

Scenarios Vary. Needs Differ. Unified by One Core.

S+ Energy Storage Multi-Scenario White Paper



Foreword

Energy storage is entering a new stage of growth. Once seen as a supporting asset, it is now becoming a core part of the power system—empowering generation, grids, loads, and microgrids to operate with greater flexibility, resilience, and efficiency.

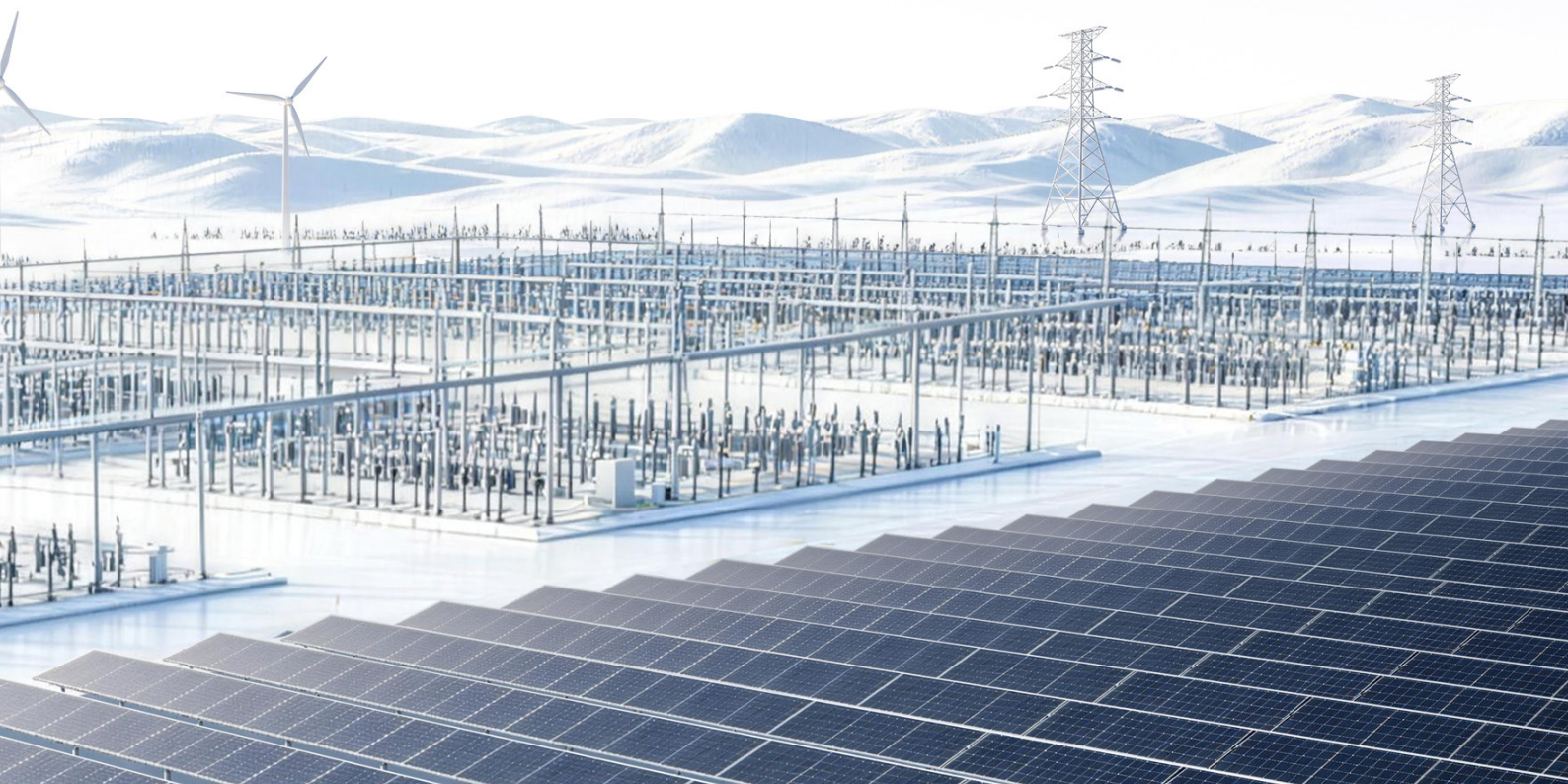
As new demands emerge across the power system, energy storage is being applied in more diverse and complex scenarios. The focus is no longer simply on whether energy storage is deployed, but on whether it can fit the scenario, work effectively within the system, and create lasting project value.

This shift is also redefining competition in the industry. The market is moving beyond a race for better product specifications. What matters now is system-level performance: the ability to adapt to real-world conditions, support long-term operation, and turn technical capability into measurable value. Grid connection is only the starting point; sustained performance is the real test.

This white paper is not simply a collection of solutions for different scenarios. It looks at the logic behind how energy storage creates value in a market where scenarios vary and needs differ. While applications will continue to evolve, the foundation behind them must remain clear, reliable, and scalable.

For today's well-defined applications, Sungrow's S+ Energy Storage approach helps translate scenario-specific requirements into practical project value. For the applications still ahead, the same foundation can support faster and more adaptive solution development.

Through this white paper, Sungrow hopes to provide a useful reference for understanding diverse energy storage scenarios and improving the quality of deployment. We also hope it will support customers worldwide in building energy systems that are more resilient, efficient, and sustainable.





Contents

01	Scenario Differentiation and Core Challenges	1
	1.1 Energy Storage Is Everywhere: Scenarios Vary, Needs Differ	2
	1.2 The Era of Standardized Energy Storage Products Has Ended	6
02	S+ Energy Storage: Scenarios Vary. Needs Differ. Unified by One Core.	9
	2.1 Grid-Connected Scenarios	10
	2.1.1 Generation + Storage: Flexible Multi-Energy Coupling Solution	11
	2.1.2 Grid + Storage: Grid-Forming Value-Stacking Solution	18
	2.1.3 Load + Storage: Load Multi-Value Solution	20
	2.2 Off-Grid Scenarios	26
	2.2.1 Microgrid + Storage: Off-Grid Power Supply Solution for Production	26
	2.2.2 Microgrid + Storage: Off-Grid Power Supply Solution for Civil Use	29
	2.3 Cross-Scenario General Capabilities	30
	2.4 S+ Dual-Engine Foundation	31
03	Capability Model and Level Definitions	34
	3.1 3S Model for Multi-Scenario Adaptation of Energy Storage	35
	3.2 Levels of Multi-Scenario Adaptation of Energy Storage	35
04	Outlook	38

C1

Scenario Differentiation and Core Challenges



Driven by factors such as the high-level penetration of renewable energies, increased demand for power system flexibility, improved electricity market mechanisms, and changes in terminal energy consumption structures, the global energy storage market continues to grow rapidly, with global newly installed capacity reaching 112 GW/307 GWh in 2025. Among these, China accounted for 54% of the global newly installed capacity, while demand in the Americas, Europe, the Middle East, and Australia also accelerated simultaneously.

Although this growth trajectory shows no signs of decelerating, the underlying logic of growth has changed: Scenarios are differentiating. Demand is diversifying. Energy storage is no longer an "ancillary asset" but a core component deeply embedded in the power system. The engine of growth is turning from policy-driven to scenario-driven.

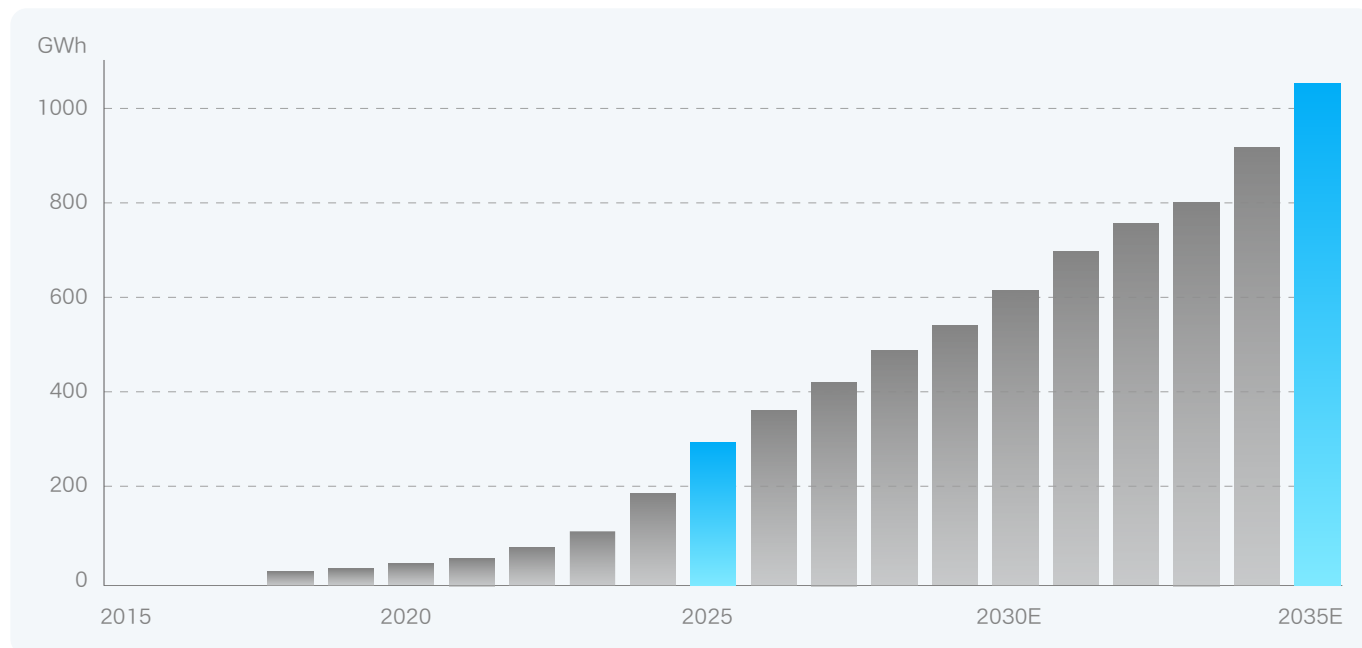


Figure 1: Annual Growth Trends and Forecast of Global Energy Storage, BloombergNEF

1.1 Energy Storage Is Everywhere: Scenarios Vary, Needs Differ

In the early stages, the logic behind energy storage growth was relatively simple: The industry adopted energy storage as long as policies mandated it, and the commercial and industrial sectors installed systems where peak-to-valley tariff spreads made it viable. The demand sources were clear, scenarios were homogeneous, and standardized products with basic integration were sufficient for deployment. Today, multiple forces overlap in different combinations across various regions and scenarios, driving the global energy storage market into a period of deep differentiation. The underlying core drivers can be summarized as follows:

- **Differences in renewable penetration levels.**

As wind and solar power transition from "supplementary energy" to "main power sources", energy storage has evolved from a supporting role to a critical grid asset. Grids at different stages of renewable penetration have vastly different requirements for storage systems. For instance, at a moderate penetration level of 30%, storage is primarily deployed for renewable integration and local consumption; at a high level of 60%, the focus shifts to grid-forming capabilities; and at an extreme level of 80%, storage becomes essential for maintaining overall system stability.

- **End-user electrification and AI acceleration.**

The exponential growth of AI computing power has introduced unprecedented high-power pulse loads, while the deployment of electric vehicle ultra-fast charging networks triggers abrupt fluctuations in distribution grids. Simultaneously, carbon trading systems have transformed carbon reduction into a financial metric. Driven by these factors, load demands have diverged from basic "electricity consumption" into entirely distinct demand profiles and value propositions.

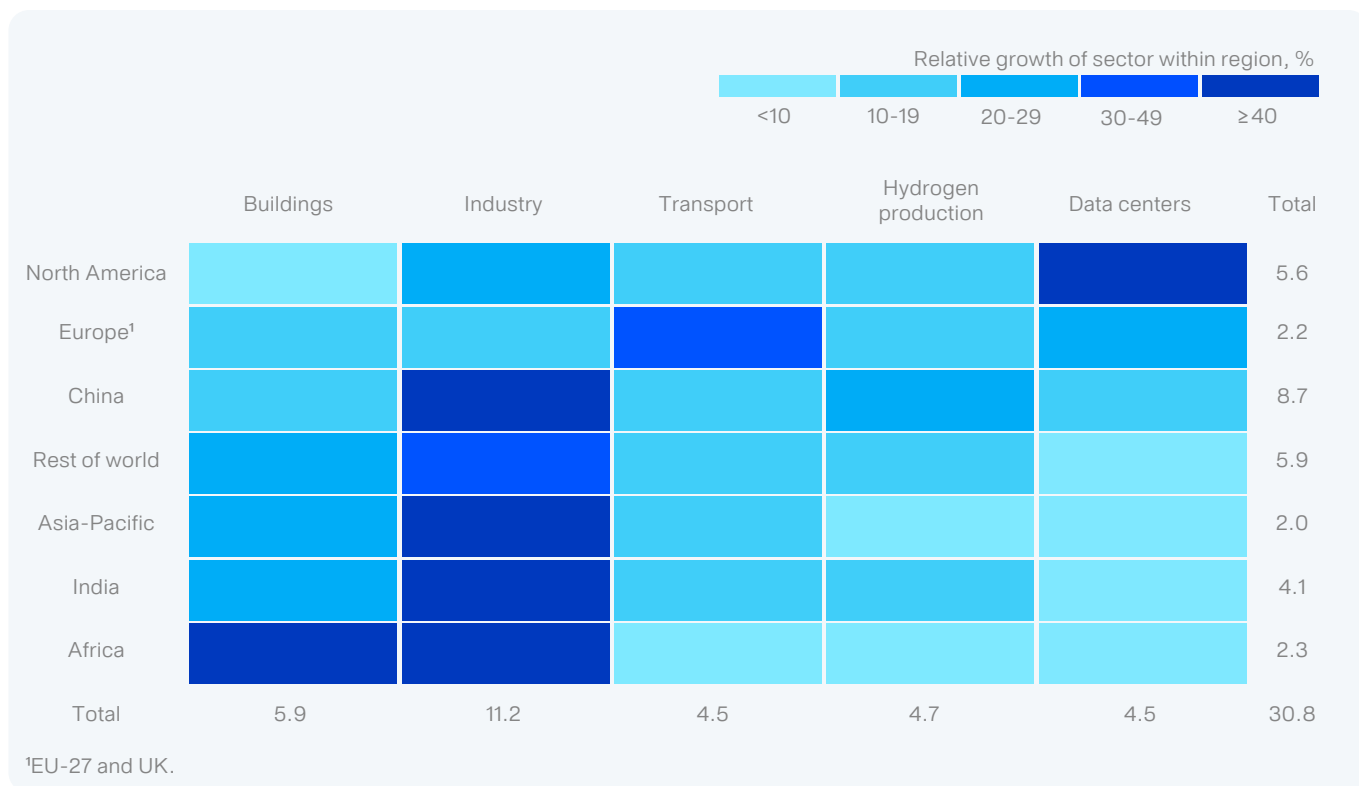


Figure 2: 2024-2050 Global Electrification Trends Forecast, McKinsey Global Energy Perspective 2025

- **Accelerated power market liberalization.**

The monetization of energy storage assets is shifting from policy-driven tariffs to market-driven price discovery. Divergent market structures and reform trajectories across nations shape distinct business models for energy storage. For instance, the UK market centers on the capacity market, Australia relies on frequency regulation, and China enforces varying spot market rules in different provinces. Consequently, the commercial logic for the same "grid-side energy storage" can be entirely different.

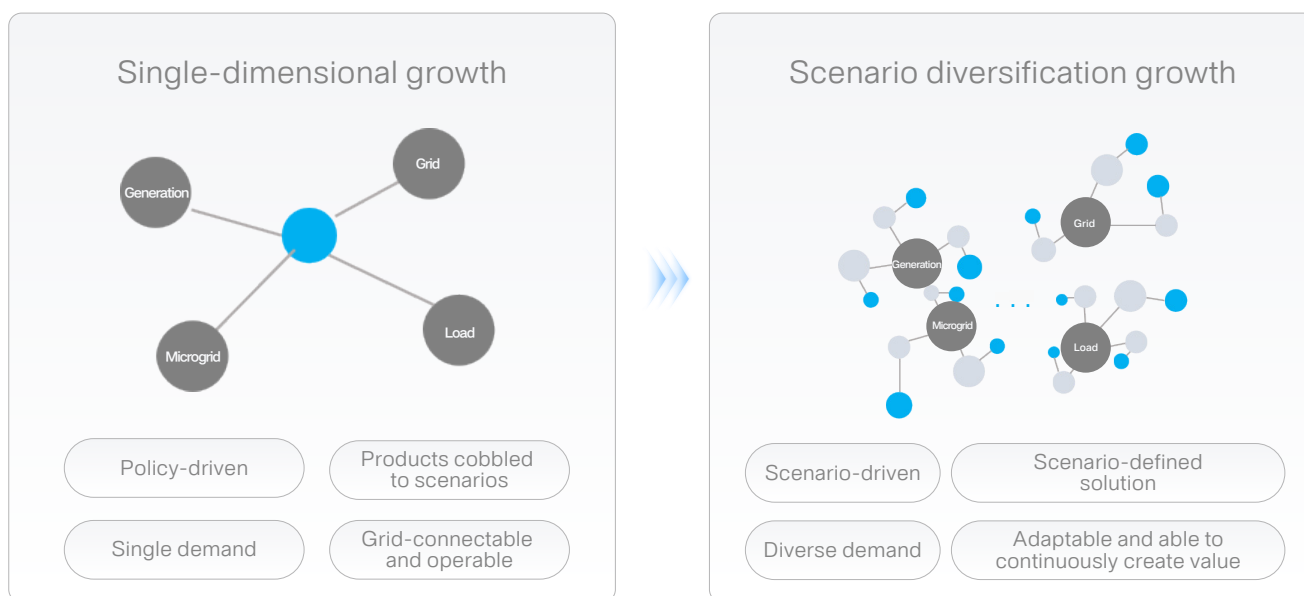


Figure 3: Energy Storage Scenario Evolution

1 Rising renewables reshape generation-side storage

Globally, the newly installed wind and solar capacity approached 700 GW in 2025, marking the transition from being a supplement to electricity increments to becoming a crucial pillar of the power structure.

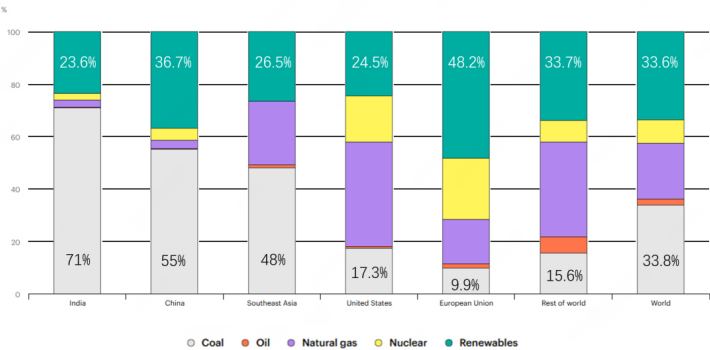


Figure 4: Electricity Generation Mix for Selected Regions, 2025, IEA

Different levels of renewable penetration create very different requirements for energy storage. Even within the broad category of generation-side storage, demand is becoming increasingly differentiated.

In large-scale PV hubs, power output is concentrated around midday, often exceeding transmission capacity. Long-duration storage is therefore needed to reduce curtailment and improve renewable integration. In regions with a high share of renewables, grid-forming storage is needed to support system stability. In remote power generation regions where electricity transmission is constrained, new local offtake models are emerging, such as storage-enabled hydrogen, ammonia, and methanol production, as well as direct green power supply to local loads.

In other words, curtailment reduction requires duration, grid forming requires fast response, and green hydrogen production requires system synergy. Even under the same label of “generation-side storage,” each scenario follows a different logic. The era of using one standard configuration for every application is coming to an end.

2 Grid-side storage revenue diversifies

As grid infrastructure ages and renewable penetration rises, conventional power systems are facing growing operational pressure. At the same time, power market reform is accelerating, and the value of grid-side energy storage is increasingly being discovered through market mechanisms rather than policy-based pricing. Because market structures differ across countries, energy storage also faces different participation models and revenue streams.

In the past, grid-side energy storage primarily focused on peak shifting and frequency regulation or peak-valley arbitrage. Now, the market focus varies across countries. For example, the UK primarily relies on the capacity market, Australia centers on frequency control ancillary services (FCAS), provinces in China have diverse spot market rules, and the Middle Eastern market is still under construction. The same energy storage system must play completely different roles in different markets.

Region in China	Market Category
Yunnan	Electricity arbitrage, ancillary services (secondary frequency regulation), regulation capacity (leasing)
Guizhou, Sichuan, Guangdong, Guangxi, Hainan	Electricity arbitrage, ancillary services (secondary frequency regulation), medium- and long-term transactions
Shaanxi, Hunan, Henan, Jiangxi, Jiangsu, Anhui	Electricity arbitrage, ancillary services (secondary frequency regulation)
Shandong, Gansu, Western Inner Mongolia, Qinghai, Xinjiang, Hebei South Grid, Liaoning, Hubei, Zhejiang	Electricity arbitrage, ancillary services (secondary frequency regulation), capacity compensation
Ningxia	Electricity arbitrage, ancillary services (secondary frequency regulation), medium- and long-term transactions, capacity compensation
Shanxi	Electricity arbitrage, ancillary services (primary frequency regulation, secondary frequency regulation)

Figure 5: Types of Energy Storage Markets in Different Regions

3 Load profiles shift, storage value diverges

Load-side applications are becoming increasingly differentiated. The shift is not only about higher electricity demand, but about new load profiles and value requirements.

AI computing brings high-power, pulse-like loads, where GPU training peaks can exceed traditional distribution capacity and even short interruptions may cause major computing losses. Ultra-fast EV charging hubs face limited grid connection capacity and highly variable demand, making energy storage a dynamic capacity buffer that helps serve random charging loads more economically.

For sustainable industrial parks, energy storage must go beyond cost reduction. It needs to support carbon management, local energy autonomy, and coordinated operation across generation, grid, load, storage, and energy-carbon coordination.

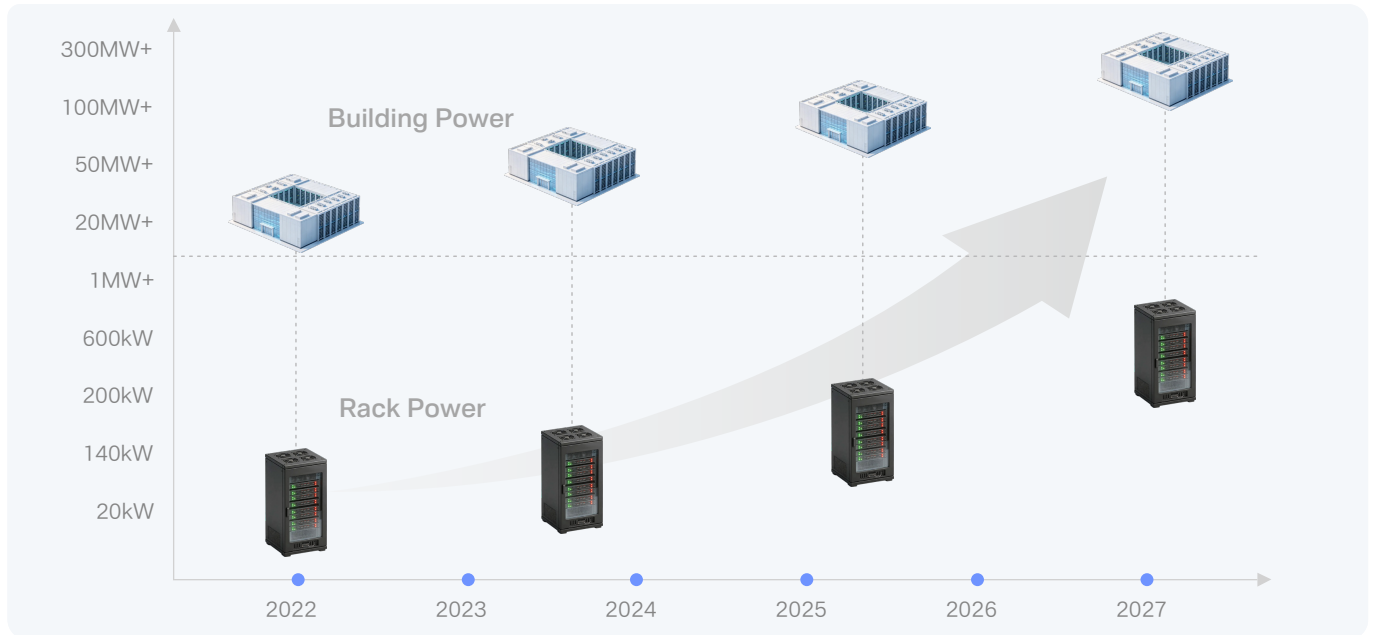


Figure 6: Rising Power Consumption of Computing Racks^①

The core challenge of load-side energy storage is not insufficient capacity, but inadequate responsiveness—not a lack of installed capacity, but a lack of ability to respond to load fluctuations, to coordinate multiple objectives, and to understand business-specific constraints. The dramatic changes in load patterns are accelerating the drive for energy storage to transition from a "supporting facility" to a dynamic regulation resource that coexists with business loads.

4 Microgrids expand, energy needs diversify

Driven by renewable energy alternatives, terminal electrification, and continuous production demands, the power supply system of micro-grid scenarios such as mines, oil fields, salt lakes, islands, remote counties, and emergency power supply is transitioning from traditional diesel-dominated power supply to a flexible power supply system centered on "power electronics + energy storage + control system".

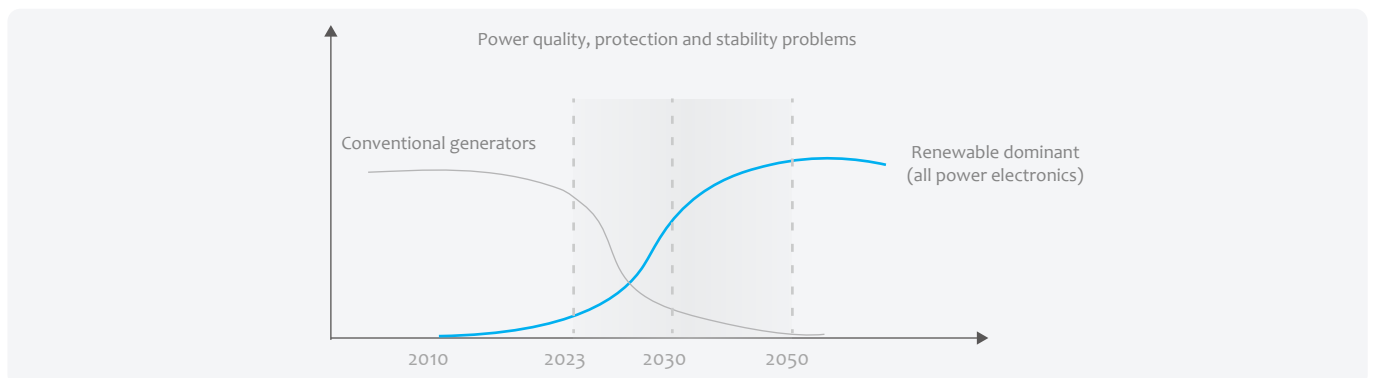


Figure 7: Mine Renewable Energy Replacement Path Diagram^②

① AI data center electricity demand is seeing rapid growth, with single-rack power rapidly climbing from tens of kilowatts to half a megawatt, or even 1 MW. Correspondingly, the total building-level power supply capacity has also jumped from 20 MW to over 300 MW.

② Data source: IEEE Electrification Magazine / MARCH 2024 <Mine Electrification and Power Electronics By Nesimi Ertugrul>

Microgrid scenarios are becoming more diverse as grid conditions, power supply responsibilities, and renewable penetration levels vary. In weak-grid areas, energy storage focuses on voltage and frequency support, load smoothing, and on/off-grid switching to improve edge-grid stability. In off-grid production sites such as mines, oil fields, and salt lakes, it must secure uninterrupted power for critical loads and enable fast recovery after faults. In island and remote community microgrids, the priority is long-duration supply and resilience during extreme weather. For mobile or temporary microgrids used in emergency response and remote border outposts, energy storage must support modular deployment, rapid microgrid establishment, and reliable operation.

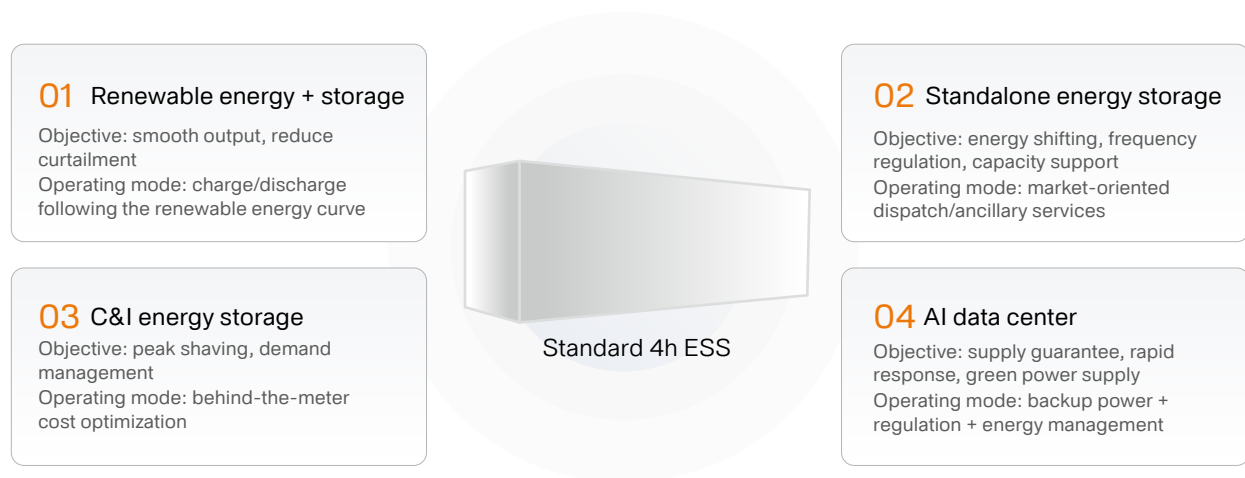
Energy storage is moving beyond a few typical use cases into a more complex stage defined by multiple constraints, multiple objectives, and deeper system coupling. As scenarios become more differentiated, standardized products and device-level capabilities are no longer enough. The challenge is shifting from equipment configuration to system-level adaptation, creating new demands for multi-scenario deployment.

1.2 The Era of Standardized Energy Storage Products Has Ended

As energy storage applications enter a deep cultivation stage, project complexity has extended from equipment configuration to system-level adaptation and long-term operation. Different scenarios have varied grid conditions and constraints, load profiles, operational goals, revenue mechanisms, and safety requirements. As a result, the challenges faced by energy storage solutions have shifted from "whether energy storage can be connected" to "whether energy storage can achieve precise adaptation, system-level synergy, and sustainable operation".

1 Different scenarios need different solutions

The differences between segmented scenarios are no longer just about capacity size or efficiency, but rather systemic differences reflected in load characteristics, control objectives, operating modes, and safety boundaries. The underlying assumption of standardized thinking is to use product parameters to cover scenario requirements. This assumption could solve basic operational problems in the past, but today it is difficult to achieve precise adaptation, economic configuration, and long-term operation simultaneously. In other words, scenario differences no longer lie in "different parameters", but rather in "different operating conditions, different constraints, and different value objectives".



2 Patchwork integration creates more problems

Energy storage is increasingly added in wind, solar, charging, hydrogen, load, and control systems. However, in many projects, energy storage is still connected as an independent device, with scenario identification, system design, equipment selection, control policies, transaction operations, and maintenance completed in segments, forming a cobbled project structure with multiple devices, multiple vendors, and multiple systems. Each scenario needs more than a standalone component. It needs a complete solution designed around the scenario itself.

A project cobbled together from multiple devices, multiple vendors, and multiple systems may look like "integration" on the surface, but is in fact "patchwork". With each component operating in its own way, design and operation are inevitably disconnected. Patchwork integration can solve the problem of "getting connected" in simple scenarios. However, in deeply coupled generation-grid-load-storage scenarios, separate definition and control of wind, solar, storage, load, and control will inevitably cause structural breakdown issues such as disconnection between design and operation, fragmentation of installation and commissioning, and disputes over after-sales responsibility.

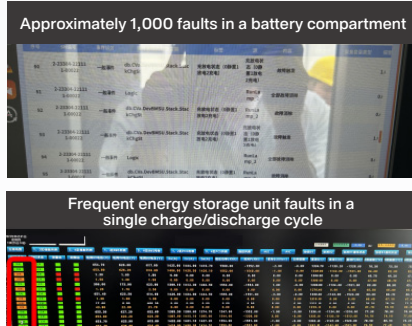
A power plant in Europe

Numerous interfaces for key equipment and difficulties in coordinating multiple manufacturers lead to grid connection failure after the plant has been installed and commissioned for 180 days.



A power plant in Asia

Devices are supplied by numerous vendors, some interfaces are inconsistent, and data is unsynchronized, resulting in chaotic control. The project failed on-site grid-connection acceptance after seven months of joint commissioning.



A power plant in Asia

Separately purchased core equipment and frequent DC/DC failures result in low system discharge capacity, inability to meet project requirements, and severe customer complaints.



Figure 8: Typical Multi-System Patchwork Risk Samples Based on Project Surveys, Anonymized

In a large-scale base project, the PV inverter, DC/AC Power Converter Unit, and battery system came from three different vendors. On-site integration of the communication protocol took nearly three months. Then, the system barely worked. However, in the first year of operation, issues such as inconsistent power fluctuations and delayed responses to dispatch commands occurred frequently. Each troubleshooting session required all three parties to be present simultaneously, and boundary responsibilities remained unclear.

3 Different markets need different strategies

In the early stages of energy storage application, project design often focused on a single objective such as peak-valley arbitrage or frequency regulation revenue. However, as energy storage gradually enters electricity spot markets, ancillary services, capacity compensation, and various complex dispatch scenarios, the focus has shifted from maximizing single revenue to multi-objective synergy of efficiency, service life, availability, power quality, and market-based returns.

A large energy storage asset portfolio in the UK once primarily relied on ancillary service revenues such as frequency response. As the original service mechanisms gradually phased out, the increasing grid-connected capacity of similar energy storage assets drove down ancillary service prices, and electricity market price differences narrowed, the underlying asset revenue of this portfolio decreased from £30.1 million to £20.5 million in the first half of 2023, a reduction of approximately 31.9%. Specifically, traditional frequency response revenue decreased by about 48%, and dynamic response revenue decreased by about 62%. This indicates that a single revenue logic is insufficient to support the long-term value realization of energy storage assets.

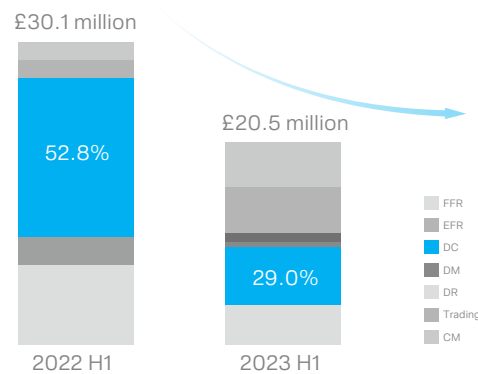


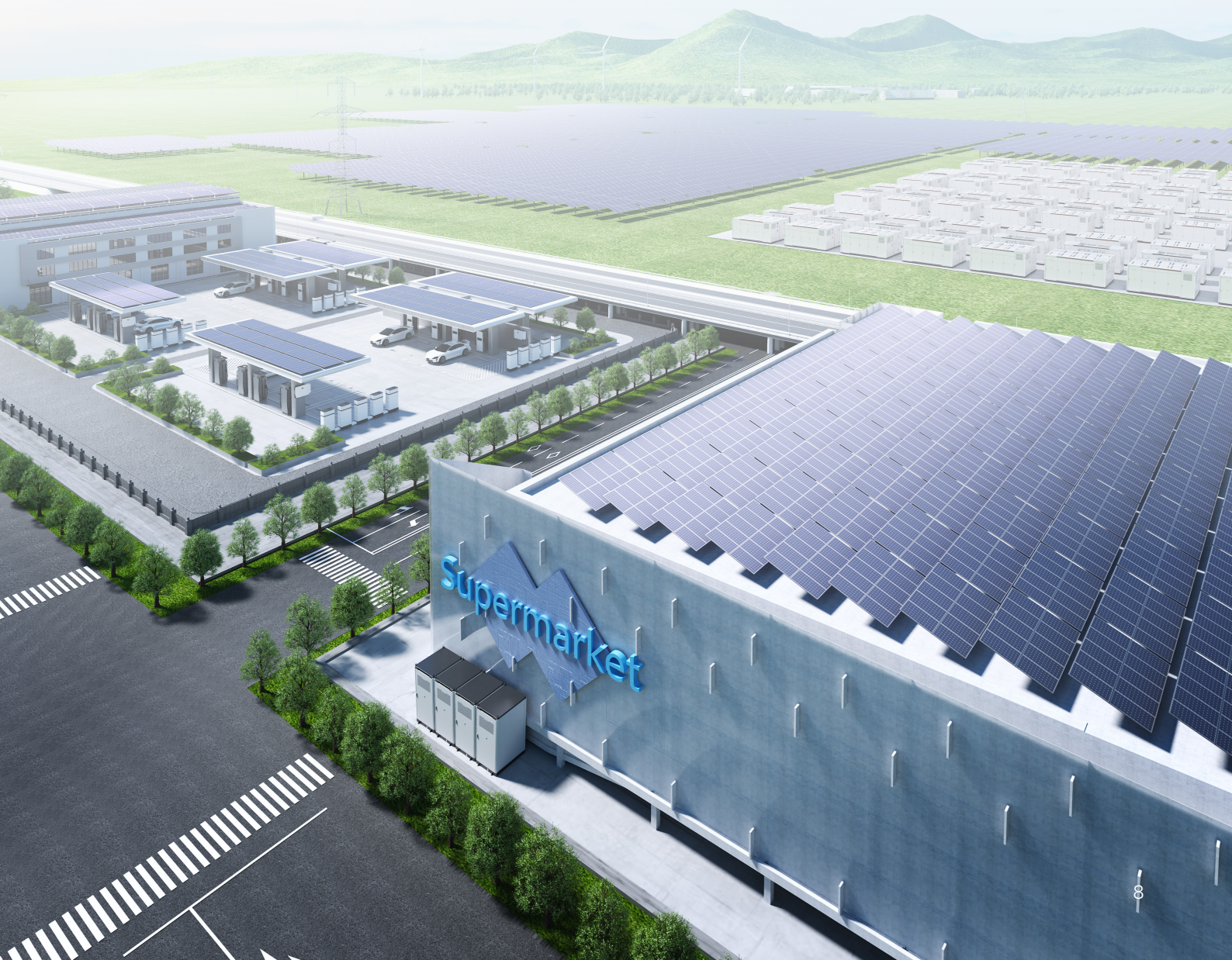
Figure 9: Changes in Revenue Composition for a UK Energy Storage Asset

Therefore, the economic value of energy storage cannot be measured by "how much it earns today" alone. It must also consider "how long it can continue to earn in the future", "how much residual value the equipment will retain", and "how long the availability can be sustained". Local optima does not mean global optima, and short-term gains do not equate to full-lifecycle returns.

Chapter Summary

In the future, energy storage will be ubiquitous, and the trend toward scenario differentiation is irreversible. On one hand, scenarios are constantly fragmenting and subdividing, each defined by distinct boundary conditions, increasingly complex operational objectives, and a growing number of devices requiring synergy. On the other hand, the industry still relies on a handful of standardized product models to address complex system problems through piecemeal solutions. This mismatch between technology supply and scenario demands constitutes the core contradiction in the energy storage industry today, rendering the old paradigm unsustainable.

A single product cannot accommodate multi-scenario requirements, and piecemeal system designs cannot deliver long-term viability. Individual equipment capability does not equate to system-level performance, and project commissioning does not equate to value realization. What energy storage demands is not merely superior hardware, but a new paradigm that originates from specific scenarios, leverages system-wide synergy, and continuously unlocks tangible value.



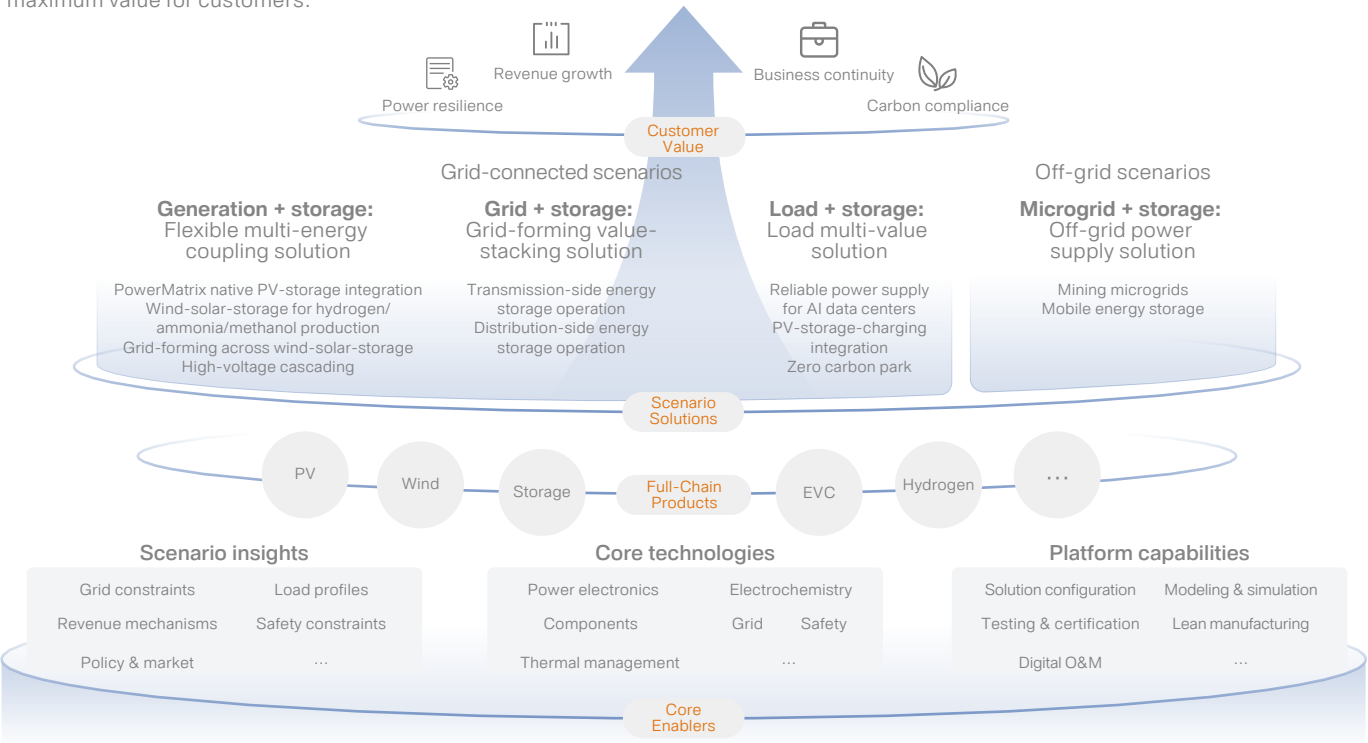
C2

S+ Energy Storage: Scenarios Vary. Needs Differ. Unified by One Core.

A Systematic Value Creation Framework for Diverse Scenarios



Sungrow adopts a scenario-driven approach, leveraging deep insights into application environments, grid dynamics, and load requirements. Drawing on nearly three decades of power electronics expertise and global engineering practice, the company integrates its proprietary, end-to-end capabilities across solar, wind, storage, EV charging, and hydrogen systems. This synergy delivers the S+ Energy Storage Multi-Scenario Solution, a systematic framework engineered to precisely adapt to diverse operating conditions and unlock maximum value for customers.



S+ Energy Storage | Scenario · Synergy · Sustain

Figure 10: S+ Energy Storage Multi-Scenario Solution Architecture

"S+ Energy Storage" represents a scenario-anchored paradigm built on full-stack, intrinsic synergy and dedicated to delivering long-term value across the entire lifecycle. "S+" is far more than a simple aggregation of products; it is about delivering fully integrated solutions tailored to real-world applications. It embodies the core logic of value creation in energy storage:

Scenario
Where should energy storage be positioned?

Scenarios define requirements; energy storage serves them. Rather than a superficial "energy storage + scenario" overlay, the process begins by deeply analyzing scenario-specific value requirements and then defining the optimal role of storage within the system. While the scenario originates value, energy storage acts as the vehicle to realize it.

Synergy
How do multiple devices operate as a unified system?

Beyond mere component assembly, true synergy is built on a shared technological foundation. By establishing a unified control logic at the system architecture level, we enable coordinated strategy execution. A fragmented solution cannot achieve a system-level optimization. Ultimately, the strength of a value chain is measured not by the sheer number of components, but by the seamless coordination of the entire system. Designed for system-level integration, it inherently operates with maximum efficiency.

Sustain
Can value be sustained across the full lifecycle?

The ultimate objective extends beyond initial commissioning to continuous value generation. As a long-term asset, energy storage operates in a dynamic environment shaped by evolving policies, market mechanisms, and load demands. Solutions must therefore feature inherent long-term adaptability. The financial viability of energy storage is determined not by short-term returns, but by the value it consistently delivers over a decade-long lifespan.

2.1 Grid-Connected Scenarios

To address the diverse needs of generation, grid, and load-side systems, the "S+ Energy Storage" paradigm delivers multiple solutions, such as flexible multi-energy coupling, grid-forming trading integration, and coordinated management for emerging loads. Rather than covering every niche scenario, this paper highlights typical application cases to demonstrate how "S+ Energy Storage" architects systems and delivers long-term value under varying constraints, serving as a systematic reference for global energy storage deployments.

2.1.1 Generation + Storage | Flexible Multi-Energy Coupling Solutions

As renewable energy penetration continues to rise, generation-side energy storage faces three structural challenges:

Temporal and spatial mismatch between generation and consumption: Power generation and demand are temporally and spatially misaligned, leading to a continuous cycle of curtailment and supply deficits.

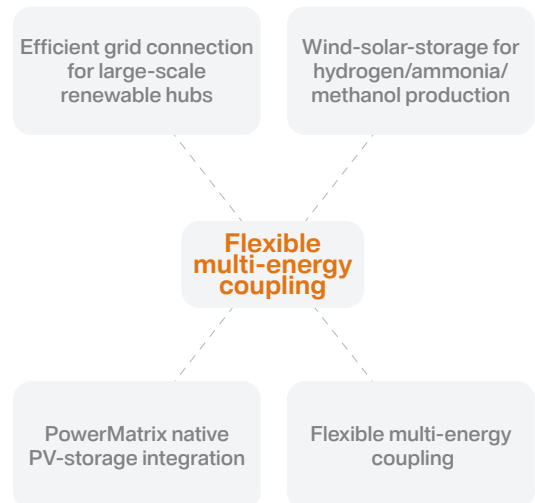
Mismatch between intermittent renewable generation and uninterrupted load demands: Renewable output depends heavily on meteorological conditions, while industrial loads, such as chemical manufacturing, require continuous power. Consequently, volatile supply cannot sustain stable production.

Grid instability under high renewable penetration: Reduced system inertia and insufficient voltage and frequency support mean that mere addition of conventional energy storage does not guarantee grid stability.

Conventional storage deployment often relies on external system overlays or loose local coupling, where PV, energy storage, and the grid operate in silos. As renewable penetration continues to mount, this siloed approach falls short of supporting uninterrupted power delivery, proactive grid stabilization, and system-level economic optimization, necessitating a paradigm shift at the system architecture level.

Leveraging its extensive experience in generation-side applications, "S+ Energy Storage" has developed four flagship solutions: native PV-storage integration (positioning high-penetration renewables as a primary power source); integrated wind-solar-storage for hydrogen/ammonia/methanol production (ensuring continuous green power delivery for green chemical manufacturing); wind-solar-storage grid-forming systems (providing proactive grid support in complex grid conditions); and high-voltage cascading solution (enabling efficient grid integration for large-scale renewable energy hubs).

Ultimately, these four solutions share a single mission: transforming renewable energy plants from "intermittent power sources" into controllable, grid-friendly, and system-value-driven energy assets.



(1) Continuous green power supply

PowerMatrix native PV-storage integration solution

As PV generation transitions into a primary power source, the central challenge for generation-side plants lies in converting their intermittent and volatile output into stable, dispatchable, and grid-supportive green power. Conventional PV-storage solutions often remain limited to external system overlays or loose local coupling, with PV, energy storage, grid connection, and control platforms operating in silos. Energy flows along predetermined paths, and system stability remains heavily reliant on external grid strength or auxiliary compensatory resources. As renewable penetration continues to mount, this fragmented approach falls short of ensuring continuous power supply, proactive grid support, and system-level economic optimization under high-penetration scenarios, necessitating a paradigm shift at the system architecture level.

PowerMatrix native PV-storage integration solution

The natively integrated PV-storage solution is anchored in the revolutionary PowerMatrix architecture. Through multi-port DC integration, modular power units, and a unified control framework, the solution orchestrates seamless, intrinsic synergy between PV, energy storage, and the grid. This architecture establishes a fully integrated energy network supporting multi-source integration and multi-path energy routing, driving an engineering transition from device-level connectivity to true system-level integration. Under this paradigm, energy storage is no longer relegated to an external balancing unit; instead, it becomes an inherent capability deeply embedded within the plant's core architecture. Simultaneously, PV ceases to be a mere intermittent power source and is transformed into a controllable, grid-supportive pillar of stable power generation.

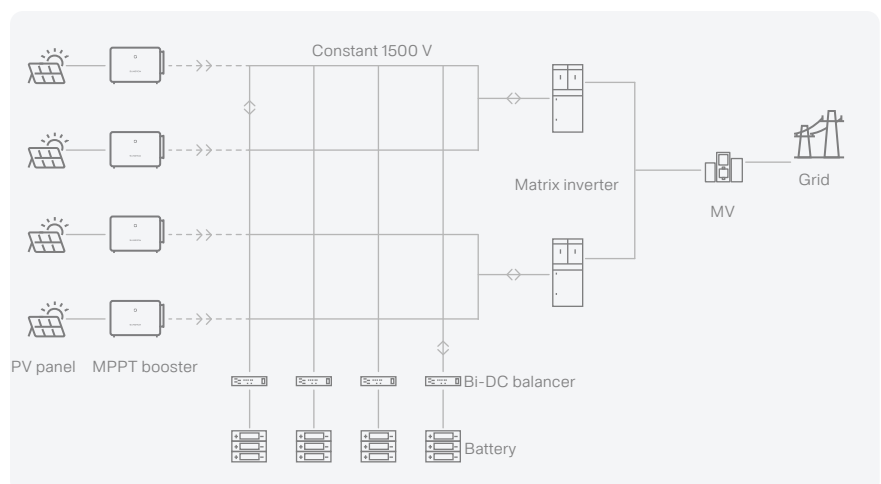


Figure 11: PowerMatrix Native PV-Storage Integration Topology

Strengths

Multi-port integration: Through standardized interfaces, unified PV-storage access, coordinated multi-port dispatch, and modular expansion, traditional generation-side and load-side components are progressively abstracted into unified "virtual energy ports." Based on real-time grid conditions, the system dynamically determines the optimal power flow and operational mode for each port.

Native PV-storage integration: By redefining the role of energy storage, augmenting PV capabilities, embedding coordination mechanisms, and improving operational efficiency, the system achieves profound structural synergy and is natively endowed with DC-side coordinated access, energy dispatch, and PV-storage co-optimization.

Hierarchical coordinated control: Utilizing a hierarchical control architecture that integrates "centralized coordination with localized autonomy," each core node possesses independent regulation and protection functions. This enables the system to maintain centralized dispatch while leveraging the rapid response of edge nodes, delivering scalability, robustness, and grid-dispatch compatibility.

Generation-side grid-forming: By embedding grid-forming capabilities directly into the PV-storage generation units, the system delivers local voltage support, frequency stabilization, inertia response, and coherent disturbance rejection within subarrays. This shifts grid stability from a centralized model to a decentralized framework, ensuring robust resilience under complex grid conditions.

Reconfigurable energy paths: Supporting multi-path redundancy, millisecond-level dynamic switching, and adaptive path routing, this feature ensures uninterrupted system operation and overall reliability.

Application value

Stability redefined

Leveraging multi-port integration, native PV-ESS synergy, generation-side grid-forming control, and hierarchical coordinated orchestration, the stability of the power plant is transformed from an externally compensated constraint into an intrinsic system capability. Annual equivalent operating hours can double, surging from approximately 1,500 hours in conventional PV plants to over 3,000 hours, matching the baseline availability of traditional baseload power sources.

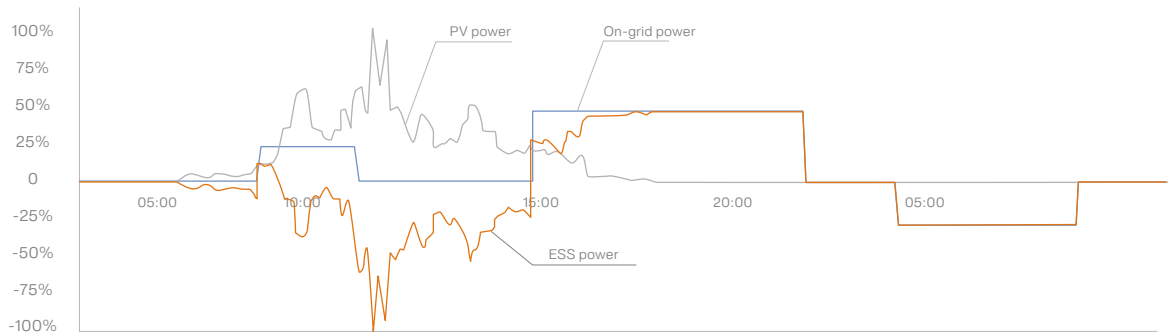


Figure 12: The Solution Smooths Output Curve

Cost redefined

Through a unified system architecture and coordinated resource allocation, cost reduction is no longer at the mercy of declining equipment commodity prices. Instead, continuous Balance of System (BOS) optimization is achieved through structural hardware integration, streamlined field engineering, flexible capacity configuration, and holistic lifecycle optimization.

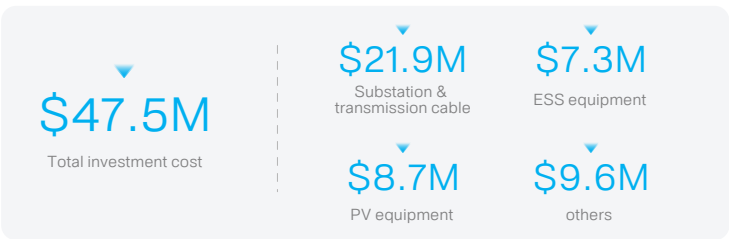


Figure 13: Initial PV-Storage Investment Savings®

End-to-end efficiency redefined

Driven by advanced topology integration and routing mechanisms, full-chain, end-to-end efficiency gains are unlocked from generation to load, boosting the energy yield by more than 5%.

③The calculation is based on a 1 GW rated plant output, a 0.5 GW / 2 GWh energy storage configuration, and 2,500 annual generation hours, compared with an AC-coupled solution.

(2) Local consumption of large-scale green power

Integrated wind-solar-storage for hydrogen/ammonia/methanol production solution

In regions rich in wind and solar resources, green hydrogen-derived chemicals (such as green hydrogen, ammonia, and methanol) are emerging as a pivotal pathway for mitigating renewable energy curtailment and accelerating high-ratio integration. However, these projects typically operate under severe operational constraints, including weak-grid or entirely off-grid environments, high volatility of wind and solar outputs, and the strict, uninterrupted operating thresholds of downstream chemical synthesis.

The core engineering challenge lies not merely in the physical interconnection of wind, solar, battery storage, electrolyzers, and chemical synthesis units, but in establishing a flexible, dynamically balanced coupling framework that renders the relationship between highly variable green power supply and continuous chemical processes controllable, dispatchable, and resilient.

Without a unified architectural design and co-optimized system control, these plants are highly vulnerable to unstable power allocation, excessive dynamic throttling of process equipment, elevated curtailment, interrupted hydrogen feedstocks, and sluggish fault recovery. Ultimately, these systematic issues severely compromise renewable energy utilization efficiency, product supply continuity, project economics, and operational safety.

Integrated wind-solar-storage for hydrogen/ammonia/methanol production solution

Aligned with its "S+ Energy Storage" engineering philosophy, Sungrow has pioneered a fully integrated wind-solar-storage for hydrogen/ammonia/methanol production solution, built upon proprietary end-to-end technologies. Rather than relying on a rigid, single-path architecture, the solution flexibly deploys customized AC- or DC-coupled topologies tailored to site-specific resource configurations, grid impedance (strength), chemical load characteristics, and project LCOE constraints.

This approach enables highly synchronized, multi-energy orchestration across wind/solar generation, energy storage systems, electrolytic hydrogen systems, hydrogen storage, and downstream chemical synthesis units. By maintaining robust voltage and frequency stability in weak-grid or off-grid scenarios, performing multi-timescale coordinated dispatch of generation, storage, load, and hydrogen systems, and leveraging continuous hydrogen supply assurance, the solution successfully transforms intermittent green electrons into highly reliable, continuously dispatchable industrial energy molecules.

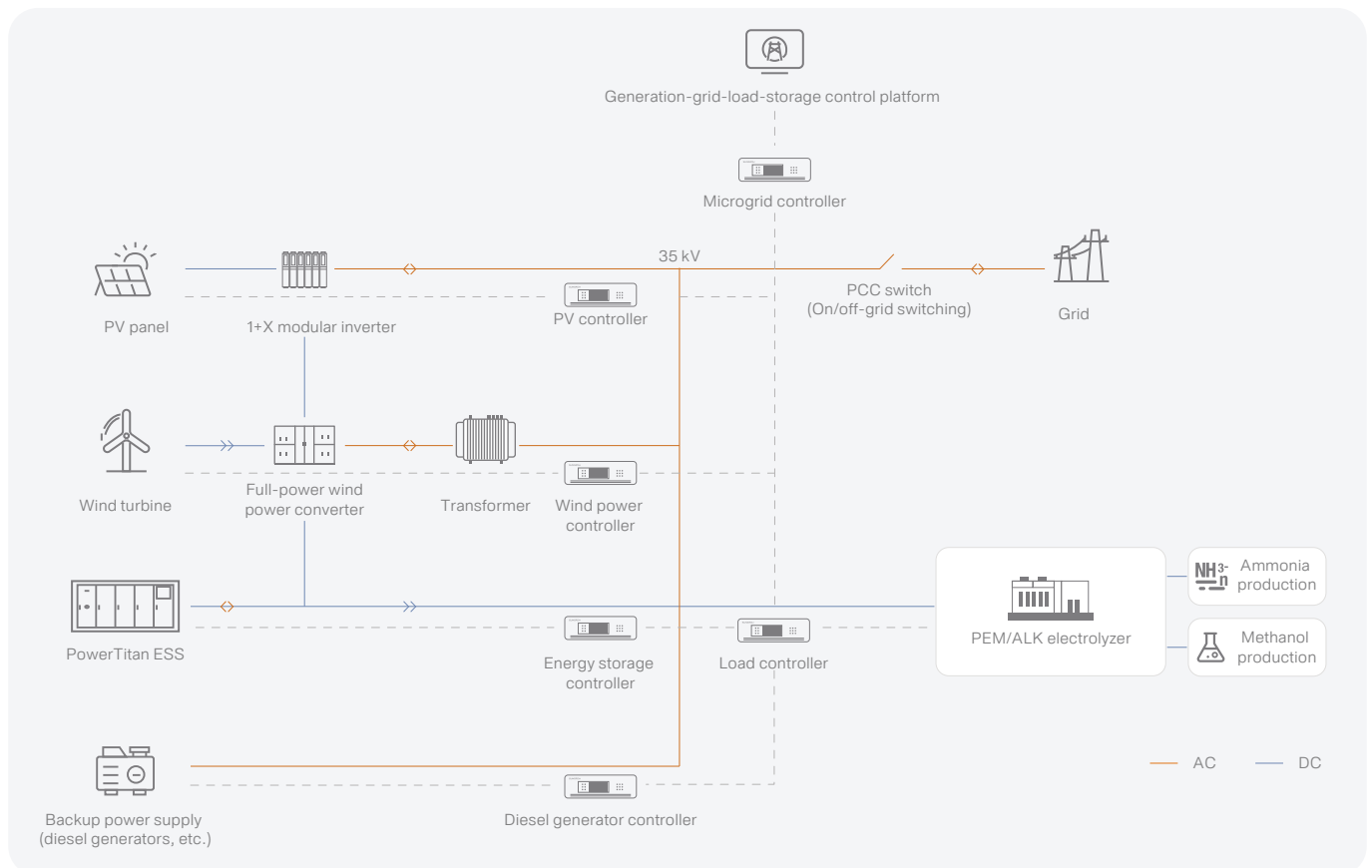


Figure 14: DC-Coupled Topology: Wind-Solar-Storage for Hydrogen/Ammonia/Methanol Production

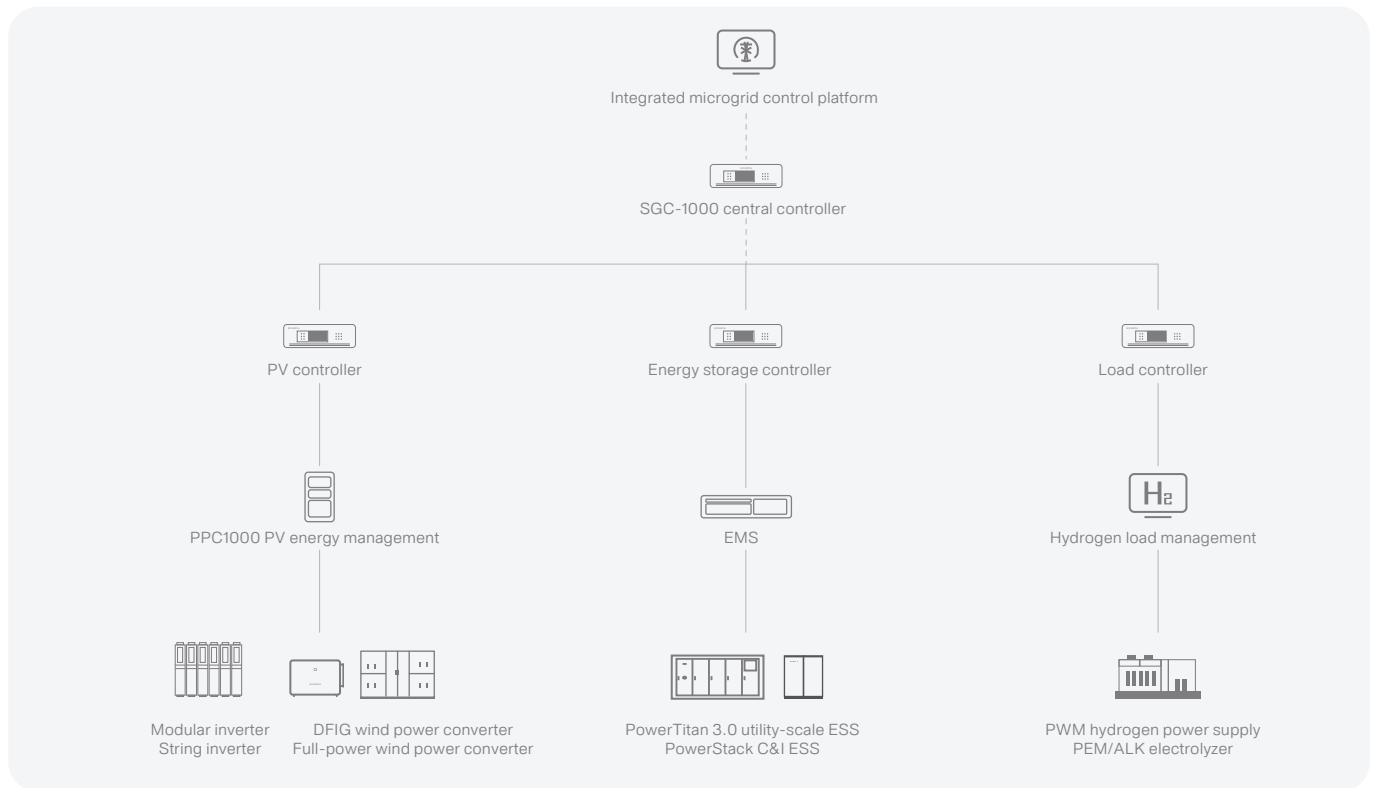


Figure 15: AC-Coupled Topology: Wind-Solar-Storage for Hydrogen/Ammonia/Methanol Production

Strengths

Enhanced grid stability and rapid fault recovery:

Integrating grid-forming energy storage, microgrid control, and multi-source coordination to improve voltage and frequency stability under weak-grid or off-grid conditions. This approach mitigates the impact of wind-solar volatility and load disturbances on system operation and supports rapid post-fault recovery.

Improved utilization efficiency and system economics:

Optimizing AC/DC architecture selection, system capacity allocation, and energy management strategies to reduce renewable curtailment and conversion losses, thereby improving renewable energy utilization, electrolyzer utilization levels, and overall system economics.

Unified generation-grid-storage-load-hydrogen orchestration:

Performing multi-timescale coordinated dispatch based on wind-solar output forecasts, energy storage status, electrolyzer operating characteristics, and downstream continuous hydrogen demand, thereby balancing short-term power, regulating hydrogen production loads, and ensuring continuous hydrogen supply.

Stable operation of downstream chemical processes:

Coordinating volatility regulation on the hydrogen production side with continuous supply from the storage side to meet the continuous process demands of ammonia and methanol production. This minimizes the impact of wind-solar volatility on downstream chemical loads while enhancing the continuity and predictability of green hydrogen, green ammonia, and green methanol production.

Application value

Green power conversion

Transforms remote wind and solar resources from basic power generation and consumption into low-carbon products such as green hydrogen, green ammonia, and green methanol, enhancing local renewable energy utilization and regional industrial capacity.

Continuous production

Through the coordinated operation of energy storage, electrolyzers, hydrogen storage, and chemical-process loads, the solution mitigates the impact of renewable energy fluctuations on continuous production, enabling green power to be integrated into chemical processes more reliably and steadily.

Carbon compliance

Reduces dependence on fossil fuels and lowers product carbon footprints, supporting the low-carbon application of green hydrogen, green ammonia, and green methanol in chemicals, metallurgy, and marine fuels.

Case: Off-grid PV-storage-hydrogen project in Italy

Project configuration:

5 MW/10 MWh energy storage + 7 MW PV + 3 MW hydrogen production system

Challenges:

Operating under off-grid conditions without external grid access, the project faces highly fluctuating PV output, making it difficult to meet the continuous operational demands of electrolyzers. Furthermore, coupling PV, storage, and hydrogen systems increases operational complexity; without unified control and coordination, system efficiency can decline and operational risks may escalate.

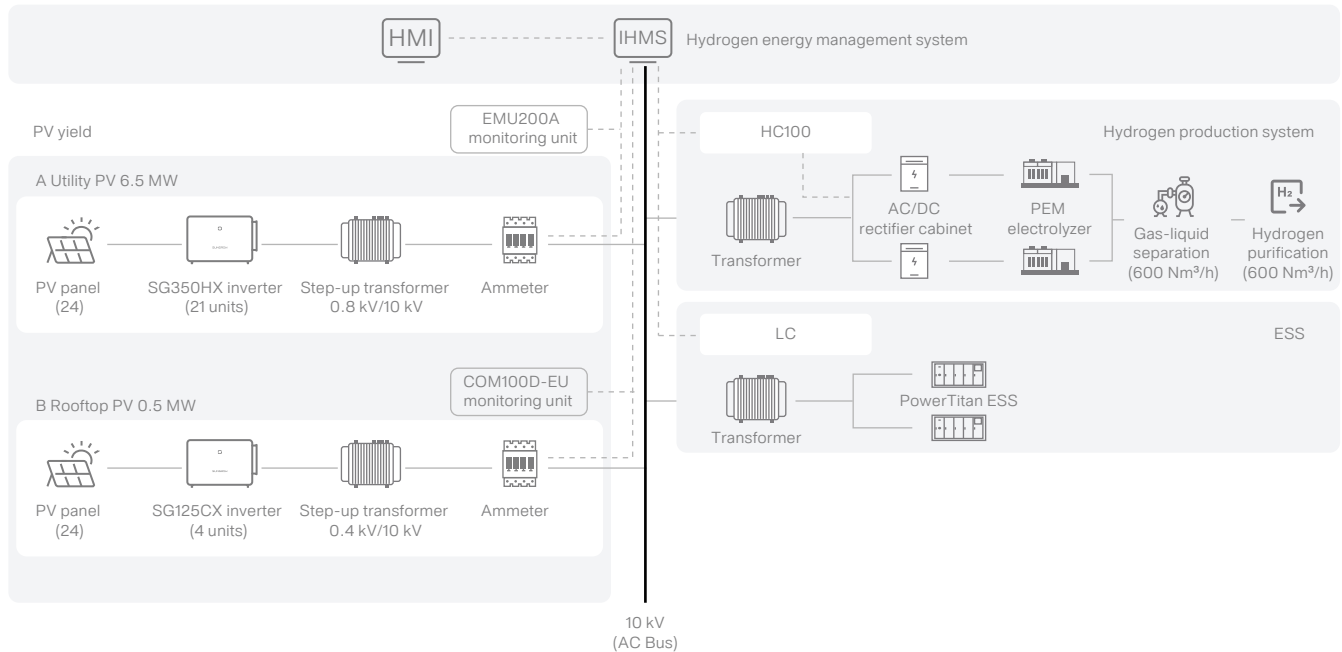


Figure 16: Architecture of the Sistemi Energetici Off-Grid PV-Storage-Hydrogen Project in Italy

Value:

Coordinating energy storage, PV generation, hydrogen-production loads, and the energy management system (EMS) enables grid-forming capability, fluctuation smoothing, and rapid recovery for the off-grid system. This value is demonstrated in three key areas:

Enabling independent off-grid operation and reducing reliance on the external grid: The energy storage system serves as the primary voltage source, providing stable voltage and frequency references for PV and hydrogen-production equipment. This ensures independent operation under weak-grid or off-grid conditions, improving the feasibility of remote green hydrogen projects.

Smoothing green power fluctuations and ensuring stable hydrogen production: Coordinated charge-discharge regulation and system-level energy management mitigate PV power fluctuations, delivering stable power input to electrolyzers. This reduces the impact of frequent fluctuations on hydrogen production efficiency, equipment lifespan, and system safety.

Enhancing system resilience and reducing downtime and recovery costs: Under extreme weather, system faults, or grid outages, the energy storage system supports critical loads and enables rapid system recovery. This reduces total system downtime and minimizes green hydrogen production losses, thereby enhancing operational reliability and project bankability.

(3) Grid stability with high renewable penetration

Grid-forming solution across wind-solar-storage scenarios

For large-scale bases characterized by long-distance transmission, extremely weak grid access, and wide-frequency disturbances, the grid-forming capability of a single energy storage unit cannot guarantee the stability of the entire plant. When wind and PV systems independently attempt grid forming, variables such as fluctuating inputs, limited overload support, and inconsistent responses among multiple devices make plant-level coordination an unresolved challenge. For example, in a GWh-scale project, core equipment may come from 3 to 4 different manufacturers, each with distinct communication protocols, control logic, and response characteristics. Lack of coordination among these devices often leads to oscillations, loss of synchronism, and harmonic amplification.

Grid-forming solution across wind-solar-storage scenarios

In its "S+ Energy Storage" practice, Sungrow developed a system-level grid-forming solution. By integrating coordinated control of wind, solar, and storage converters with multi-energy coupling technologies, these assets are managed within a unified control framework. Utilizing full-stack, in-house developed AC and DC equipment and end-to-end system synergy, this approach avoids the compatibility and integration issues typical of multi-vendor systems. Through triple-layer coupling, it achieves a transition from component-level grid-forming to system-level grid stabilization.

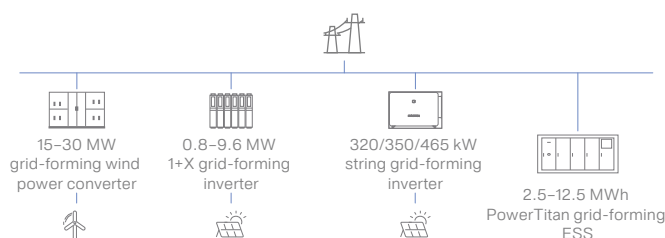


Figure 17: Grid-Forming Solution Across Wind-Solar-Storage Scenarios

- 1. Capacity optimization:** Optimizing energy storage sizing to achieve grid-forming performance with a minimum storage capacity ratio of 6%, balancing economic efficiency and system stability.
- 2. Solar-storage DC coupling:** DC-side coupling of PV and energy storage establishes a stable DC link with power-buffering capability. This enables inertia-like response characteristics and significantly enhances the grid-forming capability of the PV system.
- 3. Wind-storage heterogeneous coordination:** DC-side coupling of wind power and energy storage reconstructs the active power loop and drivetrain damping characteristics. This suppresses drivetrain oscillations caused by electromechanical-grid coupling in grid-forming wind turbines, extending mechanical lifespan and improving overall system robustness.

Backed by 20 years of expertise in grid-forming technology, over 1,000 GW of global grid-connected installations, the world's largest simulation and testing platform, and the industry's most extensive portfolio of grid access permits, Sungrow delivers tailored solutions for diverse power systems. This facilitates flexible deployment, more economical power generation, transmission, distribution, and consumption, while providing all-weather self-sufficient support and grid stability.

Strengths

Enhanced stability under complex grid conditions:

Supporting SCR 1-40 wide-range adaptability, tolerating asymmetrical sags with $\pm 180^\circ$ phase jumps, and improving the stable operation of renewable energy plants under challenging transmission conditions.

Proactive oscillation suppression:

Monitoring multi-band oscillations from 0.1 Hz to 2.4 kHz and providing active controllable damping on the PV side, while enabling adaptive, precise suppression of drivetrain oscillations from 1 to 10 Hz on the wind side (with a power response time under 40 ms). This reduces the risk of wide-band oscillations in wind-solar-storage coupled systems.

Rapid fault support:

Delivering up to three times the rated fault current during transient voltage fluctuations of 0 pu to 1.3 pu, strengthening active support during disturbances, fault ride-through, and voltage recovery.

Consistent system synergy:

Managing wind, solar, and storage under unified control and multi-energy coupling ensures coordinated dynamic responses across converters, avoiding inconsistencies caused by independent device control. This enables the plant to transition from component-level grid-forming to system-level grid stability.

Application value



Enhanced grid integration

Enabling stable grid connection for high-penetration renewable energy plants under weak-grid, long-distance transmission, high-altitude, and complex disturbance conditions. GW-scale plants can achieve 100% grid-forming operation around the clock, addressing weak-grid stability issues and reducing grid connection bottlenecks caused by low grid strength.



Improved stable power delivery

Utilizing voltage support, oscillation suppression, and fault ride-through capabilities to lower the risk of islanding, curtailment, and unplanned outages, thereby improving the deliverability, grid integration, and dispatchability of renewable energy.



Enhanced system support value

Transforming renewable energy plants from passive generation units into active system resources, better meeting the stability, flexibility, and grid-friendliness requirements of high-penetration power systems.

Case: 7.8 GWh grid-forming energy storage project in Saudi Arabia

Project configuration:

7.8 GWh energy storage project

Challenges:

The project is facing challenges such as large scale, tight deadlines, complex scheduling, and high power grid requirements.

Value:

Utilizing Sungrow's PowerTitan 2.0 grid-forming energy storage system, the project supports GW-level black start, robust frequency and voltage regulation, and enhanced power system stability. Its high-energy-density AC storage design reduces land-related costs by 55%, while the pre-installed and pre-commissioned configuration enabled faster grid connection and rapid project delivery. The project achieved full-capacity grid-connected operation in 2025 and is designed to deliver stable and efficient returns throughout its lifecycle.



Figure 18: 7.8 GWh Grid-Forming Energy Storage Project in Saudi Arabia

(4) High-voltage grid connection for large-scale renewable energy hubs

Grid-forming high-voltage cascaded solution

For large-scale renewable energy hubs and high-capacity generation-side integration, energy storage systems must not only achieve grid connection, but also maintain long-term stable operation under high-voltage, large-capacity, and complex operating conditions. Traditional low-voltage parallel architectures with multi-stage voltage boosting entail longer system paths and more hardware stages. In large-scale plants, this can lead to higher conversion losses, wider fault propagation, and increased maintenance complexity.

Grid-forming high-voltage cascaded solution

In its "S+ Energy Storage" practice, Sungrow's high-voltage cascaded architecture links multiple energy storage units in series to directly produce 35 kV AC output. This configuration reduces intermediate step-up stages and improves system efficiency and engineering adaptability for large-capacity generation-side integration. Furthermore, dual-control dual-link architecture and fault-tolerant derated operation enhance the system's ability to maintain continuous operation during grid anomalies.

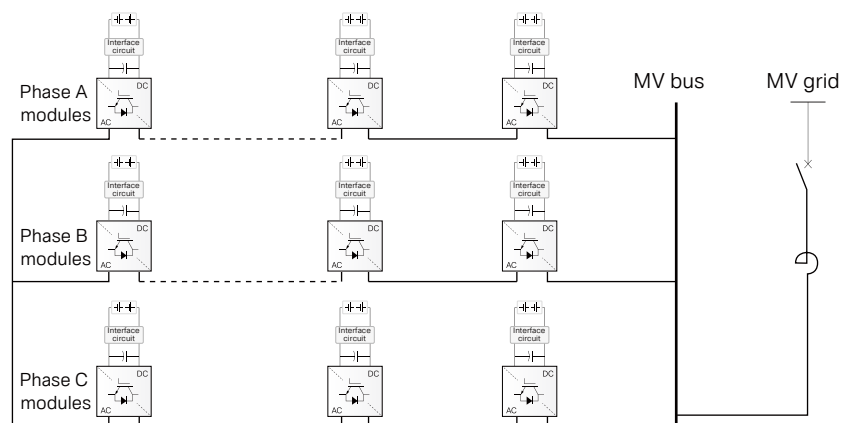


Figure 19: High-Voltage Cascaded Topology®

④ Multiple H-bridge-based energy storage units are directly connected in series to generate a 35 kV AC output, without set-up transformers.

Strengths

Shorter system paths and fewer devices:

Eliminating low-voltage DC/AC collection and step-up transformation stages to reduce transformer losses, while removing DC/AC combiner cabinets, LV switchgear, and MV step-up transformers for a simplified system configuration.

Fault isolation:

Supporting continuous operation even when up to 30% of local modules experience faults, ensuring that partial failures do not disrupt overall plant operation.

Dual-control dual-link architecture:

Implementing hot-standby redundancy for primary and backup controllers, combined with redundant critical communication links, to maintain operation during grid anomalies.

Rapid power response:

Achieving a system power response time of ≤ 30 ms to improve dispatch tracking and reduce grid deviations.

Application value



Reduced system losses and higher deliverable power

Improving generation-side integration efficiency by 3%–5% and increasing deliverable power by eliminating conversion stages.



Fewer unplanned shutdowns to protect revenue continuity

Minimizing full-plant outages caused by controller or communication failures, thereby enhancing plant availability and reducing energy generation and market transaction losses.



Fault localization for higher asset utilization

Limiting fault escalation to ensure that the storage plant can continuously participate in power dispatch, arbitrage, and ancillary services under complex operating conditions.



Less equipment and lower investment

Lowering initial capital expenditure (CAPEX) and long-term costs associated with equipment procurement, civil engineering, system integration, and operation and maintenance.

2.1.2 Grid + Storage | Grid-Forming Value-Stacking Solution

Grid-side energy storage is evolving from a device that simply connects to the grid into a dispatchable, operable, and value-generating grid resource.

Whether on the transmission side or the distribution side, energy storage is no longer limited to single functions such as energy shifting or frequency regulation. It is taking on a dual role: supporting grid stability while also operating as a power asset that can participate in markets and improve project returns.

In practice, however, many storage systems still face limitations. Some operate in isolation and cannot coordinate with other resources. Some can provide ancillary services, but rely on a narrow revenue model. Others are technically usable, but lack the flexibility to respond to changing market rules and grid requirements. As a result, the full value of energy storage is often not fully captured.

Based on the S+ Energy Storage approach, grid-side storage needs to move beyond a standalone grid-connected device and become a dispatchable, operable, and value-generating grid resource.

On the transmission side, the solution focuses on standalone storage and renewable-plus-storage projects. By combining grid-forming capabilities with market-oriented operation strategies, it helps projects participate in multiple markets while balancing grid support, revenue enhancement, lifecycle management, and asset operation efficiency.

On the distribution side, the solution focuses on transformer areas, communities, industrial parks, and other local-grid scenarios. Through integrated storage solutions, it improves the flexibility of edge grids, strengthens distributed resource aggregation, and supports more market-oriented operations.

(1) Grid edge management and distributed resource operations

Distribution-side energy storage solution

The core challenge of distribution-side energy storage is shifting from a simple capacity shortage to dynamic power quality management and aggregated operation of distributed resources. On one hand, the increasing penetration of distributed PV, charging loads, and diverse types of electrical equipment introduces high volatility and stochastic behavior at the distribution grid edge. Issues such as reverse power flows, voltage violations, harmonics, and three-phase imbalance have become more pronounced, rendering traditional capacity expansion and static compensation approaches largely ineffective. On the other hand, decentralized energy storage, PV, and controllable loads often lack unified modeling, dispatch, and operational frameworks. They typically operate only in local peak-shaving or standby modes, making it difficult to form aggregated resources that are callable, tradable, and capable of value creation.

To address these challenges, distribution-side energy storage must provide both local dynamic management and platform-level aggregated operational capabilities. At the local level, energy storage coordinated with the EMS can dynamically regulate terminal voltage fluctuations, reverse power flows, and load disturbances. At the platform level, a VPP aggregation platform enables unified modeling, forecasting, aggregation, and operation of distributed resources, forming a closed-loop workflow of "power quality management, resource aggregation, and revenue operation".

Distribution-side energy storage solution

In the "S+ Energy Storage" practice, the distribution-side energy storage aggregation solution centers on distribution-side energy storage + EMS + VPP aggregation platform, transforming decentralized energy storage, distributed PV, and flexible loads into observable, aggregatable, dispatchable, and operable flexibility resources at the distribution level.

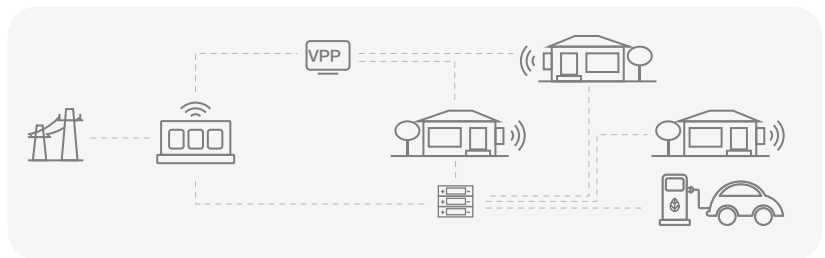


Figure 20: Distribution-Side Energy Storage Topology

Strengths

Dynamic management

Dynamically responds to changes in voltage, load, and PV generation, enhancing the operational stability of distribution grid edge nodes.

Aggregated operation

Distributed energy storage systems, PV resources, and flexible loads can be uniformly modeled and centrally managed, forming a resource pool that is predictable, dispatchable, and market-ready.

Scenario-friendly

Easy to deploy, quiet, safe, and easy to maintain, making it well suited for residential communities and urban environments.

Application value



Relieving expansion and upgrade pressure

By leveraging real-time regulation and resource aggregation, the distribution grid's capacity to accommodate distributed renewable energy and emerging load types is increased.



Expanding revenue streams

Through the combination of local management, aggregated operation, and market participation, asset utilization and long-term operational value are improved.



Optimizing end-user energy experience

Reduces electricity costs, saves up to USD 30,000 in equipment procurement, and provides residents and communities with a more stable, comfortable, and cost-effective energy supply.

Case: Ausgrid 125 kW/257 kWh FCAS community energy storage project, Australia

Community energy storage installations in Australia are typically deployed in residential areas or at the distribution grid edge, placing stringent constraints on noise levels and long-term reliability. To ensure seamless integration, the system must mitigate environmental impact on adjacent residents. Furthermore, as business models for community energy storage mature, investor expectations have transitioned from basic backup power and peak shaving toward broader value-stacking. Consequently, operations focus on improving asset utilization, capturing auxiliary revenue from ancillary service markets, and enhancing system economics.



Figure 21: FCAS Frequency Regulation Project in Australia

Powered by Sungrow's PowerStack series energy storage system, the project delivers an integrated solution combining hardware-level noise reduction and rapid EMS dispatch, tailored to the requirements of Australia's FCAS ancillary services market.

At the system level, the low-noise design and high operational reliability enable unobtrusive operation in community environments, minimizing the risk of resident complaints. The solution also improves system availability and supports long-term project sustainability.

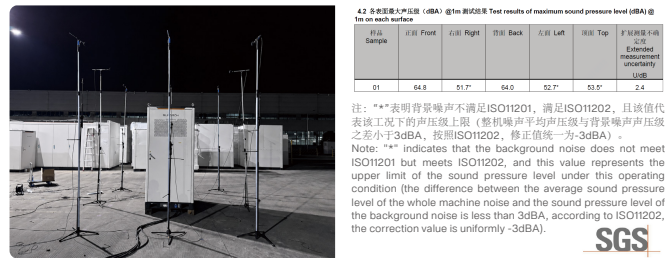


Figure 22: SGS Noise Test Results for the PowerStack Series ESS, Noise Level < 65 dBA

At the asset operation level, the system participates in Frequency Control Ancillary Services (FCAS) markets during non-discharge periods, improving asset utilization. While maintaining reliable power supply, market participation unlocks additional revenue streams, yielding an estimated 5% increase in returns. This transitions community energy storage from a dedicated power supply asset into a valuable grid-flexibility asset.

2.1.3 Load + Storage | Load Multi-Value Solution

Load-side energy storage is no longer just about reducing electricity costs. As new load scenarios such as AI data centers, ultra-fast charging stations, and zero-carbon parks continue to grow, energy storage must address multiple needs at once: power reliability, energy cost optimization, grid capacity constraints, and local renewable integration.

Different loads behave very differently. AI data centers require continuous and reliable power. Ultra-fast charging stations must handle high-impact, fluctuating demand. Zero-carbon parks require coordination across generation, grid, load, storage, and carbon management. As these scenarios diverge, energy storage must move from passive peak shaving to active load coordination.

Based on S+ Energy Storage practices, three representative solutions have been developed: green power supply for AI data centers, PV-storage-charging integration, and coordinated generation-grid-load-storage operation for zero-carbon parks.

(1) High-power continuous load power supply

Reliable power supply for AI data centers

The core challenge for AI data centers arises from the temporal mismatch between rapid computing load growth and the lead time required for grid capacity expansion. High-power computing loads drive up electricity demand, while grid connection capacity, interconnection regulations, and equipment delivery schedules constrain rapid power infrastructure deployment. Furthermore, transient peaks and periodic fluctuations from GPU training intensify stress on the power grid. Consequently, integrated energy supply systems for AI data centers must support rapid deployment while delivering grid accessibility, scalability, buffering capability, and operational continuity under conditions of power shortage, deployment delays, and highly volatile loads.

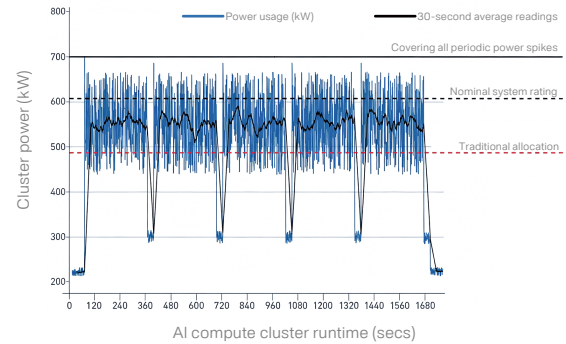
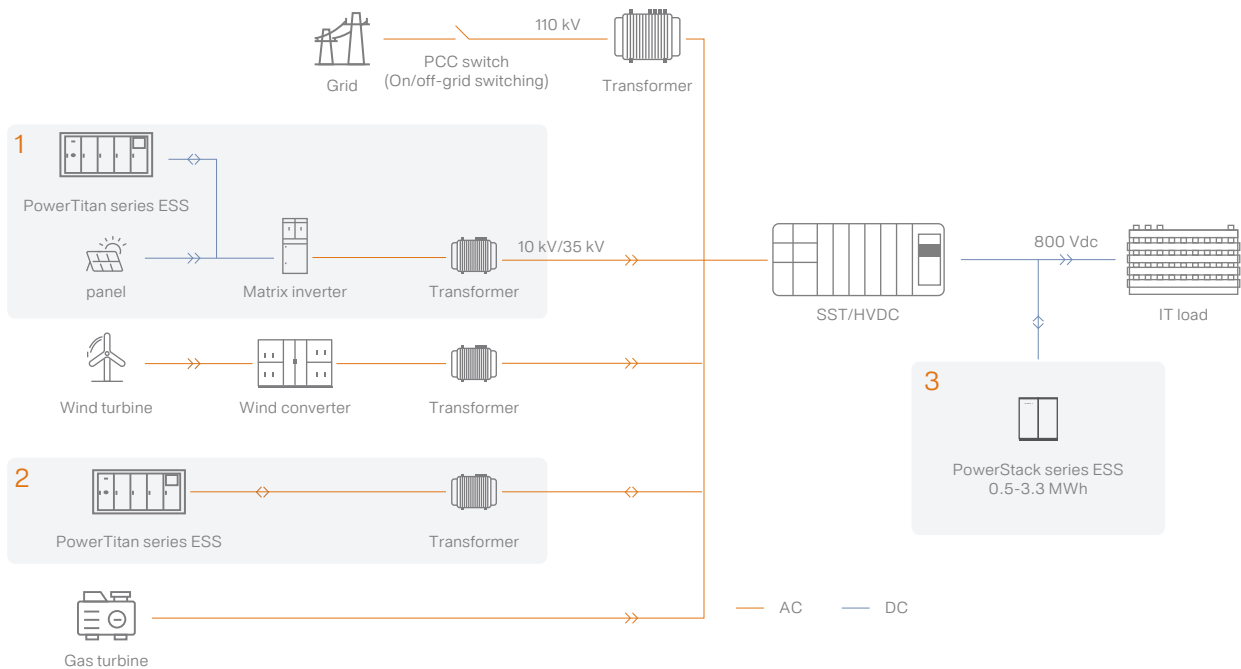


Figure 23: AI Data Center GPU Training Cluster Power Consumption Curve, Uptime

Reliable power supply for AI data centers

The AI data center energy supply solution includes three representative topologies: PV-storage DC coupling for local renewable utilization, medium-voltage AC coupling for flexible integration across applications, and 800 V DC coupling for near-load power support and optimized load smoothing. Each topology can be deployed independently or combined as needed to meet site-specific requirements.



1- PV+ESS DC Coupling Diagram

Minimizing LCOE
4 h/8 h/16 h ESS

2- Medium-Voltage AC Coupling Diagram

Flexible Application Compatibility
2 h/4 h ESS

3- 800 V DC Coupling Diagram

Optimal Load Smoothing
2 h/1 h or Lower Time-Scale ESS

Figure 24: ESS Solutions for AI Data Centers

Application value



Accelerated deployment

Integrating multi-source power supplies with dynamic energy storage supports phased power availability before grid infrastructure is finalized. This dynamic support shortens the schedule for delivering initial power availability by 50%–70%.



Enhanced power supply reliability

Utilizing grid-forming energy storage and bidirectional disturbance buffering dampens over 70% of high-dynamic AI load fluctuations. This stabilization improves system operations under weak-grid and complex power supply conditions.



Increased green power utilization

Implementing PV-storage DC coupling and coordinated wind-solar-storage dispatch increases local renewable energy consumption by 3%–5%, aiding AI data centers in transitioning toward 24/7 carbon-free energy.

Energy supply resilience validation

To validate the resilience of the AI data center green zone under highly dynamic loads and complex power supply conditions, performance is evaluated across three representative operating scenarios: load smoothing, on/off-grid switching, and black-start recovery.

■ Highly dynamic load smoothing

Simulations utilizing a typical AI data center high-dynamic-load profile analyze load fluctuation propagation before and after the integration of energy storage. Rapid charging and discharging cycles absorb periodic fluctuations and startup/shutdown transients of AI loads. This smooths power, mitigating the impact of highly dynamic computing loads on the power supply system.



Figure 25: AI Data Center Load Profile Before and After Load Smoothing

■ On/off-grid switching strategy

Voltage, current, and active power waveforms are analyzed under transient transition scenarios to validate stable busbar operation during external grid disturbances and transfer events. This control strategy reduces transient switching impacts on critical AI data center loads.

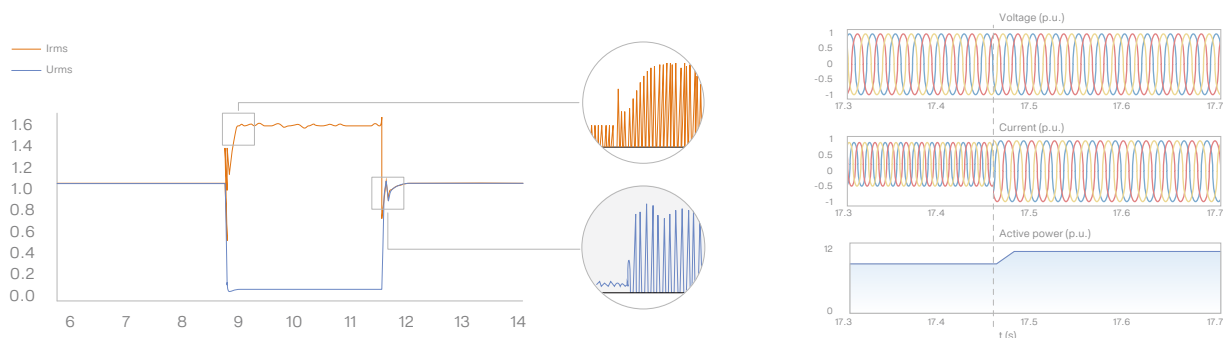


Figure 26: Validation of On/Off-Grid Seamless Switching and Fault Ride-Through Capability

■ Large-scale black start

In a system recovery scenario following a complete blackout, the energy storage system operates as a voltage source to establish and stabilize busbar voltage, restoring critical loads through a sequential load pickup strategy. This capability accelerates system restoration following extreme grid faults.

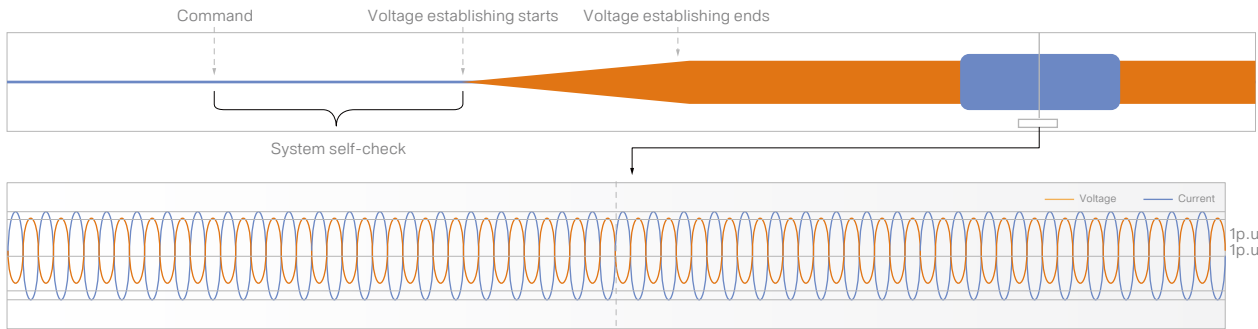


Figure 27: Validation of Black Start and Critical Load Recovery

(2) Dynamic capacity management for pulsed loads

Native PV-storage-charging integration solution

Integrating PV, storage, and high-power charging has become a widely recognized industry approach. In practice, however, stations face significant challenges: PV generation is often temporally decoupled from charging demand, and storage dispatch must balance three conflicting objectives—charging during peak PV output, discharging during peak charging periods, and recharging during low tariff hours. Operating these systems in a coordinated manner remains difficult. Consequently, many sites deploy all the necessary PV, storage, and charging assets, yet still struggle to unlock dynamic capacity management.

Native PV-storage-charging integration solution

For high-power charging scenarios, native integration must transcend a simple hardware combination. It should utilize station-level storage as a dynamic capacity pool and the EMS as the central dispatching hub, consolidating PV generation, grid procurement, storage dispatch, charging load, and tariff strategies into a unified optimization framework. This establishes a station-level operating system that coordinates power generation, storage, charging, pricing, and load behavior.

In the "S+ Energy Storage" practice, this integrated framework leverages the EMS and cloud platforms to unify the management of PV, storage, charging equipment, and grid interactions. This transitions the station from a collection of independently managed assets into an integrated, observable, predictable, and optimizable system.

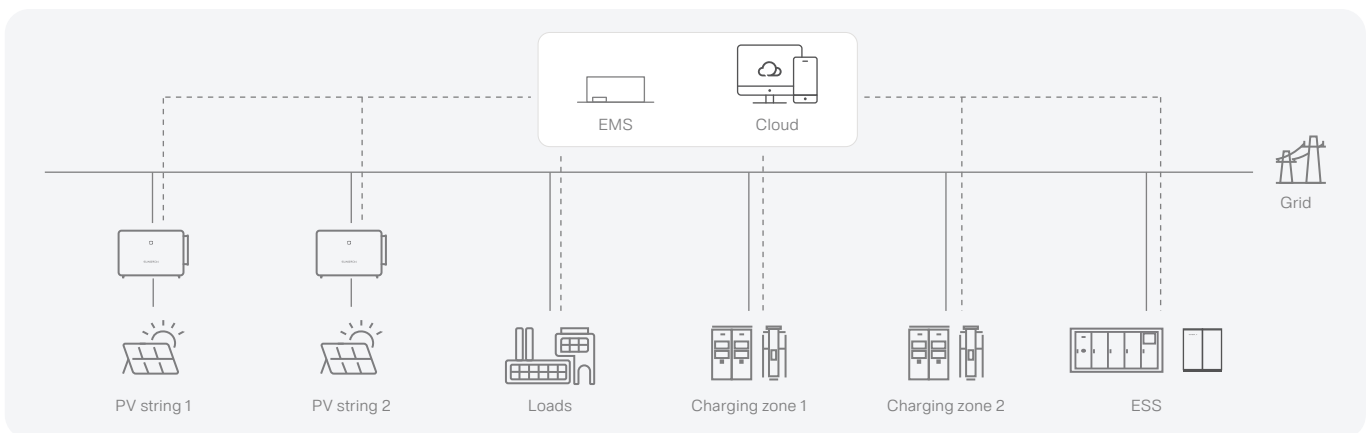


Figure 28: PV-Storage-Charging Integrated Solution

Strengths

Unified strategy and coordinated dispatch: PV, storage, and charging are managed under a unified EMS strategy, eliminating the fragmentation between operational dispatch and charging services.

Closed-loop operations for enhanced revenue: Linking tariff structures, power allocation, and user experiences enables station operations to transition from single-device control to fully optimized, system-level management.

Dynamic capacity for peak support: Storage serves as a station-level dynamic capacity pool, responding rapidly to load fluctuations during high-power charging, thereby increasing available station capacity and improving the charging experience.

Dynamic capacity expansion without transformer upgrades: Integrated storage allows stations to flexibly buffer and dispatch power, reducing dependence on the public grid and mitigating costly grid reinforcement requirements.

Application value



Greater energy autonomy

Scheduling storage dispatch precisely based on PV generation, tariff periods, and charging demand enhances the station's proactive energy management capabilities.



More reliable peak charging

Storage functions as a dynamic capacity pool, providing rapid support during high-power charging periods to absorb charging load fluctuations, increase available power, and improve peak-hour charging experiences.



Enhanced operational returns

Integrating tariff strategies, power allocation, and user experiences into a unified optimization framework lowers peak-period procurement costs, increases local renewable energy utilization, and delivers more stable revenues.

Case: Integrated PV + ESS + EV Charging Project in Bulgaria



Project configuration:

PV: 500 kW; energy storage: 440 kW/910 kWh; EV charger: 180 kW. Delivered as a one-stop solution, the project integrates Sungrow's IDC180E fast charger, PowerStack C&I ESS, SG125CX-P2 PV inverters, and energy management system.

Challenges:

The project needed to support reliable fleet charging, increase local PV utilization, reduce energy costs, and ensure stable operation during grid outages, while simplifying O&M across PV, storage, and charging.

Value:

This project highlights the value of Sungrow's reliable one-stop solution—faster commissioning, reduced operational costs, and unified remote monitoring that simplifies O&M. The PV system has reached 88.5% self-sufficiency, while the integrated design ensures seamless on/off-grid switching during outages and effective peak-shaving to optimize energy costs.

(3) Integrated operations of zero carbon park

Integrated generation-grid-load-storage collaborative solution

Zero-carbon industrial parks represent complex multi-load environments where energy management must balance conflicting objectives: cost reduction, decarbonization, supply reliability, and revenue generation. The co-existence of manufacturing, office, HVAC, and charging loads often leads to high peak demand, severe load fluctuations, and low capacity utilization. Furthermore, distributed PV, storage, and flexible loads typically operate in silos. This fragmentation hinders the coordination of green power consumption, demand response, ancillary services, and market participation, underutilizing resources and limiting revenue streams.

Integrated generation-grid-load-storage collaborative solution for parks

In complex multi-load scenarios, effective park energy management must transcend single-point energy conservation. Instead, it should leverage energy storage as a dynamic regulation hub, integrating EMS, VPP, and carbon management to enable unified modeling, forecasting, and optimized dispatch of PV, storage, flexible loads, and grid interactions.

In the "S+ Energy Storage" practice, the generation-grid-load-storage model facilitates peak shaving, demand charge reduction, local renewable integration, capacity optimization, and coordinated energy-carbon management. In mature power markets, it further diversifies revenue streams through demand response, ancillary services, and electricity trading, driving the park's transition from isolated energy-saving projects to fully integrated operations.

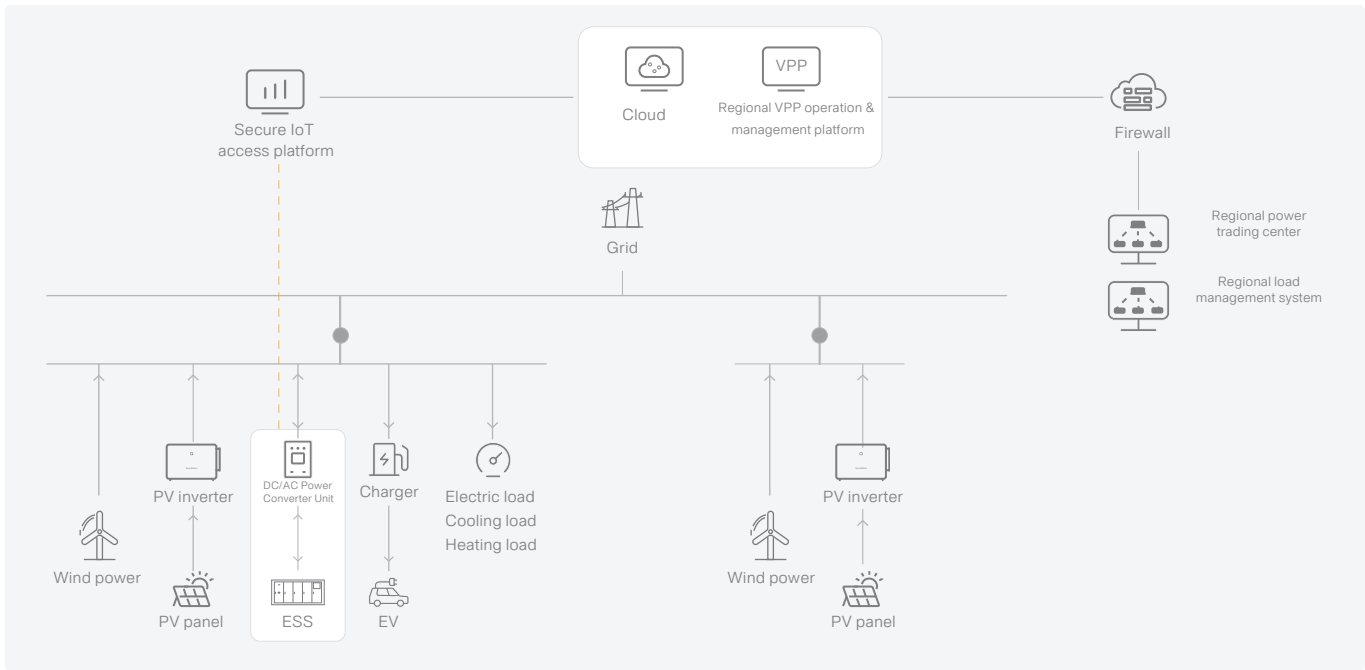


Figure 29: Architecture of the Integrated Generation-Grid-Load-Storage Solution for Parks

Strengths

Multi-energy synergy: Unified modeling and coordinated dispatch of wind, solar, storage, waste heat, and flexible loads, improving generation-load matching within the park.

Aggregated operation: Virtual Power Plant (VPP) aggregation unlocks the potential of multi-resource coordination, enabling additional revenue streams from demand response, ancillary services, and electricity trading where market conditions permit.

Application value

Demand reduction and capacity alleviation

Mitigating peak load pressure on capacity planning and demand charges through peak shaving, demand management, and flexible scheduling. Project results show a demand charge reduction of approximately 15%.

Renewable energy consumption and decarbonization

Multi-layer coordinated optimization supports park decarbonization while enhancing system revenue. Project results indicate a 5% increase in overall park revenue.

Market expansion and revenue growth

Improving resource utilization in regions with active power markets, offering an additional 5% to 10% potential for market-based revenue.

Case: Henan 20 MW/40 MWh distributed energy storage project for parks

The project supports demand management and integrated generation-grid-load-storage operation within the park. Due to irregular load fluctuations, static demand control could not align with the park's actual energy consumption patterns. Consequently, the customer deployed energy storage to reduce demand charges on the 100 kV incoming line, while maintaining the flexibility to participate in future power market trading.

The "S+ Energy Storage" solution combines EMS-based dynamic demand forecasting with high-precision metering to rapidly detect and flexibly respond to load variations in the park. This integration improves storage utilization. Project results demonstrate that the solution has helped the customer lower demand charges by approximately 8% to 15% and increase local renewable integration by around 5%.

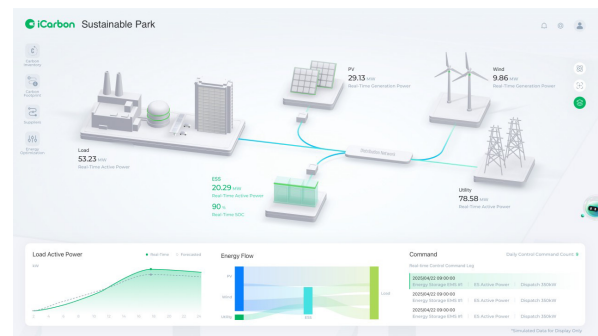
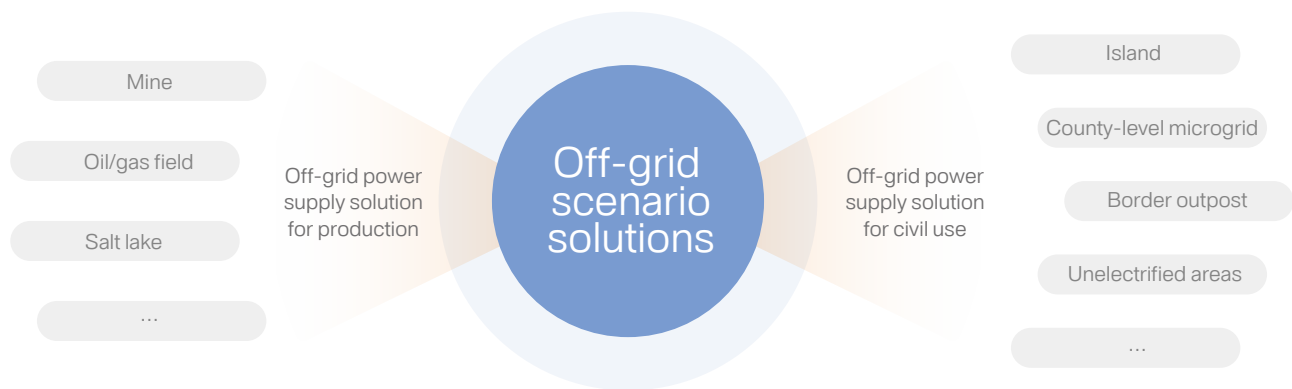


Figure 30: Sungrow iCarbon Generation-Grid-Load-Storage Solution Diagram

2.2 Off-Grid Scenarios

Generation, grid, and load constitute the three fundamental domains of energy storage applications. Microgrids are not a fourth parallel application domain; rather, they are self-governing energy systems created through the deep integration of generation, grid, and load. Microgrids emerge wherever the main grid is constrained by coverage, economics, or reliability. When the grid cannot reach the load, cannot do so cost-effectively, or cannot deliver the required level of continuity and resilience, localized energy systems become necessary. When grid connection is no longer sufficient to meet demand, energy storage transitions from a supporting asset to a lifeline, empowering generation-side microgrids with self-sufficient energy supply and load-side microgrids with self-sufficient energy consumption.



2.2.1 Microgrid + Storage | Off-Grid Power Supply Solution for Production

For such scenarios, an effective off-grid self-sufficient power supply solution must provide grid-forming, grid-stabilizing, supply assurance, and self-recovery capabilities. It must coordinate wind, solar, diesel/gas generation, energy storage, and critical loads while sustaining autonomous operation amid wind and solar variability, load impacts, constrained fuel supply, and minimally staffed operations.

Due to space limitations, rather than attempting to cover every type of microgrid, this section focuses on mining microgrids as a representative case characterized by high complexity, stringent reliability requirements, and energy-intensive loads. Mining microgrids are typically located in weak-grid, off-grid, or remote areas far from the main grid. Combined with challenges such as heavy load impacts, continuous production requirements, increasing renewable energy penetration, and limited on-site personnel, they embody the core challenge of the microgrid-plus-storage scenario: achieving decarbonization and cost reduction while ensuring stable power supply, fault isolation, and rapid system recovery. Mining microgrids are a rigorous test of the grid-forming, grid-stabilizing, supply assurance, and self-recovery capabilities of energy storage systems.

(1) Mining microgrids

Off-grid power supply solution

Renewable energy integration in mines and oil fields, combined with weak-grid or off-grid conditions, heavy load impacts, and continuous production targets, represents not only a series of complex technical and engineering challenges but also a set of combined economic and technical constraints. An effective system requires the unified dispatch of PV, wind power, energy storage, diesel/gas generator sets, the grid, and critical production loads. Without such coordination, fragmented operation across multiple systems can lead to inefficient capacity allocation, inadequate generation-load coordination, and expanded fault impacts.

Mining microgrid self-sufficient power supply solution

In the "S+ Energy Storage" practice, the mining microgrid solution positions energy storage as the backbone of system stability, while the EMS and microgrid controller serve as the dispatch center. By coordinating wind, solar, energy storage, diesel/gas generation, and critical production loads, it establishes a self-sufficient power supply system for weak-grid and off-grid environments, covering planning, delivery, operation, and maintenance. The solution enhances system resilience under complex operating conditions through three key capabilities: optimized capacity sizing based on time-series simulation and generation-load forecasting, grid-forming energy storage for voltage, frequency, and inertia support, and a five-layer protection and control framework.

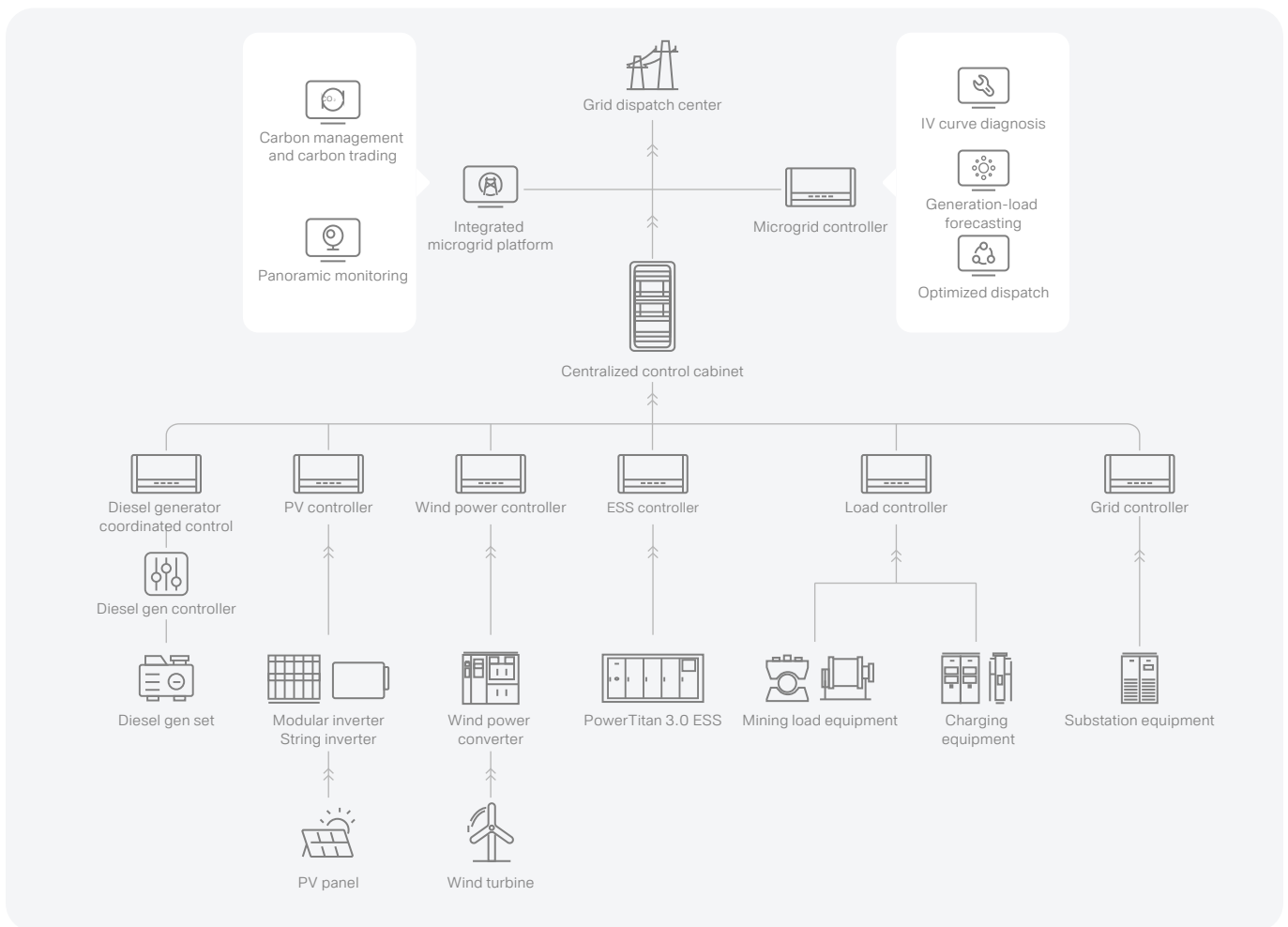


Figure 31: Topology of the Resilient Power Supply Microgrid Solution for Mining Operations

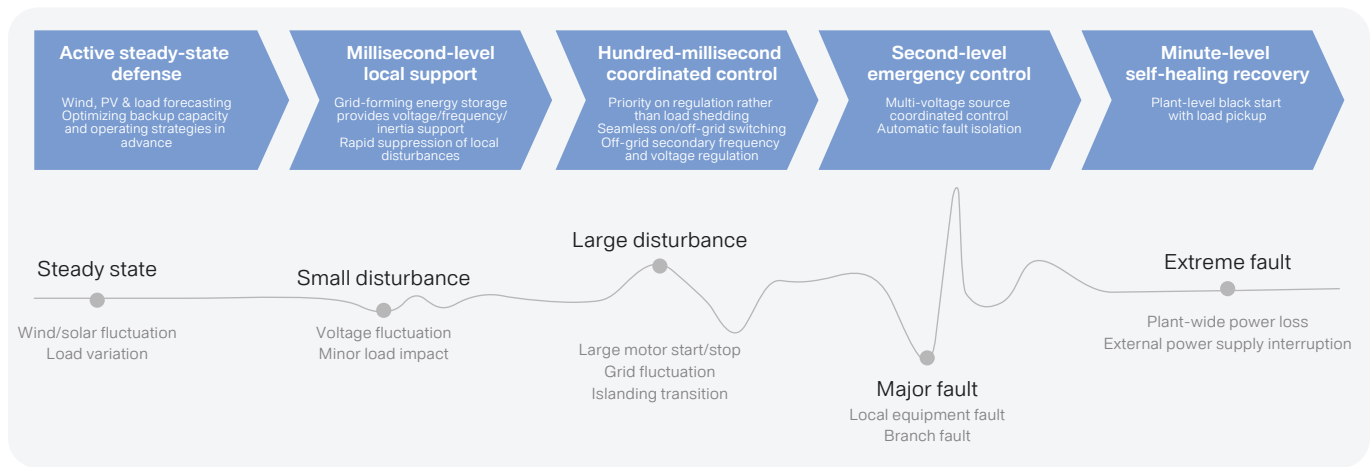


Figure 32: Five-Layer Protection and Control Framework

Strengths and value

High-precision wind, solar, and load forecasting for continuous, stable supply: Through AI-integrated modeling and real-time adaptive forecasting algorithms, power shortage events are reduced by over 80%, and load forecasting accuracy is improved by more than 10%, ensuring continuous and reliable power supply for critical loads.

Localized fault containment with uninterrupted critical loads: In major fault scenarios, multi-voltage source coordinated control and automatic fault isolation contain faults locally, protecting critical loads and preventing minor faults from causing large-scale production outages.

Minute-level power restoration after extreme outages, shortening downtime periods: In the event of extreme site-wide outages, a plant-level black start with load pickup enables GW-scale grid forming and power supply restoration at minute-level. This minimizes production losses while ensuring safe and continuous mining operations.

Case: Kathleen Valley off-grid mining project in Australia

Project configuration:

17 MW PV + 17 MW/20 MWh energy storage + 30 MW wind power

Challenges:

Kathleen Valley represents a typical remote off-grid mine operating under continuous production conditions. The project is far from the main grid and relies on a local microgrid to support loads such as the concentrator plant, camp, and underground mining operations. Meanwhile, the project aims to achieve a high share of renewable energy in the power mix during the startup phase. The core challenge is not simply "replacing diesel with renewable energy," but maintaining a real-time balance among fluctuating wind and solar output, energy storage status, generator start/stop decisions, and continuous production loads. This ensures stable mine operations while also maximizing renewable energy consumption and low-carbon operational value.



Figure 33: Australia's Largest Mining Microgrid Project

Value:

Sungrow's weak-grid/off-grid mining solution enables the coordinated operation of PV, wind power, and energy storage to achieve "Engine Off" operation, in which generators are shut down and the system is powered entirely by renewable energy under favorable wind and solar conditions. During the reporting period, the project achieved a renewable energy penetration rate exceeding 80%, surpassing the original 60% target, and recorded three consecutive days of 100% renewable energy supply. The solution supports black start within minutes, providing greater resilience for responding to extreme faults and restoring mining operations. This case demonstrates that in weak/off-grid environments, energy storage can serve as a dynamic balancing resource for high-penetration renewable energy microgrids. It supports continuous mining operations, reduces reliance on conventional generators, and enables more predictable low-carbon operations.

2.2.2 Microgrid + Storage | Off-Grid Power Supply Solution for Civil Use

(1) Land and maritime mobile microgrids

Off-grid power supply solution for civil use

Unlike fixed, self-sufficient scenarios such as mining microgrids, mobile microgrids on land and water face off-grid energy challenges where loads are constantly moving, operational conditions are dynamic, and the grid cannot be relied upon. In maritime scenarios, shipping operations face fuel costs, emissions regulations, and electrification upgrade requirements. In terrestrial scenarios, temporary operations such as mining, oil and gas exploration, and trial production still rely heavily on diesel generation, resulting in high energy consumption, high costs, and high emissions. Therefore, the core of mobile microgrids on land and water is not merely "bringing electricity to the site," but providing critical loads with self-sufficient energy capabilities that are rapidly deployable, safely transportable, independently networkable, and low-carbon under mobile, temporary, weak-grid, or off-grid conditions.

Mobile microgrids impose dual requirements on energy storage systems: inherent system capabilities and scenario coordination capabilities. On the one hand, energy storage systems must provide off-grid grid-forming capabilities, voltage and frequency support, structural reinforcement, environmental resilience, safety protection, and rapid deployability. On the other hand, they must enable rapid integration and coordinated operation with wind, solar, diesel generators, shore power/grid support, mobile carriers, and critical production or transportation loads. In these scenarios, what is required is not merely mobile energy storage equipment, but mobile, self-sufficient energy systems that cover the entire lifecycle of energy replenishment, transportation, deployment, grid-forming, and power supply.

Self-sufficient energy solution for land and maritime mobile microgrids

In the "S+ Energy Storage" practice, the land and maritime mobile microgrid solution uses energy storage systems as mobile grid-forming power sources, supported by vehicle-mounted, vessel-mounted, and lifting and transport systems. Designed for applications such as vessel electrification, mining and oilfield exploration and pilot production, and temporary work sites, the solution enables rapid integration and coordinated operation with wind, solar, diesel generators, shore power/grid support, and critical production and transportation loads. It establishes a mobile self-sufficient energy system covering energy replenishment and charging, transportation and relocation, on-site deployment, off-grid grid-forming operation, and continuous power supply.

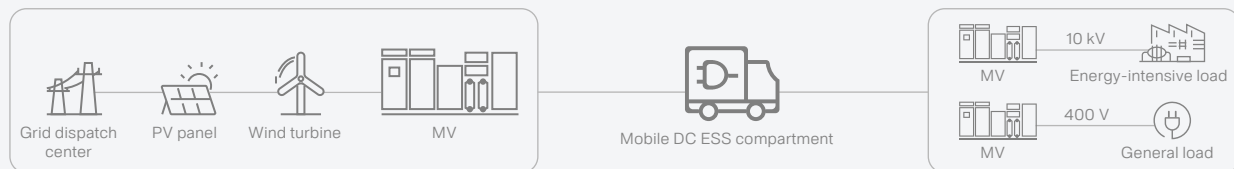


Figure 34: Vehicle-Mounted Mobile Microgrid Solution Topology

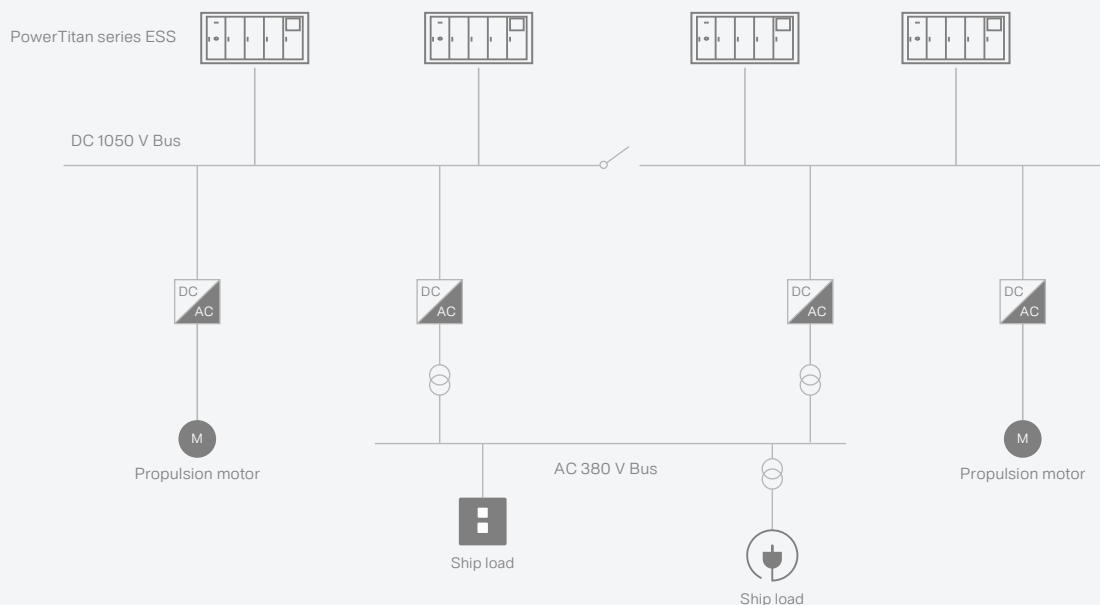


Figure 35: Vessel-Mounted Mobile Microgrid Solution Topology

Strengths

Weak-grid operation and multi-unit seamless replacement: Under weak grid, off-grid, or temporary operating conditions, the energy storage system can continuously form a grid, supporting voltage and frequency stability. Through EMS and DC/AC Power Converter Unit coordination, it enables multi-unit rotating power supply, frequent hot-swapping, and seamless replacement, ensuring uninterrupted operation of critical loads.

Mobile grid-forming and rapid deployment: Supports the rapid establishment of local power supply systems in scenarios such as vessels, mining exploration, trial production, and temporary work sites, providing independent and reliable power support for mobile loads.

Multi-source integration and reduced diesel dependence: Enables rapid integration with multiple energy sources, including wind, solar, diesel generators, and shore power/grid support. While ensuring continuous power supply, it reduces fuel consumption and carbon emissions, supporting low-carbon operations in mobile and maritime applications.

Structural reinforcement for transport conditions: Designed for hoisting, skid-mounted, vehicle-mounted, and vessel-mounted deployments, the system features enhanced structural strength, seismic protection, interface reliability, and adaptability to frequent hot-swapping, reducing risks during transportation and on-site deployment.

Environmental resilience for complex operating conditions: Designed to withstand high humidity and salt spray in maritime environments, as well as dust, vibration, and extreme temperatures on land, the solution enhances system protection, thermal management, and operational stability.

2.3 Cross-Scenario General Capabilities: The Foundational Support of "S+ Energy Storage"

Although solutions differ between scenarios, all share common capability requirements: efficient delivery, operational efficiency, ease of O&M, and safety and reliability. Regardless of whether it is a generation, grid, load, or microgrid scenario, every energy storage project must ultimately answer four fundamental questions: Can it be delivered efficiently? Can it operate efficiently? Is it safe and reliable? Can it sustain long-term operation?

Through full-stack in-house R&D, system integration, and extensive engineering experience, "S+ Energy Storage" has distilled engineered delivery, system-level efficiency, advanced O&M, and comprehensive safety into cross-scenario general capabilities. These capabilities do not define any single scenario directly, but they determine whether differentiated solutions can be reliably deployed, continuously operated, and deliver their intended value.

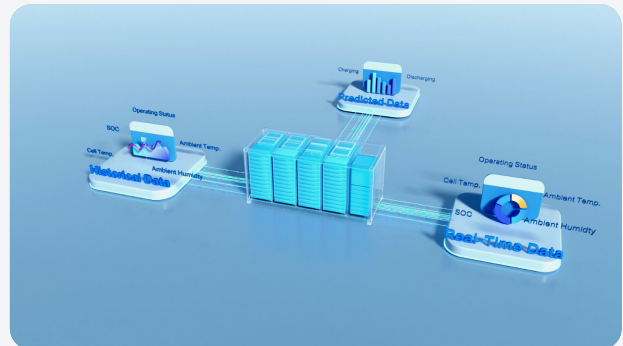
Engineered delivery

Through modular design, pre-installation, pre-commissioning, standardized interfaces, and an advanced delivery platform, extensive on-site work is completed in advance at the factory. This reduces uncertainties during installation, commissioning, and system integration, while improving delivery efficiency and accelerating grid connection for large-scale projects.



System-level efficiency

Through high-efficiency DC/AC Power Converter Unit, bionic thermal balance technology, plant-level coordinated heat dissipation design, and multi-level SOC balancing management, the solution minimizes charging and discharging losses and operational deviations, enabling efficiency gains to be consistently delivered across the entire system.



Simplified O&M

Leveraging built-in advancement, equipment status tracking, and the PowerDoctor plant health diagnostic system, the solution continuously analyzes critical equipment and system operation data, covering tracking, warnings, diagnostics, and optimization. This improves system efficiency and asset availability, and lowers the risk of unplanned downtime.



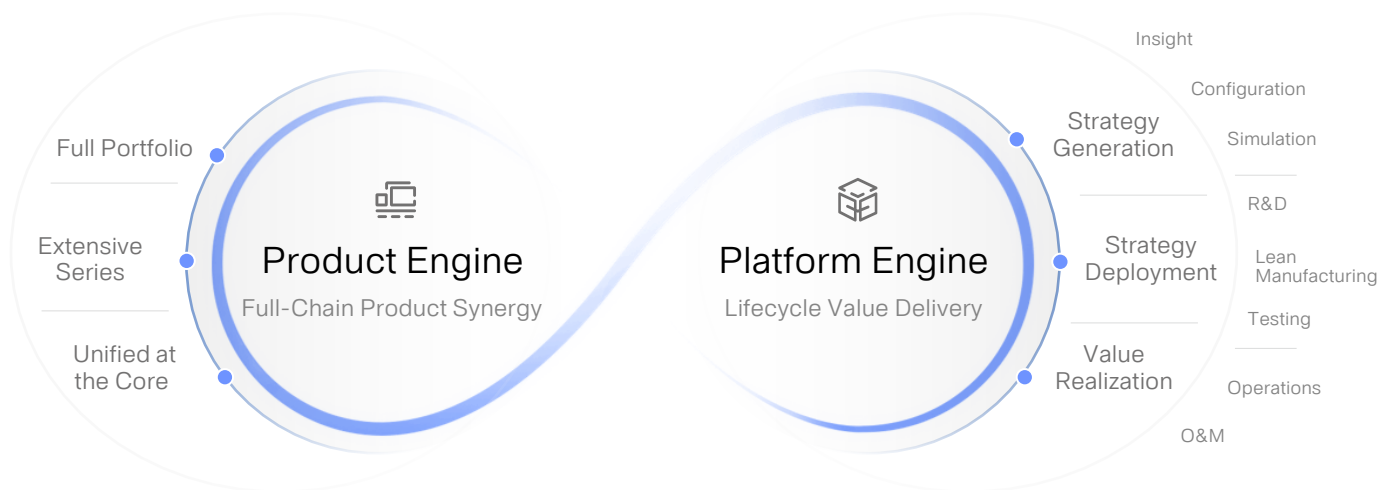
Comprehensive safety

It achieves full spatial coverage from cells, packs, racks, containers, and plants to the grid, breaking down equipment silos, and spans the entire lifecycle—including design, manufacturing, transportation, installation, O&M, and decommissioning—consistently upholding the principle that "safety originates from design".



2.4 S+ Dual-Engine Foundation

Facing the uncertainties created by increasingly diverse application scenarios, S+ Energy Storage can be applied across generation, grid, load, and microgrid scenarios to implement "one answer per case". This capability is not built on individual products alone, but on the S+ Dual-Engine Foundation, formed by the synergy between full-chain products and platform capabilities.



1 Full-Chain Product Engine: The Basis for Solutions

Full-chain products are the bones and muscles of "S+ Energy Storage". The prerequisite for a "one answer per case" approach is the ability to provide whatever a scenario requires. If product categories are incomplete, no solution can be formulated; if the product portfolio lacks sufficient series, the solution may not be precisely matched; and if products are not built on a unified architecture, the solution may not operate as intended.

Complete categories, readily available: Products span all renewable energy types, including PV inverters, wind power converters, energy storage systems, electrolytic hydrogen production systems, and charging equipment. When addressing complex scenario requirements, whatever is needed can be readily provided, freely combined, and unconstrained by category limitations.

Extensive product portfolios, precise matching: Platform-based product design rejects the notion of "one product fits all". Each category is supported by a comprehensive product portfolio with sufficient series. For example, the energy storage portfolio spans utility-scale, commercial and industrial, and small-scale commercial applications through the PowerTitan, PowerStack, and PowerKeeper series, enabling precise matching to scenario requirements rather than forcing compromises.

Unified architecture, seamless operation: A complete product portfolio is only the foundation; seamless integration is what truly matters. Built on a shared technology foundation, unified design standards, and common control logic, products are inherently compatible and natively interconnected within a unified framework. This enables complex multi-energy systems to integrate and operate seamlessly. Full-chain capability is not about "having everything"; it is about "everything working together".

2 Platform-Based Engine: Solution Generation, Deployment, and Value Realization

The platform-based capability is the "brain and nervous system" of "S+ Energy Storage". It determines how solutions are developed, providing a complete chain from scenario understanding and solution generation to value realization.

• Solution generation: Scenario insight, solution configuration, and simulation validation

Scenario insight

Dedicated product teams have deep expertise across generation-, grid-, load-, and microgrid-side applications. With a thorough understanding of application scenarios, power systems, and load profiles, they define requirements based on extensive data analysis and model-driven insights rather than experience-based assumptions.

Solution configuration

Leveraging proprietary configuration tools and an engineering knowledge base, the platform rapidly identifies optimal product combinations from a comprehensive product portfolio based on scenario requirements. Multiple candidate solutions are generated according to engineering rules and operating constraints, ensuring that solutions can be configured with greater precision rather than simply assembled.

Simulation and validation

Supported by simulation laboratories, a global grid code database, and engineering test data, candidate solutions are validated and optimized before deployment. This enables operating boundaries and potential risks to be identified during the design phase, reducing on-site trial-and-error costs.

• Solution deployment: Translating solutions into deliverable reality through R&D, lean manufacturing, and testing

R&D foundation

Rooted in over 30 years of deep expertise in power electronics technologies, this capability is backed by a repository of over 11,000 patent applications. A unified Integrated Product Development (IPD) process is implemented to ensure that all product categories share the same development framework and underlying technology foundation.

Lean manufacturing

Leveraging an advanced manufacturing system and digital flexible production lines, unified manufacturing standards are applied across all product categories. With an automation rate exceeding 90%, machines are built by robots, ensuring quality and consistency from the outset.

Rigorous testing

Supported by an accredited in-house laboratory, complemented by third-party testing and certification, validation is conducted across all levels—from component to system to plant. This dual-layer verification ensures that solutions meet stringent global standards.

• Value realization: Sustained value delivery across the full lifecycle

Full-lifecycle O&M

Leveraging a global service network and an advanced O&M system, Sungrow provides lifecycle support covering installation and commissioning, routine inspections, fault response, and operational optimization. This ensures long-term reliability of the energy storage system and extends value delivery from system handover through the entire lifecycle.

Chapter Summary

As energy storage applications become more diverse, no single standard configuration can fit every scenario. What sets scenarios apart is not only where energy storage is used, but how value is created.

S+ Energy Storage starts with the scenario and translates scenario-specific needs into system configurations that can deliver value over time.

Built on the S+ Dual-Engine Foundation, the Product Engine ensures reliable execution, while the Platform Engine supports delivery, operation, and continuous refinement across applications. Together, they provide a consistent foundation for addressing today's needs and future uncertainty—turning system capabilities into lasting value across different scenarios.



03

Capability Model and Level Definitions



When different enterprises enter the same scenario, they may all achieve basic equipment connectivity. However, their capabilities diverge in scenario identification, system orchestration, and value delivery. Based on multi-scenario deployment practices and accumulated system expertise, this white paper introduces a maturity model for energy storage multi-scenario adaptation capability, providing a reference framework for evaluating how well energy storage systems adapt to different scenarios and realize value.

3.1 3S Model for Multi-Scenario Adaptation of Energy Storage

Multi-scenario adaptation capability is not a simple stacking of single-dimensional capabilities, but a three-dimensional system composed of three main capability axes:

S1 Scenario definition capability:

The ability to define solutions based on scenario constraints, rather than cobbling solutions together from products

S2 Synergy capability:

The ability to enable multiple subsystems to operate collaboratively under a unified framework, rather than acting independently

S3 Sustained value realization capability:

The ability to continuously realize value throughout the entire project lifecycle, rather than stopping at delivery

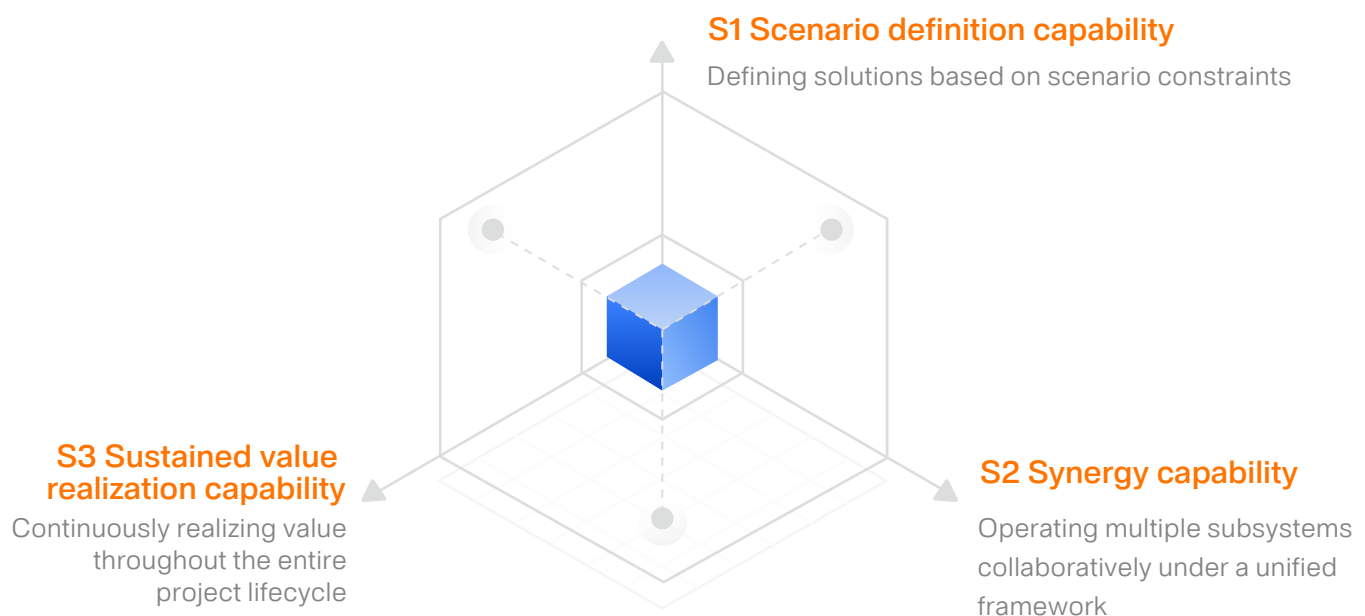


Figure 36: Maturity Model for Multi-Scenario Adaptation

These three dimensions should not be viewed in isolation. Together, they form a progressive path from scenario understanding and system synergy to value realization. Scenario understanding defines the direction, system synergy enables execution, and continuous value realization turns solution capabilities into long-term customer value.

3.2 Levels of Multi-Scenario Adaptation of Energy Storage

Based on the maturity of the S1, S2, and S3 three-dimensional capability axes, the scenario adaptation capability of energy storage solutions can be divided into four levels. It should be noted that the levels reflect differences in capability forms and applicable boundaries, rather than a simple ranking of solution value—the requirements for capability levels vary depending on different scenario stages and project needs. However, from a trend perspective, the more complex the scenario and the more composite the value proposition, the more urgent the demand for higher-level capabilities.

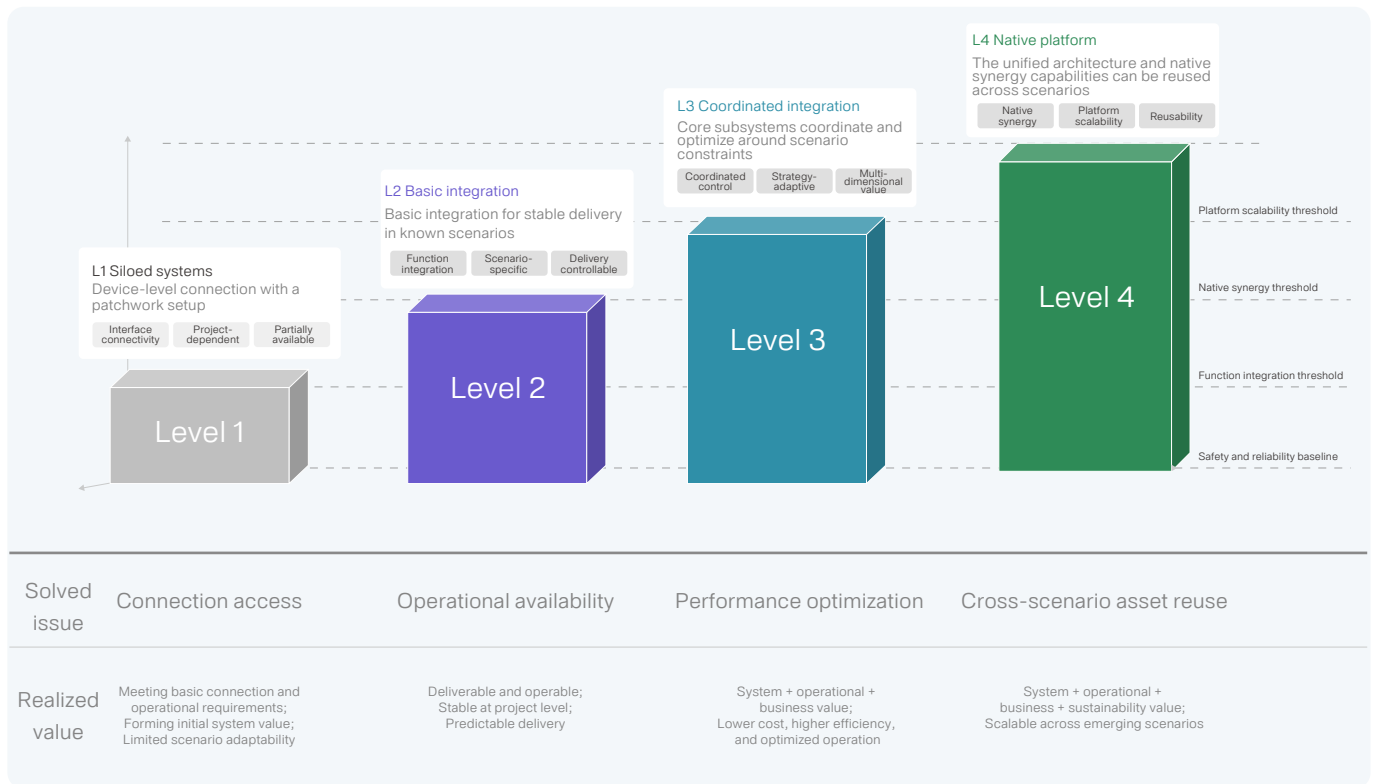


Figure 37: Maturity Model for Multi-Scenario Adaptation Capability

Level 1 Siloed systems

Projects are patched together from equipment supplied by multiple vendors, with each subsystem operating independently. Interface connectivity is treated as project completion. The solution is connected, not integrated.

Typical characteristics: Interface protocols are negotiated on site, control strategies are independent, fault boundaries are unclear, and traceability is difficult.

Applicable scenarios: Energy storage projects with single functional requirements and low system complexity.

Capability: Basic grid connection and functional availability are met. Once the scenario becomes complex, problems quickly escalate.

Value realization: Basic system value—connected but unstable.

Level 2 Basic integration

System integration capability is in place to deliver stable performance in known scenarios. However, system synergy remains limited. Optimization relies on experience and on-site commissioning. A new scenario requires starting over.

Typical characteristics: Functions are deliverable, and operation can be guaranteed, but strategies are hardcoded, and benefits are theoretical.

Applicable scenarios: Projects with relatively fixed scenarios and limited optimization space.

Capability: The project can operate, but it cannot realize the full value of the scenario.

Value realization: Complete system value—built, stable but suboptimal.

Level 3 Coordinated integration

Core subsystems (battery cells, DC/AC Power Converter Unit, battery management system, energy management system, thermal management, etc.) operate collaboratively under a unified control framework. Strategies can be dynamically adjusted according to scenarios, revenue can be optimized, service life can be managed, and operations can be scheduled.

Typical characteristics: Trading strategies coordinate with equipment status, charge/discharge strategies respond to market opportunities, and fault warnings feed into O&M decisions. Strategies are not hardcoded but evolved.

Applicable scenarios: Complex scenarios with multiple coupled objectives that require continuous optimization.

Capability: System value is extended to operational value, but a new scenario still requires a long customization lead time.

Value realization: System value + operational value—ensuring not just operation, but also optimizable value.

Level 4 Native platform

The unified architecture and native synergy capabilities can be reused across scenarios. There is no need to define a solution from scratch for a new scenario. Instead, scenario identification, solution configuration, and value realization are completed on the existing capability foundation.

Typical characteristics: The delivery timelines for new projects are significantly shortened. Scenario strategies can be configured in a modular way, while core capabilities continue to accumulate and evolve through project experience. Instead of being rebuilt from scratch each time, the solutions are developed from the same foundation.

Applicable scenarios: Diverse demands with rapid scenario iteration and uncertain future.

Value realization: Multi-dimensional value is not measured by the number of projects delivered, but by the ability to create different forms of value in each new scenario type using the same set of capabilities.

Capability: The system value, operational value, business value, and sustainability value are realized together.

Chapter Summary

Scenarios may change, but the foundation must remain consistent. True multi-scenario adaptation is not a collection of separate solutions, but a maturity framework that connects capability development with value realization. L1 addresses connection, L2 supports basic integration, L3 enables optimization, and L4 allows capabilities to be reused across scenarios. As maturity increases, energy storage moves from basic system value to broader scenario-based value.

For S+ Energy Storage, adaptation is not defined by the number of scenarios already covered, but by whether the same capabilities can be applied to new scenarios and turned into practical value.

C4

Outlook

Looking ahead, energy storage is entering a more scenario-driven stage. Applications will continue to become more segmented, system design will be judged by the value it creates in real projects, and the market will increasingly favor companies with true full-stack capabilities.

While scenarios vary, the foundation behind them must remain consistent. With nearly three decades of experience in renewable energy, Sungrow has built integrated capabilities across wind, solar, storage, EV charging, and hydrogen. These are not separate product lines placed side by side, but capabilities connected through a shared technology platform and framework. This allows Sungrow to better understand the operating logic of different power systems and address the real challenges behind each application.

"S+ Energy Storage" is the answer to the next stage of energy storage: anchored in scenarios, based on systems, and centered on value.

Energy storage will be essential to the transition toward a low-carbon energy future. Together with partners worldwide, Sungrow will continue to bring reliable, scenario-based energy storage solutions to more applications, contributing to a cleaner and more resilient energy future.



Clean power for all

Sungrow Power Supply Co., Ltd.

Add: No.1699 Xiyou Rd, New&High Technology Industrial
Development Zone, 230088, Hefei, P.R.China

Tel: +86 5516532 7834

Email: info@sungrow.cn

Website: www.sungrowpower.com

