described excluding discount rates, which do not significantly affect this analysis.

4. Necessary Efforts for Future Expansion of PSCs

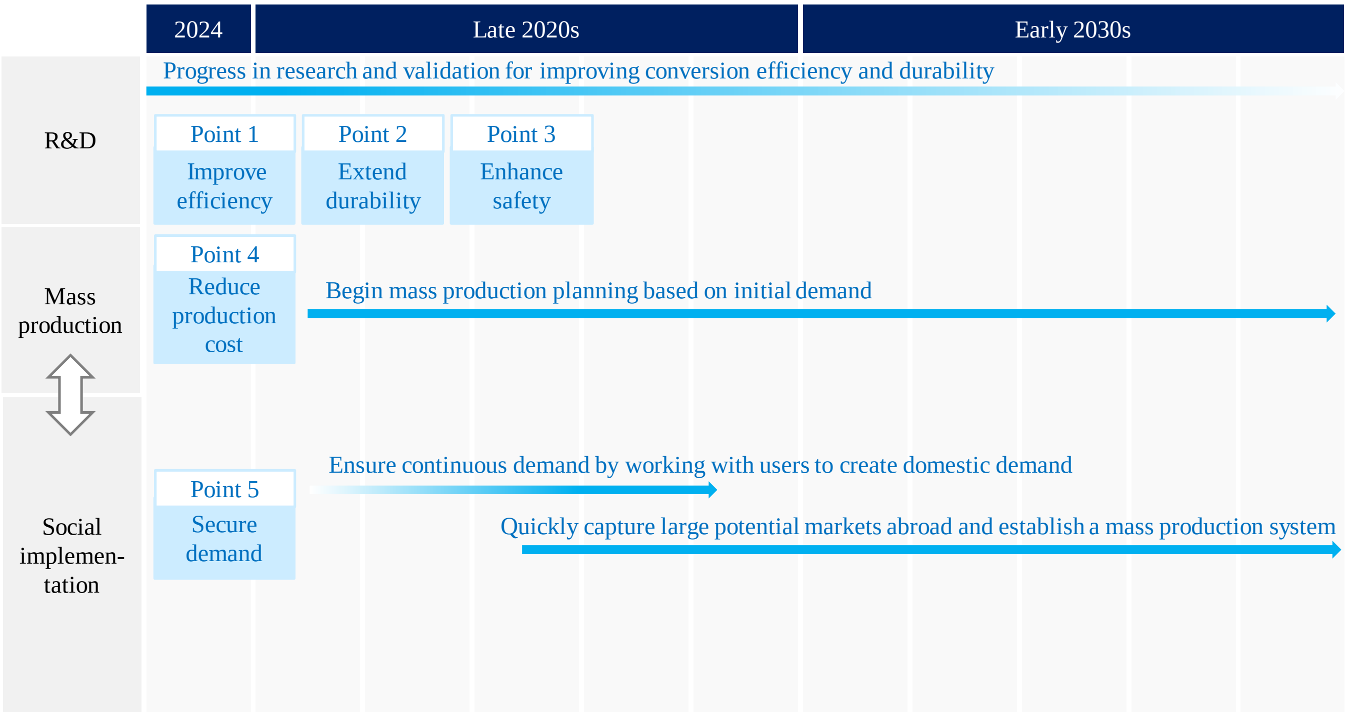
Based on previous discussions, for the widespread adoption of PSCs and to enhance the competitiveness of Japanese manufacturers, it is essential to improve conversion efficiency (Point 1), extend lifespan (Point 2), and enhance safety (Point 3) through continuous R&D. Additionally, establishing a production system early on and reducing manufacturing costs through mass production (Point 4) is crucial. To facilitate mass production investments by manufacturers, securing reliable buyers and ensuring continuous demand (Point 5) are also necessary (Figure 4-1).

4-1. Research and Development (Points 1, 2, 3)

First, regarding conversion efficiency, while tandem-type cells in the R&D phase have reached around 29% efficiency and glass-type cells around 26%, module-based efficiency for practical application remains at approximately 20% for tandem-type and 14% for glass-type in small sizes (200-800 cm^2). Further research and development are needed to reach the theoretical target of 30% or higher.

In terms of durability, while progress is being made, perovskite solar cells are vulnerable to oxygen and water in the atmosphere. Currently, high-cost encapsulation materials are required to protect them, which drives up the overall product cost. Additionally, photodegradation and thermal degradation due to sunlight are significant challenges in extending the lifespan. Going forward, it will be essential to improve the durability of each layer and reduce the cost of encapsulation materials.

Figure 4-1 Timeline for Future Initiatives



(Note) Created by DBJ.

Furthermore, perovskite solar cells contain lead, which is second only to iodine in quantity. As installations expand to residential areas and farmland, it will be important to either prove that the lead content meets the standards set by regulations like the EU's RoHS directive or develop lead-free alternatives using materials such as tin or germanium.

4-2. Securing Demand (Point 5)

As mentioned earlier, while PSCs have high potential compared with existing silicon-based cells, they are still in the process of technological development and cost reduction, and their commercial deployment is yet to come. For widespread adoption, it will be necessary to deepen the development and validation of use cases through collaboration between manufacturers and users, and initially, policy-driven demand assurance will be crucial.

Regarding manufacturer–user collaboration, currently, manufacturers and companies in the electricity, real estate, and telecommunications sectors are working on developing and reducing the costs of installation and maintenance methods, as well as verifying durability, with specific use cases in mind. In some cases, considerations related to commercialization are also progressing, and these pioneering users are likely to support the creation of initial demand (Figure 4-2).

Figure 4-2 Examples of Manufacturer–User Collaborations

Manufacturer × Municipality			
Sekisui Chemical	Tokyo Metropolitan Government	2023	Demonstration experiment at wastewater treatment facilities
Manufacturer × Construction / Real Estate Companies			
Sekisui Chemical	JR West Japan	2025	Installation at station locations
Toshiba	Tokyu Corporation	2023	Demonstration experiment within station
EneCoat	Mitsui Fudosan	2023	Research on utilization in housing
Manufacturer × Energy Companies			
Sekisui Chemical	TEPCO	2028	Installation in high-rise buildings
Sekisui Chemical	JERA	2023	Demonstration experiment at thermal power plants
Manufacturer × Automotive Companies			
EneCoat	Toyota	2023	Research on utilization in vehicles
Manufacturer × IT / Telecommunications companies			
EneCoat	KDDI	2023	Demonstration experiment at base stations

(Note) Created by DBJ.

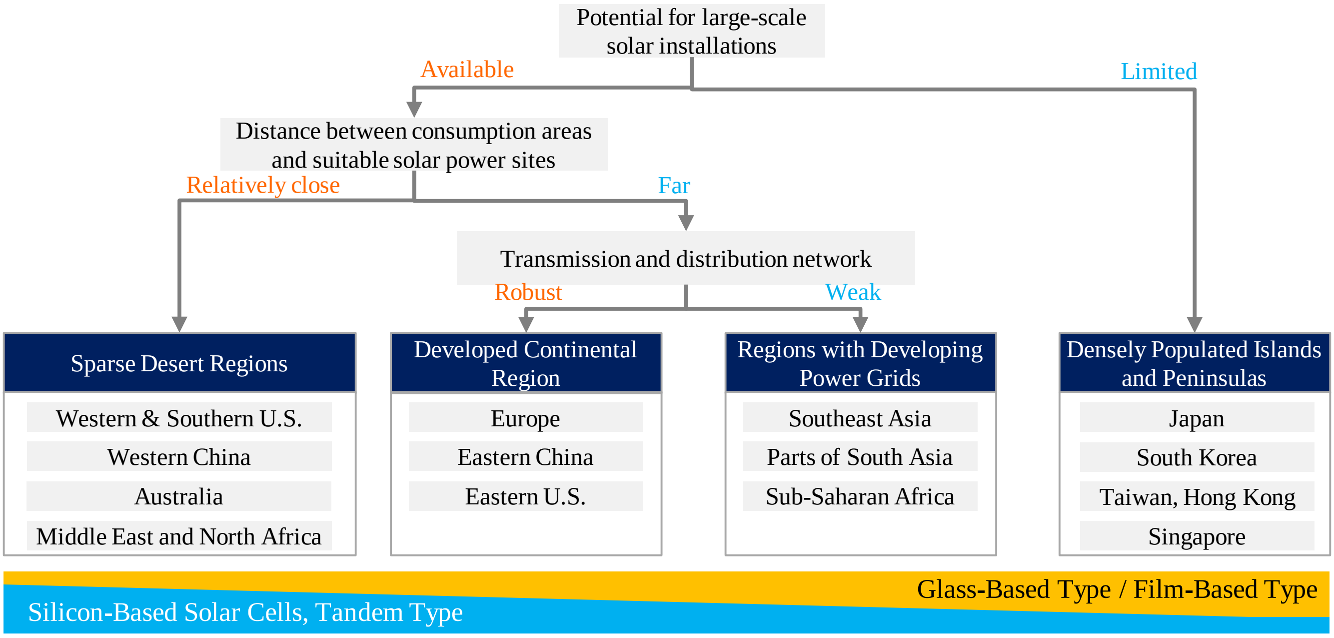
Moreover, to ensure that these pioneering efforts do not remain isolated, strategic institutional design and policy support are essential. Specifically, expanding private sector adoption through subsidies at the time of introduction, as implemented in traditional renewable energy with feed-in tariff and feed-in premium schemes for self-consumption, should be considered. Additionally, prioritizing installations in government- and municipality-owned facilities, as well as various infrastructure assets such as roads and railways, could be effective.

If the introduction of PSCs gains momentum in the future, financial institutions’ support through corporate finance or project finance is expected. However, it should be noted that, in the case of roofs, which constitute a key initial installation site, if the business operator rents the roof from the building owner, there is a possibility that PSCs may need to be removed if the building is sold to a third party or if the owner goes bankrupt, as the business operator does not hold rights that can be asserted against third parties. Additionally, for installations on walls or windows, there is a higher risk of sunlight obstruction due to new buildings being constructed nearby compared with rooftop or ground-mounted installations; so, it is essential to monitor construction plans in the surrounding area.

Furthermore, to secure continuous and stable demand, which is essential for manufacturers to make mass production investments and ultimately expand profitability, it is important to actively explore global markets, not just within Japan. According to the IEA’s “World Energy Outlook” (WEO), with projections based on silicon-based solar cells, Japan’s share of global solar power generation in 2050 is estimated to be only around 1%, indicating that the largest markets are overseas. Additionally, for new applications unique to PSCs, it will be necessary to pay attention to the development of overseas markets, particularly in regions with geographical conditions similar to Japan, such as South Korea, Taiwan, and ASEAN countries.

Among overseas markets, the suitability of either existing silicon-based or perovskite types can be classified based on the availability of land for large-scale solar installations, the distance between power plant sites and consumption areas, and the robustness of existing transmission and distribution networks (Figure 4-3). First, existing silicon-based and tandem types are considered suitable for areas where ample land for large-scale solar installations is available near power consumption areas or where the transmission and distribution networks between large-scale solar sites and consumption areas are already well-developed. In these areas, where additional costs for strengthening the grid are minimal, the pure conversion efficiency of the panels becomes important. This classification mainly includes regions like the western United States, Australia, and the Middle East, which have high solar irradiance and desert or steppe climates with available land near cities, as well as Europe and China. In these regions with high potential for mega solar installations, hydrogen production projects utilizing tandem perovskite solar cells are also expected to emerge.

Figure 4-3 Categorization of Potential Deployment of PSCs based on Regional Conditions



(Note) Created by DBJ.

On the other hand, <u>the potential of glass-based and film-based types can be realized in areas where the additional costs for grid enhancement would be significant if large-scale solar installations were introduced, or in areas with limited potential for large-scale solar installations</u>. For example, in Southeast Asia and South Asia, which have fragile grids and face increasing electricity demand due to economic growth, the introduction of large-scale solar projects that burden the grid could lead to rising system costs. Therefore, the introduction of glass-based and film-based types, particularly in large metropolitan areas like Delhi, Jakarta, and Manila, where populations are dense and electricity demand is high, is expected to secure supply capacity while reducing the integration costs. Currently, Southeast Asia and South Asia experience significant population concentration, with ten megacities already having populations exceeding 10 million. The demand for film-based and glass-based types is expected to increase in line with further urbanization and economic growth.

Additionally, the installation of glass-based and film-based types in urban areas is likely to be a practical solution in countries like South Korea, Taiwan, and Singapore, where the land area or the proportion of flat land is limited, just like in Japan, and the potential for mega solar installations is constrained relative to electricity demand.

4-3. Mass Production (Point 4)

Alongside securing demand both domestically and internationally, it is crucial for manufacturers to establish a mass production system early on to reduce costs and ensure supply. However, investing in mass production at this stage carries significant risks due to the short demonstration periods and the still-developing mass production technologies. Therefore, the provision of risk capital by financial institutions and robust government support are necessary. In the medium-to-long term, collaboration among companies should also be considered to achieve the social implementation of PSCs. In the short term, there are certain hurdles to building such collaboration, given that each company uses different substrates and membrane-forming methods. By pooling their expertise and financial resources related to PSCs, they could build a system that allows for continuous scale expansion.

Conclusion

As discussed in DBJ Research No. 420, “New Possibilities for the Power System Created by Innovative Technologies” (August 9, 2024), the power system is facing the difficult challenge of balancing the increased electricity demand driven by electrification and digitalization with the need to reduce GHG emissions from electricity. PSCs, which were highlighted in this report, are a critical technology that can help address this challenge. Given that PSCs are a form of variable renewable energy (VRE), where power generation fluctuates depending on weather and time of day, the evolution of DR and energy storage technologies will also be necessary for their smooth integration into the power grid.

Realization of a society with PSCs and a transition in the power system will require strategic institutional design, policy support, bold efforts by users and manufacturers, and measures of financial support. These crucial elements are expected to enhance the mass production of PSCs in Japan and accelerate the early adoption of PSCs all over the world.

Appendix
Characteristics of Various Types of Solar Cells

Type		Major country	Expansion of installation sites: Light weight	Expansion of installation sites: Flexibility	Expansion of installation sites: Transparency	Reduction of LCOE ($/MWh): Durability	Reduction of LCOE ($/MWh): Conversion efficiency	Reduction of LCOE ($/MWh): Manufacturing cost	Technical maturity
PSCs	Film-based	Japan China	◎	◎	◎	△ or ◎ (Under research)	△ or ○ (Under research)	△ or ◎ (Mass production next)	△
PSCs	Glass-based	Japan China	△	×	◎	○ or ◎ (Under research)	△ or ○ (Under research)	△ or ◎ (Mass production next)	○
PSCs / Silicon-based	Tandem	China U.K.	× or ○ (Could improve with the use of 'semi-flexible')	× or ○ (Could improve with the use of 'semi-flexible')	×	○ or ◎ (Under research)	○ or ◎ (Under research)	△ or ◎ (Mass production next)	○
Silicon-based	Existing	China	×	×	×	◎	○ (Already near limit)	○ (Already near limit)	◎
Silicon-based	Semi-flexible	China	○	○	×	○ or ◎ (Under research)	○	○	○
Silicon-based	BIPV	China Japan	×	×	○	○ or ◎ (Under research)	△ or ○ (Under research)	○	○

(Notes)
1. Created by DBJ.
2. Legend: ◎ = Excellent, ○ = Good, △ = Needs Improvement, × = Unsatisfactory

Contact: Economic & Industrial Research Department, Development Bank of Japan
e-mail：report@dbj.jp