# Comparative Study of Photovoltaic Technologies and Energy Storage Systems of Different Scales

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**Abstract.** Driven by the global energy transition and the goal of carbon neutrality, photovoltaic power generation has become the core force in the development of renewable energy. However, its intermittency and volatility pose challenges to the stable operation of the power grid. This paper systematically studies the compatibility of different-scale photovoltaic technologies (household, community sharing, and utility-scale power stations) with energy storage systems, and explores their differentiated characteristics in terms of technology, economy, and policy. The research shows that residential rooftop systems need to address issues of space limitation and cost, while building-integrated photovoltaic (BIPV) and intelligent management are the future directions; community sharing projects achieve energy democratization through multi-energy complementarity and energy storage optimization, but rely on policy coordination; utility-scale power stations, although having scale benefits, still need to overcome technical bottlenecks such as the stability of perovskite cells and the adaptability to the power grid. The research results provide a theoretical basis for the scientific matching of photovoltaic technologies and energy storage, and are of great significance for promoting the grid integration of high proportions of renewable energy and achieving a low-carbon energy transition.

**Keywords:** Photovoltaic Technology; Energy Storage System; Scale Difference; Energy Transition.

## 1 Introduction

Driven by the global energy transition and the goal of carbon neutrality, photovoltaic power generation has become the core force in the development of renewable energy. However, different application scales (such as residential, industrial and commercial distributed, and centralized power stations) have significant differences in their roles in the energy system, and differentiated energy storage solutions are needed to achieve stable power supply. With the rapid increase in the penetration rate of photovoltaics, its inherent intermittency and volatility pose severe challenges to grid operation, such as unstable grid frequency caused by large-scale grid connection (like the "duck curve" problem in Germany) and the phenomenon of power curtailment in regions with abundant sunlight resources (such as in the northwest of China, where the curtailment rate has reached 5% to 10%), which is due to insufficient capacity for absorption.

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Energy storage systems can effectively smooth out fluctuations and improve the absorption efficiency. At the same time, different application scenarios have differentiated requirements for energy storage technologies: residential and distributed photovoltaic systems usually require energy storage to have high safety and long lifespan (such as Tesla Powerwall) to support self-generation and self-consumption; centralized power stations pay more attention to the low cost per unit of large-scale energy storage (such as pumped storage and sodium-sulfur batteries), to meet peak load regulation and frequency regulation requirements; in addition, emerging application scenarios such as photovoltaic hydrogen production and microgrids have further expanded the diverse requirements for energy storage power and capacity. In this context, how to scientifically compare the compatibility of different-scale photovoltaic technologies and energy storage systems, and optimize their technical and economic performance, has become a key issue in promoting the grid connection of a high proportion of renewable energy and achieving a low-carbon energy system.

This paper systematically studies the current development status of photovoltaic technology, the differentiated characteristics of the three application modes (residential/community/utilities), and their technical challenges. By analyzing the latest breakthroughs in crystalline silicon, thin film, and perovskite photovoltaic technologies, and comparing the costs, performance, and policy requirements in different application scenarios, it reveals the key issues in efficiency improvement, cost reduction, and large-scale application of photovoltaic systems. The research results provide important references for photovoltaic technology selection and have positive significance for promoting the clean energy transition and achieving the dual carbon goals.

## 2 Current PV Technologies

In recent years, photovoltaic technology has witnessed rapid development. Its photoelectric conversion efficiency has been continuously improving while costs have been steadily decreasing. At the same time, new materials and structural designs have been constantly emerging. The progress in this field is attributed to the innovative work of several top research teams worldwide. Through groundbreaking research, they have solved the key problems in the development of photovoltaic technology, driving the transformation of the entire industry.

In the crystalline silicon solar cell field, the PERC (Passivated Emitter and Rear Cell) technology developed by the Martin Green team from the University of New South Wales in Australia has significantly enhanced the carrier collection efficiency by optimizing the back passivation layer of the battery, achieving a production efficiency of 23%-24%. This breakthrough has greatly reduced the cost of photovoltaic power generation, making PERC technology quickly become the mainstream in the market [1]. This technology also reduces electron recombination losses, increasing the power output of the module by 10-15W, significantly improving the investment return of power stations. Moreover, PERC cells are highly compatible with existing production lines, with low enterprise renovation costs, accelerating the industrialization process.

The TOPCon (Tunnel Oxide Passivation Contact) technology proposed by the Fraunhofer Institute for Solar Energy Systems in Germany achieves excellent surface passivation through the introduction of an ultra-thin oxide silicon layer. The laboratory efficiency has exceeded 26% [2]. This technology has a higher theoretical efficiency limit (28.7%) and provides a new idea for breaking through the efficiency bottleneck of crystalline silicon cells. Its low-temperature process characteristics can reduce energy consumption, and the double-sided rate can reach over 85%, which is particularly suitable for high-reflection environments such as desert power stations. The LeTID attenuation rate of TOPCon cells is lower than that of PERC, and its long-term reliability is better.

The HJT (heterojunction) battery developed by Panasonic of Japan and CSEM of Switzerland combines the advantages of amorphous silicon and crystalline silicon. Domestic enterprises have achieved a production efficiency of over 25% [3]. Its dual-sided power generation feature can increase the system power generation by more than 10%, with a temperature coefficient as low as -0.25%/℃, and it has obvious advantages in power generation under high-temperature conditions. The HJT battery process steps are few (only 4 main processes are required), and it is naturally suitable for thinning (it can be reduced to below 100 μm). There is great potential for cost savings in silicon material. Moreover, its symmetrical structure brings low mechanical stress, making it more suitable for the development of flexible components.

In the field of thin-film solar cells, the NREL laboratory in the United States has continuously optimized the interface engineering of CdTe (cadmium telluride) cells. In 2020, the efficiency of these cells was increased to 22.1% [4]. They have excellent low-light performance (the average daily power generation duration is 1-2 hours longer than that of crystalline silicon) and significant cost advantages, with a system balance cost (BOS) reduction of 15%. The temperature coefficient of the CdTe module is only -0.21%/℃, making it particularly suitable for high-temperature areas. Its full-vacuum preparation process is completely lead-free, significantly enhancing environmental friendliness. Additionally, the CdTe film only requires a thickness of 2 μm, and the material utilization rate is 100 times that of crystalline silicon.

The CIGS (copper indium gallium selenium) battery developed by ZSW in Germany achieved a record efficiency of 23.4% through gradient regulation of components [5]. Its flexible nature provides new possibilities for building-integrated photovoltaics, with a bending radius of less than 5mm, suitable for special scenarios such as curved roofs. The CIGS battery can still maintain an efficiency of over 85% under low light conditions (200W/m$^2$), making it suitable for urban environments. By using stainless steel or polyimide substrates, the component weight can be reduced to 2kg/m$^2$, significantly lowering the installation cost. Its bandgap adjustable range (1.0 - 1.7 eV) makes it an ideal bottom cell for tandem batteries.

The most revolutionary breakthrough comes from perovskite solar cells. The team of Henry Snaith from the University of Oxford was the first to report high-efficiency perovskite cells in 2012, solving the stability problem of organic-inorganic hybrid perovskite materials [6]. This technology is prepared by a solution method, and the production cost can be reduced by more than 50% compared to crystalline silicon. The perovskite material has an absorption coefficient of up to 10^5 cm^-1, and the active layer thickness only needs to be 300-500 nm, with very little material consumption. Its band gap can be precisely controlled (1.5-2.3 eV), providing an ideal choice for the design of multi-junction tandem cells.

UNIST in South Korea has increased the efficiency of a single-junction perovskite cell to 25.7% through interface engineering [7]. The 2D/3D heterostructure they developed extended the device's operational life to over 1000 hours (at 85°C). The new passivation technology raised the open-circuit voltage to 1.2V, approaching the theoretical limit. The team also achieved an efficiency of 18% for a 30×30 $cm^2$ module, laying the foundation for industrialization. Through component engineering (such as the mixture of FA and MA cations), the photothermal stability of the cells was significantly improved.

The perovskite/silicon tandem solar cell jointly developed by EPFL in Switzerland and KAUST in Saudi Arabia has set a world record of 33.7% [8]. This technology enhances the current of the silicon cell to 19.5 $mA/cm^2$ through an optical coupling design, approaching the theoretical maximum. They developed ultra-thin composite electrodes (<100 nm) that maintain high conductivity while achieving over 95% light transmittance. The new interconnection structure enables a voltage superposition efficiency of 98% for sub-cells and a module area loss of less than 5%. This technology is expected to achieve a production efficiency of over 28% within the next five years.

In the field of emerging technologies, the Brabec team from the FAU University in Germany has developed an organic photovoltaic (OPV) cell with an efficiency exceeding 19% [9]. The solution processing characteristics have opened up new avenues for low-cost flexible electronics. The roll-to-roll production cost can be reduced to 0.3 dollars/W. The semi-transparent nature of the OPV cell (visible light transmittance > 40%) makes it perfectly suitable for agricultural photovoltaic scenarios. By developing new non-fullerene receptor materials, the device thermal stability has been enhanced to 80°C/1000 hours. Its weight is only 0.5 $kg/m^2$, making it particularly suitable for on-board mobile energy applications.

The quantum dot solar cells developed by the Edward Sargent team at the University of Toronto achieved an efficiency of 18.1% through band engineering [10]. Their tunable bandgap property (1.3-1.8 eV) gives them unique advantages under specific spectral conditions, and their underwater application efficiency can reach over 15%. The new ligand exchange technology has increased the carrier diffusion length to 300 nm, breaking through previous limitations. The near-infrared quantum dots they developed can extend the spectral response range to 1400 nm, and the theoretical efficiency of the single-junction cell can reach 45%. The quantum dot ink prepared by solution method is suitable for large-scale printing and has great potential for production costs.

# 3 PV and ESS Deployment Across Scales

## 3.1 Residential Rooftop Systems

Residential rooftop photovoltaic power generation and energy storage systems are becoming an important solution for distributed energy. Their typical configuration includes monocrystalline silicon photovoltaic panels, solar charging controllers, energy storage batteries, and bidirectional inverters, among other core components. Modern residential photovoltaic systems, such as those represented by Tesla solar roofs, use high-efficiency monocrystalline silicon photovoltaic panels to convert solar energy into direct current. The conversion efficiency can reach over 20%, maximizing the generation of electricity from the limited roof area. The system is equipped with an intelligent solar charging controller that optimizes charging efficiency in real time using the MPPT (Maximum Power Point Tracking) algorithm, and also has overcharge protection, which can extend the battery life. The energy storage unit typically uses deep-cycle lead-acid batteries or more advanced lithium-ion batteries, with a storage capacity of generally 10-20 kWh, capable of meeting the household's nighttime electricity demands. The bidirectional inverter is the core of the system, not only converting direct current into 220V/50Hz alternating current for household appliances, but also enabling the function of surplus electricity being fed back to the grid. Such off-grid or grid-connected systems achieve intelligent control through an energy management system (EMS), automatically optimizing charging and discharging strategies based on electricity demand and price peaks and troughs, allowing the household's energy self-sufficiency rate to reach 70%-90%. Tesla solar roofs are even more innovative, integrating photovoltaic cells with roof tiles for a unified design, ensuring power generation efficiency while enhancing the architectural aesthetics, representing the development direction of residential photovoltaic systems.

## 3.2 Community-Shared Solar Projects

The community shared solar project is an emerging distributed energy model, usually deployed in centralized sites (such as open land, industrial rooftops, etc.), with a system scale ranging from medium to large. It can provide clean electricity for multiple households or businesses. These projects typically adopt grid-connected interactive design and are centrally maintained by professional teams to ensure efficient and stable operation. Unlike traditional household photovoltaic systems, community solar allows residents to participate through crowdfunding investment, while enjoying tax reduction and other policy benefits, thereby lowering the personal investment threshold.

In terms of technology integration, community solar projects often combine multiple renewable energy sources, such as photovoltaic and wind energy, heat pumps or biomass energy, to enhance the stability and utilization rate of energy supply. For instance, the Bomen Solar Farm in Australia adopts the "solar energy + energy storage" model. Residents receive electricity income by purchasing shares of solar panels, and the system is equipped with lithium-ion batteries to balance peak and off-peak electricity demand [11]. Similar projects are gradually becoming popular in the United

States, Europe and other regions. For example, the "Solar Gardens" model in the United States allows tenants or households without rooftop photovoltaic installations to share solar power and achieve precise metering and electricity bill settlement through smart meters [12].

This model not only enhances the scale benefits of photovoltaic power generation, but also promotes the democratization of community energy, enabling more households to enjoy the economic and environmental benefits of renewable energy at a low cost. In the future, with the application of virtual power plants (VPP) and blockchain technology, community shared solar projects are expected to further optimize energy distribution, enhance grid flexibility, and promote the construction of low-carbon communities [13].

### 3.3 Utility-Scale PV Plants

Large-scale photovoltaic power stations are usually constructed in remote or non-residential areas, utilizing vast land resources to achieve large-scale power generation, and then transmitting the surplus electricity to the power grid through high-voltage transmission networks. In recent years, perovskite solar cells have attracted widespread attention due to their organic-inorganic hybrid material characteristics. Research conducted by the National Renewable Energy Laboratory (NREL) in the United States indicates that this technology has a higher theoretical efficiency (over 30%) and lower manufacturing cost potential compared to traditional silicon-based cells, making it particularly suitable for large-scale power station applications [14]. Additionally, the third-generation concentrated photovoltaic (CPV) solar power generation system developed by NREL further improves the photoelectric conversion efficiency, while combining energy storage technology enhances the reliability of the system capacity [15].

In terms of grid integration, large-scale photovoltaic power stations are usually equipped with large-scale energy storage systems (such as lithium-ion batteries, flow batteries or pumped hydro storage) to mitigate the impact of intermittent power generation on the grid and enhance grid stability. For instance, the 2.2 GW photovoltaic power station in Qinghai Province, China, combined with an energy storage system, has achieved a high proportion of renewable energy consumption and reduced the overall energy cost. Moreover, the electricity from these power stations can be flexibly allocated, which can be used for local industrial electricity consumption or participate in power market transactions through the smart grid to achieve dual optimization of economic and environmental benefits.

In the future, as the commercialization of perovskite technology progresses and the cost of energy storage continues to decline, large-scale photovoltaic power stations will play a more central role in the global energy transition, providing stable and low-cost clean power support for the goal of carbon neutrality.

## 3.4 Comparative Analysis

As shown in Table 1, there are significant differences among residential rooftop systems, community-shared solar projects, and utility-scale PV plants in terms of user experience, cost, technological trends, limitations, and future development directions. In terms of user experience, residential rooftop systems require users to manually monitor the system operation, while community-shared solar projects can offer a higher self-consumption rate and energy autonomy, and utility-scale PV plants have the advantage of the highest power supply reliability, without requiring user participation in management. From the perspective of cost, the cost of residential rooftop systems is relatively high, with all expenses borne by users; community-shared solar projects use community cost-sharing to control the cost at a medium level; while utility-scale PV plants have extremely high costs due to the need for large-scale infrastructure investment. In terms of technological trends, residential rooftop systems mainly adopt off-grid systems and monocrystalline solar panels, community-shared solar projects focus on multi-technology integration (such as solar power + energy storage + wind power), and utility-scale PV plants focus on utility-scale technologies such as perovskite cells and concentrated photovoltaics. The limitations of the three also vary: residential rooftop systems are limited by roof area and load-bearing capacity; community-shared solar projects need to optimize the community energy storage system and face complex policy coordination issues; utility-scale PV plants have difficulty being deployed in densely populated urban areas or residential areas. In terms of future development directions, residential rooftop systems will evolve towards building-integrated photovoltaics (BIPV), community-shared solar projects need to formulate more intelligent management strategies and improve benefit distribution policies, and utility-scale PV plants need to focus on solving stability and scale challenges, such as improving grid compatibility. These differences reflect the diverse technical, economic, and social needs and development paths of different photovoltaic application scenarios.

**Table 1** Comparative Analysis of Photovoltaic Systems

| Comparison Dimension | Residential Rooftop Systems | Community-Shared Solar Projects | Utility-Scale PV Plants |
|---|---|---|---|
| User Experience | Requires manual monitoring by users | Higher self-consumption and energy autonomy | Highest power supply reliability (no user management needed) |

| Comparison Dimension | Residential Rooftop Systems | Community-Shared Solar Projects | Utility-Scale PV Plants |
|---|---|---|---|
| Cost | Medium to high (fully user-funded) | Medium (cost-sharing among community members) | Extremely high (requires large infrastructure investment) |
| Technology Trend | Off-grid systems + monocrystalline panels | Multi-technology integration (PV+storage+wind) | Utility-scale technologies (perovskite cells, CPV) |
| Limitations | Constrained by roof area and load capacity | Requires optimized community storage systems and complex policy coordination | Difficult to deploy in urban/residential areas [3] |
| Future Direction | Building-integrated photovoltaics (BIPV) | Smarter management strategies and improved benefit distribution policies | Addressing stability and scalability challenges (e.g., grid compatibility) |

## 4 Challenges and Future Directions

Photovoltaic systems face their own technical challenges and development opportunities in various application scenarios. For residential rooftop systems, the core challenge lies in how to overcome the physical limitations of roof area and load-bearing capacity while reducing the initial investment cost for users. The future development direction will focus on Building Integrated Photovoltaic (BIPV) technology, achieving higher space utilization efficiency through deep integration with building materials, and exploring collaborative optimization with smart home systems and electric vehicle charging facilities. Innovative products such as Tesla solar roofs have demonstrated the potential of integrating photovoltaic modules with architectural aesthetics, but how to further reduce costs remains an urgent issue to be addressed.

Community shared solar projects and utility-scale photovoltaic power stations face challenges from different aspects. Community projects need to improve energy storage system optimization technologies and benefit distribution mechanisms. The practical experience of countries like Germany shows that reasonable policy design is crucial for the sustainability of the projects. While utility-scale power stations have scale benefits, they need to solve key technical bottlenecks such as the stability of perovskite cells and the compatibility with the power grid. The third-generation concentrating photovoltaic system being developed by the National Renewable Energy Laboratory (NREL) of the United States, as well as the application of virtual power plants (VPP) technology, are expected to enhance the stability and economy of large-scale photovoltaic grid connection. These technological advancements will jointly drive the development of photovoltaic systems towards higher efficiency, lower costs, and greater intelligence.

## 5 Conclusion

This article systematically explores the current development status and application models of photovoltaic technology. Firstly, the article comprehensively reviews the latest research progress of the current mainstream photovoltaic technologies. Secondly, the article innovatively constructs a comparison of three types of photovoltaic application models, comparing the differentiated characteristics of residential rooftop systems, community sharing projects, and utility-scale power stations from five dimensions including user experience, cost structure, and technical compatibility. The residential system is limited by physical space but has great potential for intelligence, the community project relies on policy coordination yet has the value of energy democratization, while the public power station requires a huge investment but has the lowest unit power generation cost. This structured comparison provides a decision-making basis for the selection of technologies for different application scenarios. Finally, the article prospectively discusses the technical challenges and future directions faced by various systems. For key issues such as residential BIPV integration, community energy storage optimization, and the stability of perovskite cells, a technical roadmap for multi-level collaborative development of "building-community-grid" is proposed. This research not only presents the cutting-edge dynamics of photovoltaic technology but also provides a systematic analytical perspective for industry applications.

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