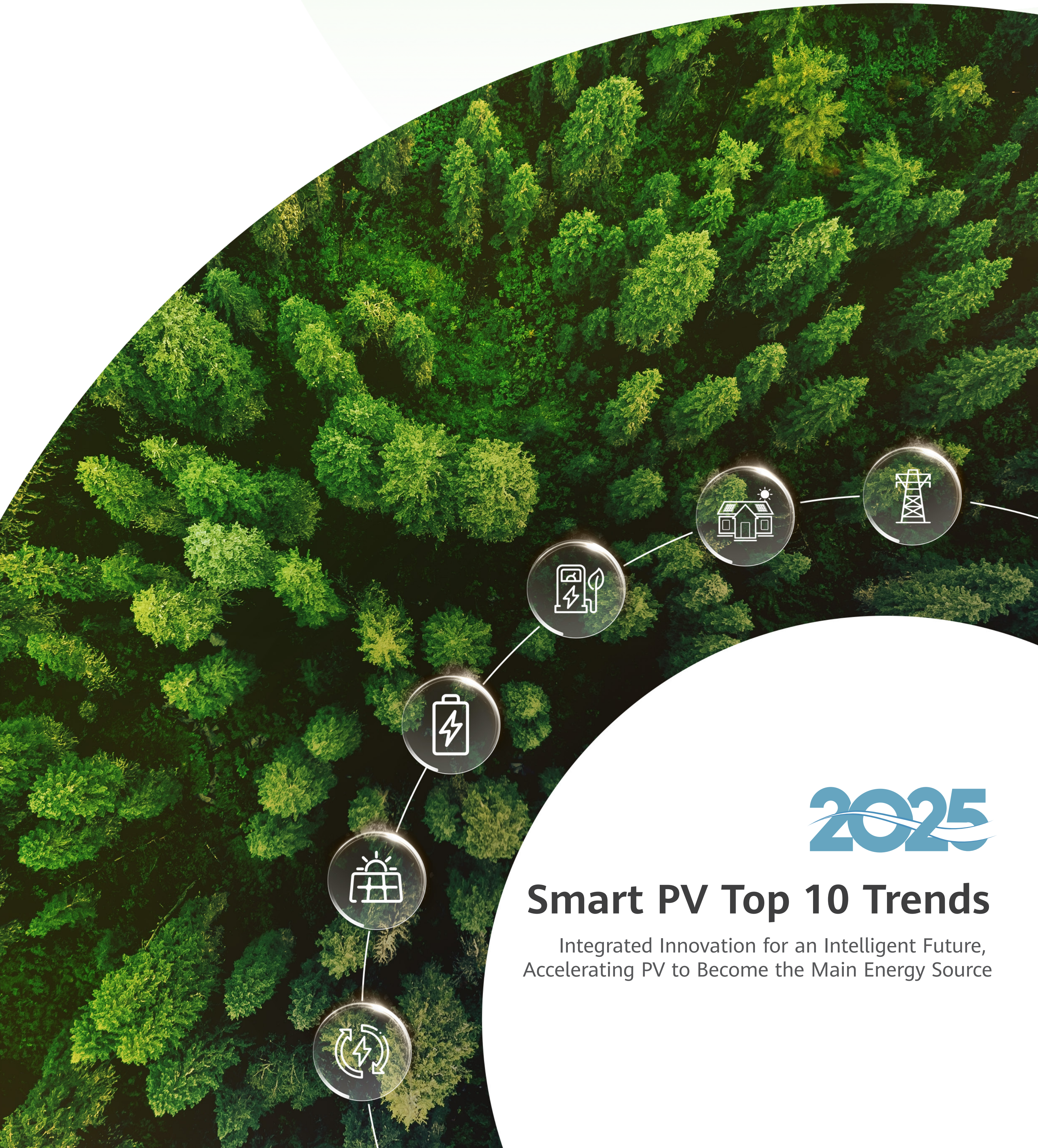


2025

Smart PV Top 10 Trends

Integrated Innovation for an Intelligent Future,
Accelerating PV to Become the Main Energy Source

Foreword

Thanks to favorable renewable energy policies, the global PV market has been growing rapidly in 2024, with a capacity addition exceeding 520 GW. The energy storage market was also booming, with more than 190 GWh added to the global capacity. PV and energy storage have become a national or regional strategy for major economies around the world. Particularly, grid-forming energy storage systems (ESSs) have been proved effective to resolve power grid stability challenges and accelerate the evolution of PV from a supplementary source of power to a major one.

According to the Global Renewables and Energy Efficiency Pledge and the Global Energy Storage and Grids Pledge signed at the 28th and 29th Conference of the Parties (COP 28 and COP 29) to the United Nations Framework Convention on Climate Change (UNFCCC), the global PV and ESS capacities are expected to exceed 5400 GW and 1500 GW by 2030, respectively. Countries around the world are working together to cope with climate change and strive for carbon neutrality goals.

As the global energy transition accelerates, the PV and energy storage markets will see huge development potentials in 2025. Based on its extensive insights, Huawei has identified top 10 trends for high-quality development of the PV and energy storage industry that is underpinned by one core, three pillars, and six technical applications.

CONTENTS

01 Trend 1:
Renewable Energy Generators Will Accelerate PV to Become the Main Energy Source.

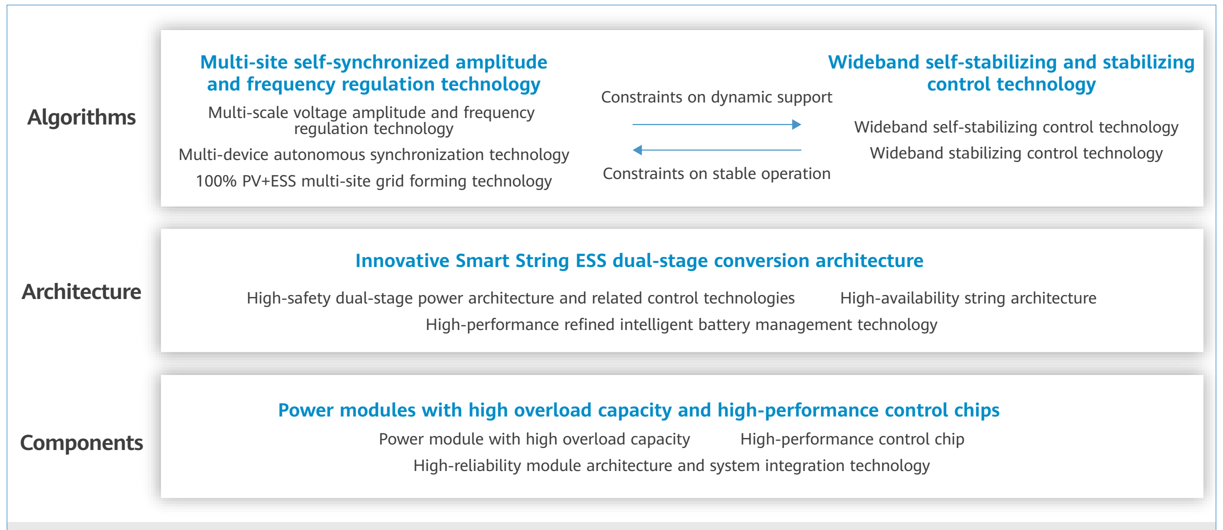
Favorable Policies and Booming Businesses Expedite PV Capacity Growth, Posing Challenges to Power Grid Stability

Carbon neutrality has become a global mission. Major economies around the globe are intensifying efforts to develop renewables. Among them, PV will play a key role. As predicted by the International Energy Agency (IEA), the global PV capacity will triple by 2030. Thanks to favorable policies and cost reduction, the PV industry will continue to develop rapidly in the future, making significant contributions to the global energy transition and climate change combat.

A high proportion of renewables and power electronic equipment present new challenges. Power systems need to effectively suppress the volatility in renewable power generation, improve the utilization of renewables, and damp oscillations from power electronic equipment to ensure power grid stability. The challenges must be resolved as PV has evolved from a supplementary source of power to a stable and important source, and will become a major source.

Smart Renewable Energy Generator Technologies Are Getting Mature and Have Passed Multiple Field Tests

Huawei's Smart Renewable Energy Generator solution can effectively solve the problems caused by a high proportion of renewables and power electronic equipment. At the heart of the solution is a grid forming technology system that covers components, architecture, and algorithms.



▲ Figure 1-1: Huawei's Smart Renewable Energy Generator innovation system

01 Power modules with high overload capacity and high-performance control chips together build reliable and stable underlying core component capabilities to effectively support the transient-state operations of the power grid.

02 The innovative dual-stage conversion architecture for smart string ESSs decouples voltage control from active power control, ensuring the stability of the power grid, the long-term reliability of ESSs, and responsiveness to power grid requirements.

03 The wideband self-stabilizing and stabilizing control technology facilitates stable grid connection of the equipment and wideband oscillation damping for the power grid, enabling multiple types of power supplies to run stably in parallel.

04 The multi-site self-synchronized amplitude and frequency regulation technology implements self-synchronized parallel grid forming, allowing multiple sites to be self-synchronized for reliable operation at a large scale.

Based on comprehensive technological innovations, the renewable energy generator technologies have passed field tests. Huawei has collaborated with the power grid and power generation company, in conjunction with China's National Energy Administration and State Grid, to promote Field tests in grid-forming ESS projects. Since September 2022, they have successfully completed multi-scenario, multi-scale, and multi-condition Field tests on the renewable energy generator technologies in several projects in Northwest China, involving more than 2300 test items, including the demanding 35 kV and 110 kV short-circuit tests passed in one attempt. The technologies are proved to effectively resolve power grid stability challenges caused by an increasing penetration of renewables, enabling PV to become the main energy source in the future.

Huawei's Smart Renewable Energy Generator Solution Has Been Put into Mass Commercial Use and Passed Technology Appraisal

Huawei's Smart Renewable Energy Generator solution have been put into mass commercial use in various power grid environments, including weak grids, extremely weak grids, and microgrids, as well as natural environments such as high temperature, high altitude, and freezing cold. Typical applications include the world's largest PV+ESS (1.3 GWh) microgrid power plant in The Red Sea destination of Saudi Arabia, the 100 MWh DC sending-end grid-forming ESS plant of China Green Development Investment Group (CGDG) in Golmud, Qinghai, and the grid-forming ESS plant for an extremely weak power grid in Gertse County, Ngari Prefecture.

The Gertse PV&ESS plant of XZKT began to run in grid-forming mode in November, 2024. This project features a high altitude, low temperature, and extremely weak power grid. The 6MW/24MWh grid-forming ESS increases the PV output from 1.5 MW to 12 MW, improving the grid integration of renewables. A higher share of renewables alleviates the pressure of local power supply. The project sets a good example in effectively solving the integration of renewables to a weak power grid in China.

▲ Figure 1-2: PV+ESS plant (grid-forming) in Gertse County, Ngari

In July 2024, the Chinese Society for Electrical Engineering organized a technology appraisal meeting in Beijing, which aimed to evaluate the key technologies and applications of the Smart String Grid-Forming ESS designed to cater to various scenarios with a high proportion of renewables. The appraisal committee comprised experts from research institutions and companies including the Chinese Academy of Sciences, the Chinese Academy of Engineering, and State Grid Corporation of China (SGCC). The committee agreed that Huawei's grid forming technologies improve the stability of a new power system subject to a high proportion of renewables and enhance the grid integration of renewables in actual engineering applications.

▲ Figure 1-3: Huawei's Smart String Grid-Forming ESS underwent a rigorous technology appraisal meeting in Beijing

The renewable energy generator solution will be more widely adopted for commercial use, accelerating PV to become the main energy source and making significant contributions to carbon neutrality.

02 Trend 2: All-Scenario Grid Forming

Ubiquitous energy storage and grid forming will ensure the long-term stability of new power systems.

Multiple Challenges Hinder the Development of New Power Systems

With the rapid development of renewables, an increasing number of mechanical electromagnetic systems are being replaced by power electronic equipment and traditional power grids are transforming to new power systems. The balance and safety of power systems have become a major concern. For example, equipment cannot stay available at any time due to the random and fluctuating output of renewables; components with low overload capacity lead to weak transient capabilities and reduced immunity resistance; frequency adjustment and voltage support capabilities are insufficient compared with synchronous generators; and a high proportion of power electronic equipment introduces wideband oscillation risks.

Energy Storage and Grid Forming Play a Key Role in Power Generation, Transmission, Distribution, and Consumption of New Power Systems

ESS is a flexible resource that is crucial to power generation, transmission, distribution, and consumption of new power systems.

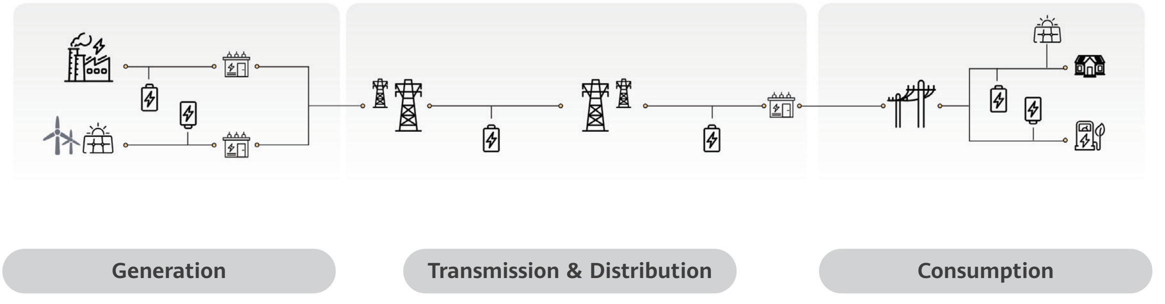


Figure 2-1: ESSs in power generation, transmission, distribution, and consumption

In power generation, the ESS smooths wind and PV power output, promotes renewables integration, and reduces wind and PV power curtailment. In power transmission, the ESS relieves line congestion and improves transmission efficiency. In power distribution, the ESS can be deployed to improve power quality and reduce the pressure on capacity expansion. In power consumption, responsive resources on the load side can be mobilized to optimize the control capability after the power supply is connected.

The large-scale integration of renewables compromises the short-circuit capacity of the power grid, leading to operation issues. To improve the stability of the power grid, grid forming and energy storage technologies can be leveraged to deliver the stable voltage, frequency, and power angle equivalent to synchronous generators. In power generation, grid forming capability can be used to improve the short-circuit capacity and inertia of power plants and enhance the power grid. In power transmission and distribution, grid forming technology can be applied to improve the voltage and frequency stability of the transmission network and damp wideband oscillations from the power grid. In power consumption, grid forming technology can enhance the off-grid switching capability to ensure continuous and stable power supply when the power grid is faulty.

In the future, grid forming technology will spread from the ESS to more power electronic equipment. It will be widely adopted in PV and wind power scenarios to ensure stable power generation, transmission, distribution, and consumption.

Grid Forming Technologies Has Received Increasing Attention from the International Community

More than 10 organizations or associations around the world have released standards or white papers on grid forming technologies. Europe is at the forefront of grid forming technology implementation. The EU RfG2.0 will require that grid-connected renewable power plants provide the grid forming capability after grid codes take effect from 2028. EU countries have started to develop their local standards and regulations accordingly.

Two association standards formulated under the leadership of the State Grid Xinjiang Electric Power Research Institute have been published: Technical specification for application of grid-forming energy storage system and Test specifica-tion for application of grid-forming energy storage system. In addition, a number of national, association, enterprise standards on grid forming technologies are being prepared.

These standards provide technical support and regulatory guidelines for grid-forming ESSs, reflecting their significance in the international community. Moreover, these standards create a favorable development environment for grid forming technologies and will drive their large-scale commercial use in new power systems.

03 Trend 3: Cell-to-Grid ESS Safety

ESS safety is the foundation. A more robust safety protection system will promote the high-quality development of the industry.

A More Robust ESS Safety Protection System Is Vital for Stable Operation of New Power Systems

ESS safety is critical to the safe and stable operation of a new power system. To promote the sustainable and high-quality development of the energy storage industry, a more robust safety protection system must be established. The safety design across scenarios and dimensions extends the ESS protection from no fire propagation to smoke only and no explosion and from automatic isolation of power grid faults to automatic recovery. The design ensures the safety and reliability of the ESS throughout its lifecycle to safeguard the entire power system.

Cell-to-Grid Safety Protection Builds a Reliable ESS Architecture

To ensure smoke only and no explosion in an ESS in case of emergency, the safety design must extend from the cell level to the grid level.

01 At the cell level, strict tests must be performed according to cell lifecycle application scenarios to ensure cell safety and reliability at the source and build the first line of defense for the safety protection system. Moreover, to identify cell risks in advance, AI technologies can be used to implement multi-dimensional diagnosis, detect problems such as cell inconsistency and internal short circuits, and generate early warnings on thermal runaway risks.

02 At the pack level, effective sealing and high insulation designs should be adopted, which include rapid cooling, heat insulation, and positive-pressure oxygen blocking. Positive-pressure oxygen blocking maintains positive pressure in a pack in case of emergency, preventing oxygen from entering the pack to ensure that thermal runaway in the pack will not lead to a fire.

03 At the container level, an exhaust system, fire suppression system, and explosion venting system should be well designed, and protection measures against thermal runaway should be taken to ensure that fire in an ESS will not spread to adjacent ESSs. A common practice in the industry is to design a path that traverses the entire ESS for exhausting combustible gases, which may cause gas spreading in the ESS. Each rack should be equipped with a directional channel for exhausting combustible gases generated during pack thermal runaway to the outside of the container along the shortest path. The design prevents combustible gases from spreading in the container and ensures that the ESS will not explode.

04 At the system level, the ESS must use a DC/DC and DC/AC dual-stage architecture. When high voltage ride-through occurs on the power grid, the DC/DC circuit adjusts the voltage in real time to ensure that no backfeed current enters batteries and no cell thermal runaway occurs.

05 At the grid level, grid-forming equipment such as ESS and PCS serves as synchronous generators to ensure grid stability. The grid-forming ESS not only provides a stable voltage source for the power grid, but also actively suppresses various disturbances on the power grid, and alleviates stability problems such as transient voltage and frequency of the power system, effectively improving the grid integration of renewables.

Huawei's Smart String Grid-forming ESS Platforms Received the Highest-Level Energy Storage Safety Certificates from TÜV Rheinland

Huawei's ESS safety design integrates power electronics, digital, thermal, electrochemical, and AI technologies. Smaller safety protection units mean safer protection for the ESS. Refined monitoring and management at the cell, pack, container, system, and grid levels comprehensively safeguard the ESS.

Huawei's Smart String Grid-forming ESS Platforms (LUNA2000-4472, LUNA2000-215, and LUNA2000-7 series) has passed energy storage safety tests such as fire resistance, internal and external ignition, and explosion venting, and received the world's first highest-level energy storage safety certificates from TÜV Rheinland. If a fire is caused by external factors in extreme scenarios, pack thermal runaway will not propagate.

▲ Figure 3-1: Huawei ESSs received the highest-level safety certificates from TÜV Rheinland

04 Trend 4: Full-Lifecycle Intelligence

Power Plants Will Run Automatically Throughout Their Lifecycle Intelligent Management.

Huge Renewable Installations Increase Challenges in Planning, Construction, Maintenance, and Operations

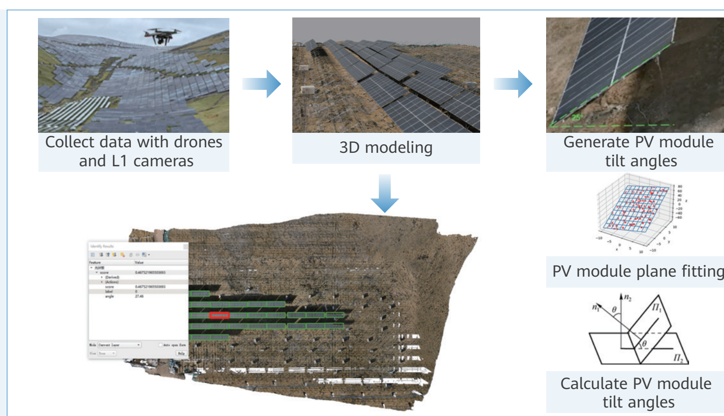
GW-level or larger power plants continue to emerge. Large scale, harsh environments, and complex operations will become major challenges for power plant management.

Power plant planning and construction usually involve heavy workload, numerous workers, and tight project duration. Consequently, quality management may be ineffective and omissions or incorrect installations may not be detected in a timely manner. In addition, onsite manual supervision cannot identify operation risks effectively. After a power plant is connected to the grid and put into service, many faults may occur because a large number of devices are in use and it is difficult to formulate troubleshooting plans, detect faults, and locate devices. As a result, the energy yield will be affected due to delayed troubleshooting. During plant operations and transactions, plant revenue cannot be guaranteed and transaction risks increase due to unstable output of renewable power and uncertainties in electricity prices.

Renewable Power Plants Will Run Automatically Throughout Their Lifecycle

- **In the design phase**, intelligent simulation software simulates and compares the energy yields under different layouts and orientations based on factors such as weather, temperature, and geological environments. Then the software automatically determines the PV module layout and cable connections, improving the project design efficiency and quality.

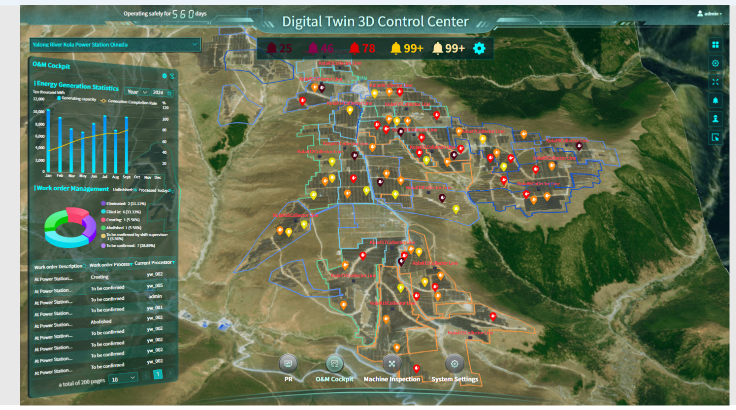
- **In the construction phase**, 3D reconstruction and incremental modeling technologies are used to build the real-world 3D model of the power plant. Intelligent image processing technology is used to split the entities in the model to identify PV modules and pile foundations. Then, a vectorized tilt identification algorithm and verticality monitoring algorithm are used to determine the PV module installation angle and pile verticality. Deviations between the actual construction and the design scheme are detected to effectively improve the quality control capability during PV plant construction.



Drones and 3D modeling are used to quickly calculate the tilt angles of PV modules. By comparing the changes in the tilt angles of PV modules at different time points, users can identify issues such as pile foundation sinking, support deformation, and screw loosening. The approach replaces manual inspection, saves O&M labor, and improves inspection efficiency.

▲ Figure 4-1: Intelligent tilt angle recognition to assist in project inspection

- **In the O&M phase**, twin modeling technology is used to restore the real-world situation of the power plant so that O&M personnel can locate and rectify faults in an optimal way. Technologies such as intelligent big data analytics, multi-dimensional sensing, and multi-physical-field modeling are used to warn battery exceptions, prevent risks from spreading, and implement active safety. As various robot technologies are mature and costs continue to decline, professional machines are preferred to carry out periodic and repeated work such as inspection and cleaning to improve efficiency.



◄ Figure 4-2: Power station digital twin system

- **Regarding operations and transactions**, the proportion of renewables in spot trading is increasing. Customers focus more on the accuracy of weather and power forecast, and thus large models are trained with massive data to enhance the forecast accuracy. Moreover, AI is integrated with optimization solvers to simulate market operations, explore data patterns in the electricity market, predict electricity prices, and assist traders in bid decision-making to reduce transaction risks and improve plant revenue. AI will play an increasingly important role in operations and transactions.
  AI technologies will digitalize all plants and enable digital, intelligent, and unmanned management. Autonomous driving will be a reality for renewable power plants.

China's First Coastal Mudflat PV Project with Full-Lifecycle Intelligence Was Put into Production

The Yinggehai PV Project of Hainan Holdings Energy Co., Ltd. is located in Ledong Li Autonomous County, Hainan Province. It is the largest centralized PV plant in Hainan Province and has a total installed capacity of 430 MW. The project faced challenges including high temperature, high humidity, high salinity, numerous devices, and a large area.

Huawei worked with partners to establish a full-lifecycle intelligent management system for the project. Digital twin technology is used to build a real-world model for the PV area. In-depth analysis based on the performance ratio (PR) is conducted for quantitative evaluation. A smart cockpit is established to implement intelligent scheduling against fault alarms, improving O&M efficiency up to 50%.

▲ Figure 4-3: The Yinggehai PV Project

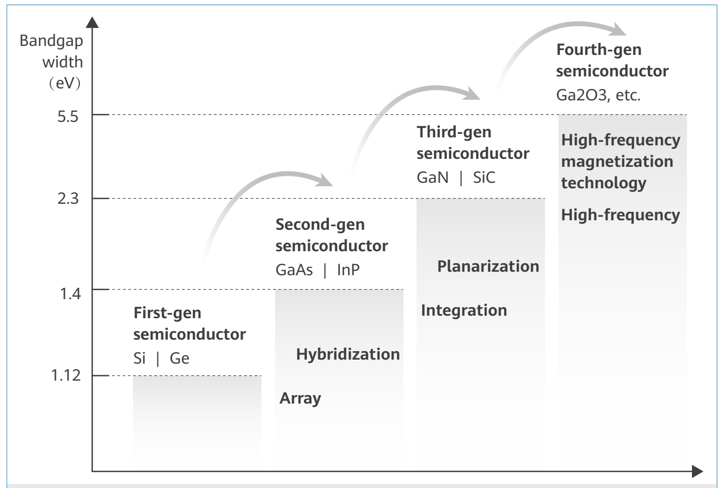
05 Trend 5: High Frequency and Density

A combination of third-generation semiconductors and digital technologies will continuously increase the power density of power electronic converters, which is set to improve the quality and efficiency of PV systems.

Evolving Semiconductor Technology Lays the Foundation for Improving the Power Density of Power Electronic Converters

Semiconductor technology has evolved to the fourth generation. In the mid-20th century, semiconductor materials dominated by germanium and silicon laid the foundation for computers and communications. The second generation, represented by gallium arsenide and indium phosphide, ushered in the era of high-speed communications and LED lighting. Then the third-generation semiconductor materials — silicon carbide and gallium nitride — became vital to the development of power electronics technologies thanks to their wide bandgap characteristics. Now in the fourth generation, we are exploring ultra-wide-bandgap materials such as gallium oxide to meet the demands of ultra-high power and extreme environments in the future.

Third-generation semiconductors have been maturely applied. Compared with the previous two generations, the wide-bandgap semiconductor materials have a higher saturated electron drift velocity and thus are able to achieve a shorter delay and faster switching to improve the operating frequency and conversion efficiency. Third-generation semiconductors have a large bandgap width, making electron transitions difficult. Devices using such materials have a higher breakdown field and thus can withstand higher voltages but with a smaller size and higher reliability. Furthermore, the thermal conductivity can be increased for devices to tolerate higher temperatures while remaining stable. The materials reduce the area of heat dissipation components and increase the power density of products.



▲ Figure 5-1: Semiconductor technology evolution

Third-Generation Semiconductors Are Being Applied in the PV Industry to Enhance Quality and Efficiency

Third-generation semiconductor technology has been widely used in the PV industry for recent years. Silicon carbide has high thermal conductivity and thus is not easy to overheat in high-density applications. Gallium nitride has high electron mobility and therefore is more suitable for high-frequency applications. Third-generation wide-bandgap semiconductor components will significantly reduce the switching loss of power semiconductors and drive the switching frequency of power electronic converters such as inverters and PCSs to continuously increase from 100 kHz to MHz. Moreover, a combination of third-generation semiconductor, digital high-frequency control, and magnetic technologies will comprehensively improve the overall working efficiency of power electronic converters and raise the power density of products to a higher level.

Driven by technological innovations from wafers to systems as well as efficient heat dissipation, packaging, and integrated driving technologies, the power density of PV inverters and PCSs is expected to increase by more than 30% in the next three to five years, boosting the quality and efficiency of PV systems.

High-Density Inverters Are Easy to Transport and Install

In October 2024, Max Li-Power Energy Technology rolled out a 5 MW distributed PV plant for Qingchuang Meiju in Shenzhen, Guangdong. It is the distributed power plant with the largest installed capacity in Longgang District. Huawei's latest 150K high-power inverters are used in this project. The inverters deliver a conversion efficiency of up to 98.8%, expected to achieve an annual energy yield of over 7 million kWh and save 3000 tons of standard coal each year. The project will boost the low-carbon transformation and green economy for sustainable development.

The high-density design reduces the product weight and saves space in installation. The devices can be mounted on a wall at the rooftop. They are easy to transport and install, ensuring efficient project construction and fast delivery.

▲ Figure 5-2: Max Li-Power building a distributed PV plant for Qingchuang Meiju in Shenzhen

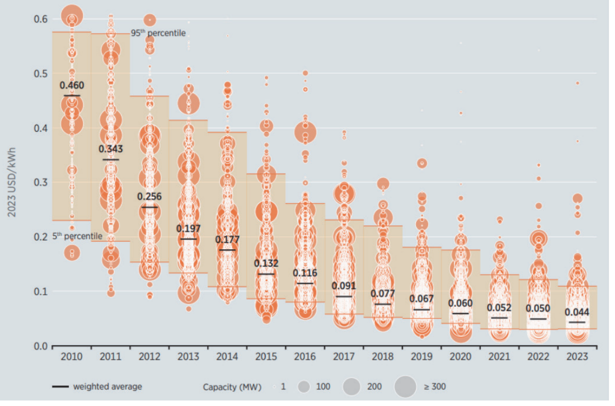
06 Trend 6: High Voltage and Reliability

High-voltage application will reduce the LCOE of PV+ESS systems, and high-reliability design will optimize system availability.

Continuously Increased Voltage Levels Lead to a Significant Decrease in the LCOE of PV Systems

The DC voltage of PV systems will increase from 600 V to 1500 V, and the AC voltage will rise from 220 V to 1000 V or higher. Driven by technological innovations, DC and AC voltage levels will continue to increase and the system LCOE will keep declining. High voltage will also reduce line loss and improve power generation efficiency. Therefore, high-voltage development will be the future of PV plants.

According to the International Renewable Energy Agency (IRENA), the global weighted average LCOE of PV plants dropped by 90% from $0.46/kWh in 2010 to $0.044/kWh in 2023 and the LCOE of PV systems declined by 56% compared to conventional energy, accelerating the pace of substituting conventional energy with the renewable PV.



▲ Figure 6-1: Global utility-scale solar PV project LCOE and range, 2010-2023
Source: IRENA

Higher Voltage Levels Require Higher Reliability

The trend of high voltage leads to cost reduction in the PV industry and poses higher requirements on system reliability. Utility-scale clean energy plants are constructed in more diversified scenarios, which can be deserts and wastelands with high temperature and heavy dust, mountainous areas and plateaus with freezing cold and high altitudes, and coastal areas with high humidity and salt fog. The harsh environments increase challenges to device and system reliability.

At the device level, technological innovations in new materials, components, and structural design make high reliability possible in harsh environments. As the scale of PV plants expands, the number of single-node faults increases. Real-time monitoring of voltage, current, temperature, and other parameters allow devices including PV inverters to accurately detect faults and take protective actions such as proactive current limiting, switching off, and shutdown to stay safe in case of failure.

In terms of system reliability, the dual-stage string architecture can better support the stability of the power grid than the central architecture. Especially, it ensures the stable output of active power around the clock during high- and low-voltage ride-through. Moreover, AI-based predictive maintenance technology can be used to implement fault warning and predictive maintenance, ensuring high system reliability and stable operation of the power grid.

2025 Smart PV Top 10 Trends

Building a Highly Reliable Power Plant on the Roof of the World

▲ Figure 6-2: Huawei inverters work well in high altitude project

The CGN 170 MW zero-carbon PV+ESS+Heating demo project is located in Ngari Prefecture's snowy plateau about 4500 meters above sea level, where the lowest temperature drops to –28°C. The region is also suffering from sandstorms for a long time, with extremely harsh natural environments. As an important power supply project in the local region, this demo project sets high requirements on device reliability, but the remote location and high altitude cause great challenges to the routine O&M of the plant.

Huawei's high-power smart PV inverter SUN2000-300KTL-H0 is the industry's first inverter that provides three-level safety protection: Smart String-level Disconnection (SSLD), Smart Connector-level Detection (SCLD), and MPPT-level DC Insulation Diagnosis. It operates safely and efficiently even in harsh environments. With high grid adaptability, the inverter remains stably connected to an extremely weak grid (SCR ≥ 1.1), effectively improving the power quality. In addition, the inverter is equipped with a unique intelligent fan dust removal function, which significantly reduces the number of site visits and improves the O&M efficiency of the plant.

So far, the power plant has been running safely for more than two years. The project has established a benchmark for high-quality power plants on snowy plateaus in the industry. It not only ensures stable local power supply, optimizes the energy mix, but also promotes the green development of the local economy.

▲ Figure 6-3: Top view of the zero-carbon PV+ESS+heating demonstration project

07 Trend 7: 100% Renewable Microgrid

Economical and stable renewable microgrids will be preferred in areas with electricity shortages.

Microgrids Need to Strike a Balance Between Economy and Stability

Electric energy is one of the most widely used sources of energy. However, the global electricity supply varies significantly in different regions. By 2024, about 750 million people around the world are still living without access to electricity[1].In areas where electricity supply is available but electricity infrastructure is weak, extreme weather and load surge result in frequent power outages.

In the past two decades, microgrids found difficulty in striking a balance between economy and stability.

Diesel generators have been used as the main power supply in some areas. Although diesel generators are proved to be a stable power supply, its power generation cost is about $0.4/kWh, which is much higher than the cost of thermal power generation. In addition, diesel generators emit loud noise and are difficult to maintain.

Although traditional renewable power microgrids cost less than diesel generators, the microgrid stability cannot be ensured due to random and fluctuating renewables as well as insufficient dispatching and control.

Innovative Hierarchical Architecture Facilitates Economical and Stable Operation of 100% Renewable Microgrids

Hierarchical control is vital for a microgrid system to achieve an optimal balance between economy and stability. With time-based control and function implementation considered, a microgrid control system is divided into three layers: stable grid forming control, efficient coordinated control, and smart optimized dispatching.

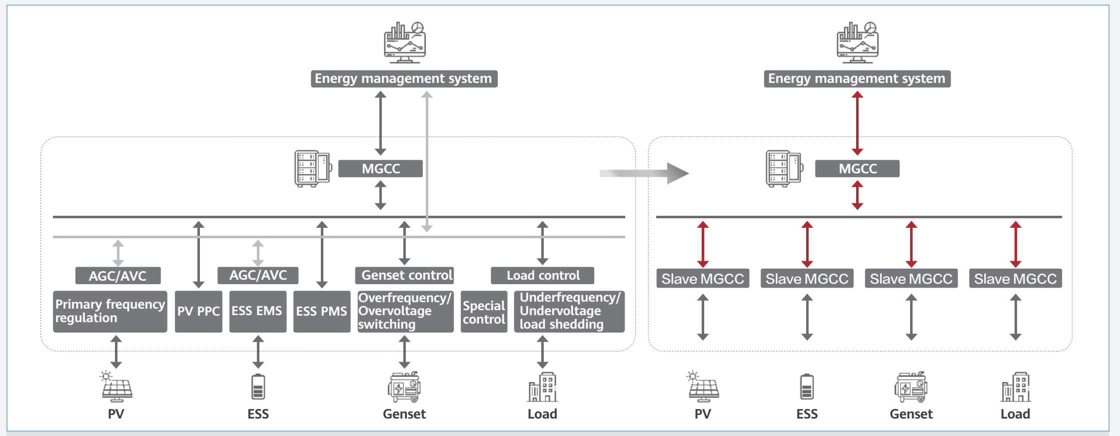
01

Stable grid forming control: Based on the frequency and voltage regulation capability of equipment, the grid-forming power supply and microgrid topology are well designed to achieve stable and synchronous grid forming with 100% diverse renewables and ensure the continuity of power supply to loads.

[1] *Laura.C.* (2024) Electricity access continues to improve in 2024 – after first global setback in decades.
Electricity access continues to improve in 2024 – after first global setback in decades – Analysis – IEA

02

Efficient coordinated control: The microgrid controller serves as the hub on this layer to execute rapid coordinated control of generation, grid, load, and storage in the system within 100 ms. When the power load is unbalanced, fluctuation smoothing is implemented to stabilize the microgrid frequency and voltage, in addition to achieve seamless off-grid switching and fast black start. In the future, the coordinated control layer will become highly integrated. A set of equipment will converge data collection, centralized control, and communication functions. The integrated design will significantly improve data collection and processing efficiency, ensure high performance, reduce equipment investment, and simplify subsequent commissioning and maintenance, laying a solid foundation for large-scale replication and system capacity expansion.



▲ Figure 7-1: Evolution of microgrid coordinated control

03

Smart optimized dispatching: The energy management system works in the center of this layer to implement minute-level optimized dispatching and operation safety margin management, ensuring power balance within the microgrid. Microgrid optimized dispatching needs to predict the future power generation based on weather or historical power generation data, properly plan the charge and discharge power of the ESS based on forward-looking results, and estimate the consumption based on power generation. Bidirectional coordination between generation and consumption will help achieve energy independence.

Renewable Microgrid for Mabende Mining in Congo-Kinshasa Reduces the LCOE by 50%

In 2024, a mine microgrid solution was applied to the development and construction of mining areas for Mabende copper mining in Congo-Kinshasa for the first time, helping build a next-generation green and efficient mine production system. This innovative solution breaks free from the dependence on an external power grid and diesel generator, and resolves challenges such as capacity expansion of the power distribution network. In addition to ensuring an annual stable energy supply for 8760 hours, the solution slashes the O&M cost and improves the production efficiency. It reduces the LCOE by 50% compared with diesel generators and cuts carbon emissions by 119.32 tons each year.

▲ Figure 7-2: Mabende mining renewable microgrid project in Congo-Kinshasa

08 Trend 8: PV+ESS+Charger+Load Synergy

Power distribution networks will gain higher flexibility, accelerating green power deployment across industries.

Accelerated Green Energy Transition and Transportation Electrification Pose Challenges to Stable Operation of Power Distribution Networks

According to IEA, the PV penetration rate in 18 countries exceeded 10% in 2024, twice the number of countries in 2023[1]. Gartner predicts that the number of global electric vehicles (EVs) will reach 85 million by 2025, an increase of 33% from 2024[2].

As the clean energy and transportation electrification accelerate, the PV penetration rate keeps going up and random loads will be connected on a large scale. Consequently, the load carrying capacity and renewables integration capability of power distribution networks will become insufficient. Moreover, distributed PV installations develop rapidly and daytime loads become increasingly complex. As a result, energy backfeed may occur during low-load periods, undermining grid stability. In addition, EV charging fluctuates like a tide, which may result in local power overload.

PV+ESS+Charger+Load Synergy Improves the Flexibility of Power Distribution Networks

The renewable energy market has been expanding from PV only to PV+ESS, and then to PV+ESS+charger integration. PV+ESS+charger+load synergy promotes the consumption of PV power, prevents energy backfeed, and increases the PV penetration rate. It also prevents power distribution overload, reduces the pressure on capacity expansion and revamping, and accelerates the construction of EV infrastructure. Digital technologies can be leveraged to implement multi-dimensional refined management of generation, grid, load, and storage on campuses, increase the certainty of power generation and load prediction, and maximize the complementation of distributed PV and adjustable charging loads to boost the plant revenue.

▲ Figure 8-1: PV+ESS+charger synergy to boost charging station revenue

Diverse energy sources can be harnessed for coordination, and load flexibility can be improved to offer more flexible adjustment capabilities so that grid power can be balanced within and across regions. Such synergy will promote green and grid-friendly energy consumption and accelerate the rapid deployment of renewables in scenarios such as factories, campuses, and shopping malls.

Interaction of Mobility and Energy Drives Low-Carbon Transformation in the Transportation Industry

A charging station in Bijiashan Park, Shenzhen integrates a world-leading integrated "PV+ESS+charger" technology. It is the first "PV+ESS+charger" demonstration station of CNPC in Shenzhen. Huawei's integrated PV+ESS+charger solution adopted in the project will produce more than 50,000 kWh of green electricity each year. The station is also equipped with energy storage equipment that automatically adjusts its working mode based on the ambient temperature and battery working conditions, maximizing system efficiency while minimizing energy consumption. It is estimated that the charge and discharge capacity for peak staggering will reach 300,000 kWh each year. By promoting intelligent management, optimized configuration, interconnection, and efficient utilization of PV+ESS+charger+load, more EVs will be charged with renewables to empower low-carbon mobility.

▲Figure 8-2: CNPC ultra-fast charging station with PV+ESS in Bijiashan Park, Shenzhen

[1] Snapshot of Global PV Markets 2024, IEA PVPS

[2] Forecast: Electric Vehicle Shipments, Worldwide, 2023–2032, Gartner

09 Trend 9: Energy Community Sharing

Evolving from self-consumption to community sharing, green power will be better circulated and coordinated among homes.

Energy Will Be Not Only Consumed Within Households, But Also Aggregated and Shared Across Communities

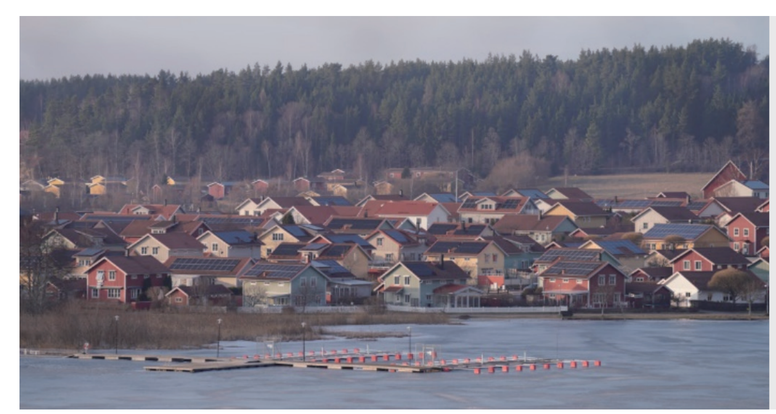
PV+ESS systems integrate energy production and consumption on the user side, improving the self-consumption rate. With the broad adoption of intelligent home energy management, power generation and consumption will be intelligently coordinated, promoting the use of green power while cutting electricity bills.

In the future, energy will not only be used within a household but also aggregated in a community for sharing under regional independent energy management. Power from different communities can also be traded in the electricity market for virtual power plants (VPPs). This will not only improve regional energy reliability and stability, enhance the device connection capability, but also allow more green power to be shared among homes for mutual benefits. Community-based power management will become an effective support for the power grid, helping solve the problem of renewable integration.

Energy community sharing offers significant advantages in deploying renewables, improving efficiency, ensuring reliable power supply, reducing electricity fees, and creating jobs. It will promote the energy transition and benefit governments, enterprises, and other users.

A Town in Sweden: Building a Global Benchmark for Residential Energy Communities

Gnesta, a small town in Sweden, faced challenges such as high electricity demand, negative tariff, diverse house orientations, and shading. To resolve the challenges, more than 1000 households across the town has deployed Huawei's residential PV+ESS solution by the end of 2024, making Gnesta a town with the densest PV deployment in Sweden. Huawei's residential solution helped achieve 100% energy self-sufficiency and energy interconnection, building an energy community with distributed PV+ESS.



◀ Figure 9-1: Solar community in Gnesta, Sweden

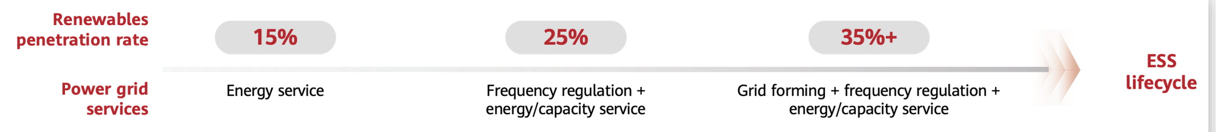
Local residents have shifted their focus from power generation and consumption at home to thinking about the influence of PV on the entire community. Instead of just buying out-of-box products, they have chosen an evolving lifestyle. The transformation enables energy to be coordinated and shared across communities for mutual benefits, promoting the rapid development of the renewable energy industry.

10 Trend 10: Flexible Adaptation to All Business Models

Integrated platforms will adapt to diversified business models and create more benefits.

ESS Business Models Are Becoming More Diversified

New-type energy storage has been put into commercial use and its large-scale development is unfolding. With the increasing penetration rate of renewables, business models covering the ESS lifecycle are becoming more diversified to better support new power systems. ESSs will extend from energy services to diversified business models including frequency regulation, capacity, and grid forming services.

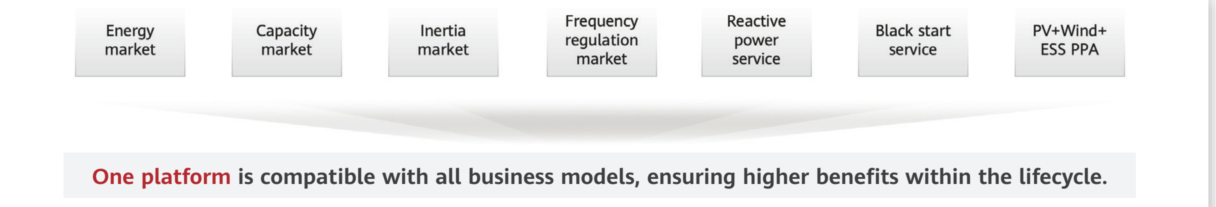


▲ Figure 10-1: ESS business models are becoming more diversified

However, the business models may change with policies and electricity market rules. To support a combination of multiple business models, ESSs need to meet higher requirements on the cycle life, discharge rates, software and hardware capabilities, grid compatibility, and solution flexibility.

Integrated Platforms Will Adapt to Diversified Business Models and Create More Benefits

An ESS should adopt a flexible architecture design. Based on the hardware configuration, the ESS should support flexible capacity expansion and smooth evolution of the solution through a high integration of software and hardware. The ESS should be applicable in diverse business models throughout its lifecycle, for example, inertia response, primary/secondary frequency regulation, intra-day and inter-day transactions, and wideband oscillation damping. While creating higher benefits for users, the ESS should reduce revamping costs. Smart software algorithms can be used to dynamically adjust charge and discharge policies and manage energy in multiple modes. Diverse ESS applications models should also be leveraged to build a flexible resource system for new power systems.



▲ Figure 10-2: Integrated platforms adapt to diversified business models

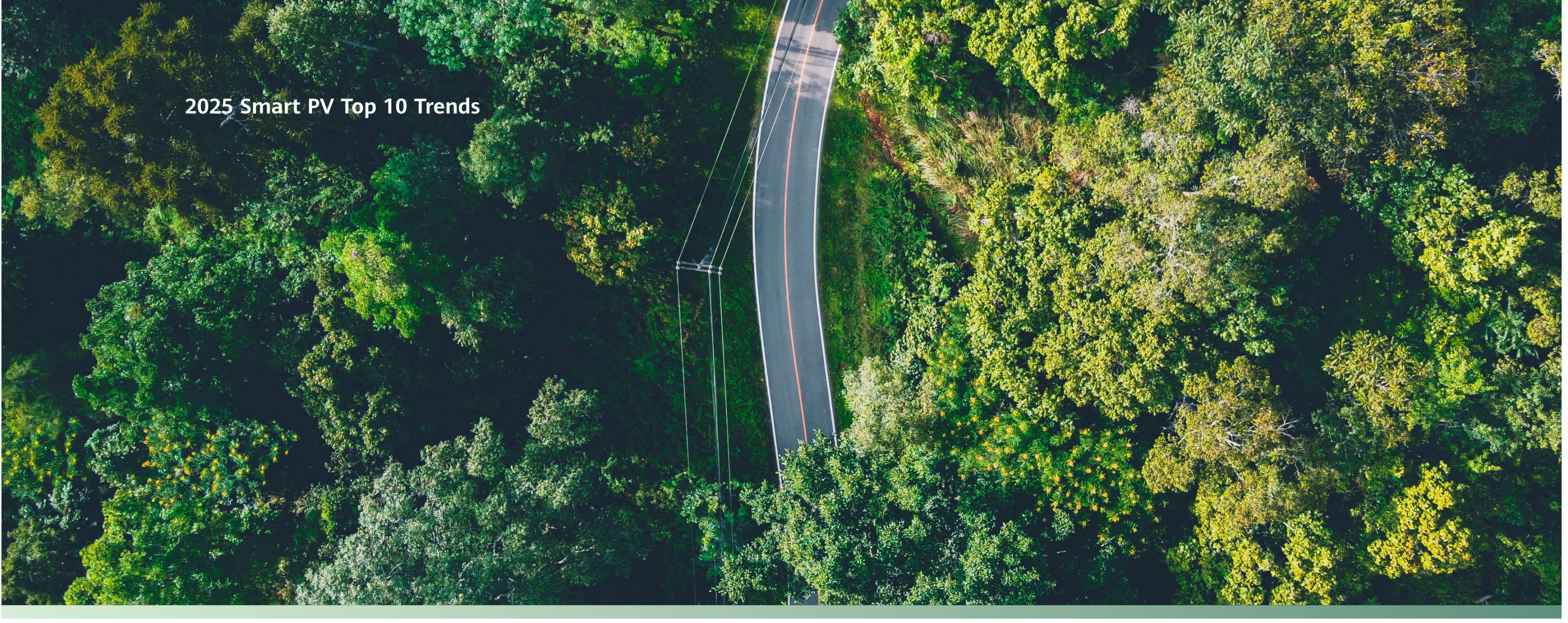
In addition, openness and sharing are required to interconnect with the electricity market and finally build an ESS that supports all business models to effectively support the development of new power systems.

Multiple ESS Business Models Are Adopted to Increase the Comprehensive Revenue by 10%

The PV+ESS project in Binhu Double-Crane Pharmaceutical Campus, Wuhan, Hubei Province is a low-carbon project jointly built by Huawei Digital Power and China Resources Power. With a PV capacity of 1.62 MW, the project uses ten 215 kWh BESSs connected in parallel and implements SmartEMO to intelligently schedule PV, ESSs, and chargers. PV self-consumption, TOU, and demand charge reduction are all achieved to maximize the revenue.

The SmartEMO system predicts solar power and loads at a high precision through online learning algorithms, and constantly optimizes the scheduling solution without manual intervention. The campus implements a combination of three business models: PV maximum self-consumption, ESS time-of-use arbitrage, and flexible demand reduction. Compared with traditional ESS control, it is estimated that the comprehensive revenue of PV+ESS will increase by more than 10%.

▲ Figure 10-3: PV+ESS project in Binhu



Summary

The large-scale application of renewable energy generator technologies will usher in a new era of grid forming, drive the deployment of clean energy, and accelerate carbon neutrality. This means not only a technological and commercial revolution, but also a great campaign for sustainable development.

Huawei hopes to work with industry players and all organizations and individuals that aspire for green and sustainable development to explore the future of the PV and ESS industry. Together we will drive the industry development with insights and innovations, and accelerate PV to become the main energy source for every home and business, building a better, greener future.

HUAWEI

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