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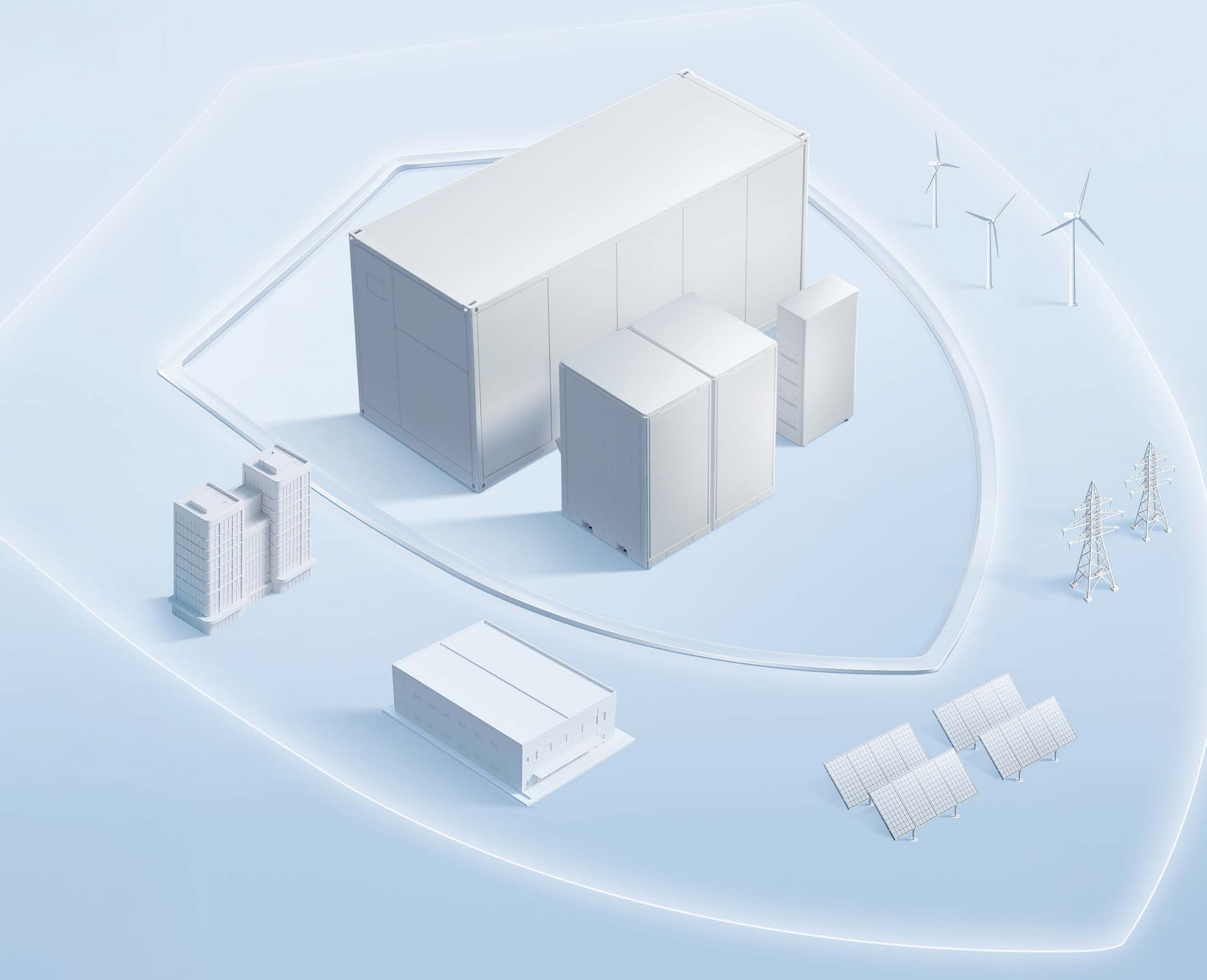
# A Holistic Approach to Safety

Sungrow Energy Storage White Paper



# Foreword

Amid the accelerating global energy transition, energy storage is evolving from a technological breakthrough to large-scale deployment, emerging as a strategic enabler for achieving carbon neutrality. At the same time, rapid industry expansion is accompanied by increasingly complex safety and reliability challenges. Traditional single-layer protections and short-term cost-driven approaches are no longer sufficient to address system-level risks, representing a critical constraint on sustainable development.

In response, leading authorities—including the International Electrotechnical Commission (IEC), the National Fire Protection Association (NFPA), and China’s National Energy Administration—have successively upgraded regulatory frameworks, signaling the industry’s shift toward “system-level, full-lifecycle” safety standards.

As an independent third-party inspection, testing, and certification organization, TÜV Rheinland recognizes that certification extends beyond compliance: it is a strategic safeguard for quality and safety. Throughout the full product lifecycle—from research and development to manufacturing, deployment, and eventual decommissioning—we apply rigorous, science-based methodologies with a global perspective. This approach not only provides authoritative verification for products but also strengthens the industry’s overall safety framework, facilitating the concurrent advancement of innovation and risk management.

The holistic safety concept presented in this white paper responds to the evolving safety requirements of the energy storage sector. In spatial terms, it ensures comprehensive protection from battery cells through to the power grid; in temporal terms, it establishes full-lifecycle oversight from development to decommissioning. Guided by technology and grounded in responsibility, TÜV Rheinland remains committed to partnering with the industry to advance energy storage toward a high-quality, sustainable future.

Weichun Li

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# 01

# Energy Storage Development Trends and Challenges

## 1.1 Scaling Up: High-Capacity, High-Density Energy Storage Systems

From a market perspective, the global energy transition is accelerating. The integration of a high proportion of renewable energy is creating new opportunities for energy storage. According to BloombergNEF, global cumulative energy storage installed capacity is expected to increase twelvefold by 2035 compared to 2024, reaching 7.3 TWh.

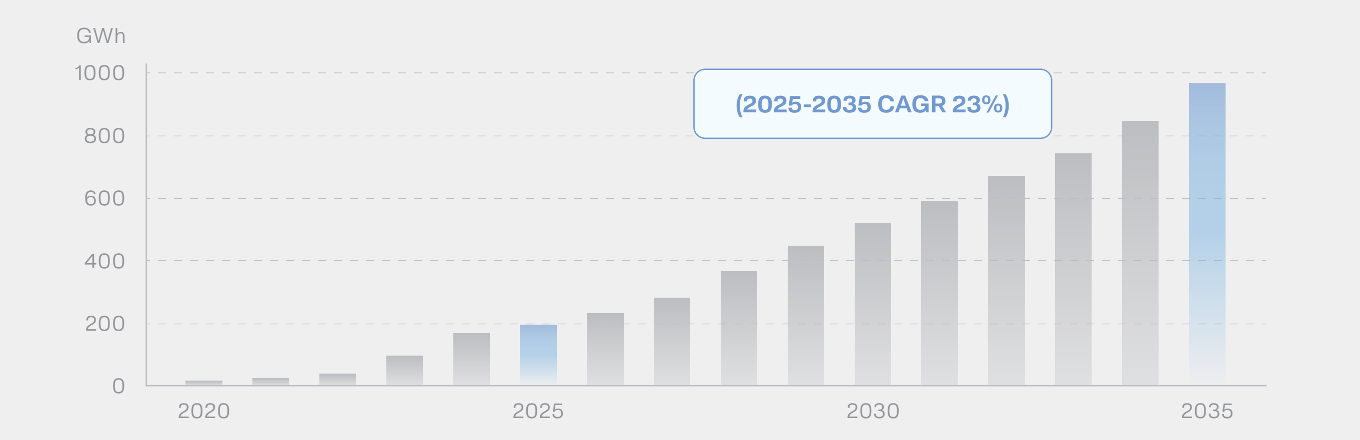


Figure 1: BloombergNEF Global Annual Energy Storage Newly Installed Capacity

At the product level, the capacities of individual battery cells, containers, and plants are continuously increasing. In 2021, the capacity of mainstream cells was around 280 Ah, the capacity of individual containers was around 3 MWh, and the scale of individual plants was in the range of hundreds of MWh. By 2024, the capacity of battery cells has increased to over 500 Ah, the capacity of individual containers has exceeded 6 MWh, and the scale of individual plants has surpassed the GWh level.

## 1.2 Rising Challenges: Higher Risks in Large-Scale Plants

As energy storage expands, system safety has become an increasingly significant concern. Clean Energy Association (CEA)'s 2024 statistics indicate that 70% of safety design defects in energy storage systems originate from the system and modules, while 30% stem from the cells. This not only exposes the widespread industry misconception that equates cell safety with overall system safety, but also reflects the pervasive nature of system safety risks.

| Defects | |
|---|---|
| Fire suppression system | 26% |
| Appearance | 23% |
| Thermal management system | 18% |
| AC/DC power distribution | 16% |
| Insufficient structural rigidity | 14% |
| DC combiner panel | 11% |
| BMS | 11% |
| Rack frame | 9% |
| Leakage | 7% |

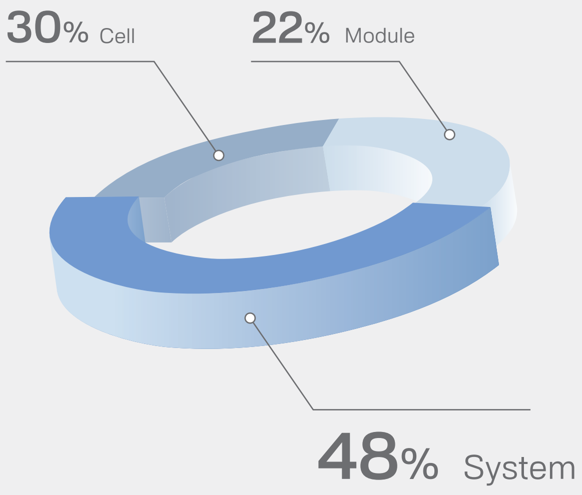


Figure 2: Statistics on Safety Defects in Energy Storage Systems

According to public data, as of H1 2025, there have been 125 recorded energy storage fire incidents globally, posing severe challenges to life and property safety.

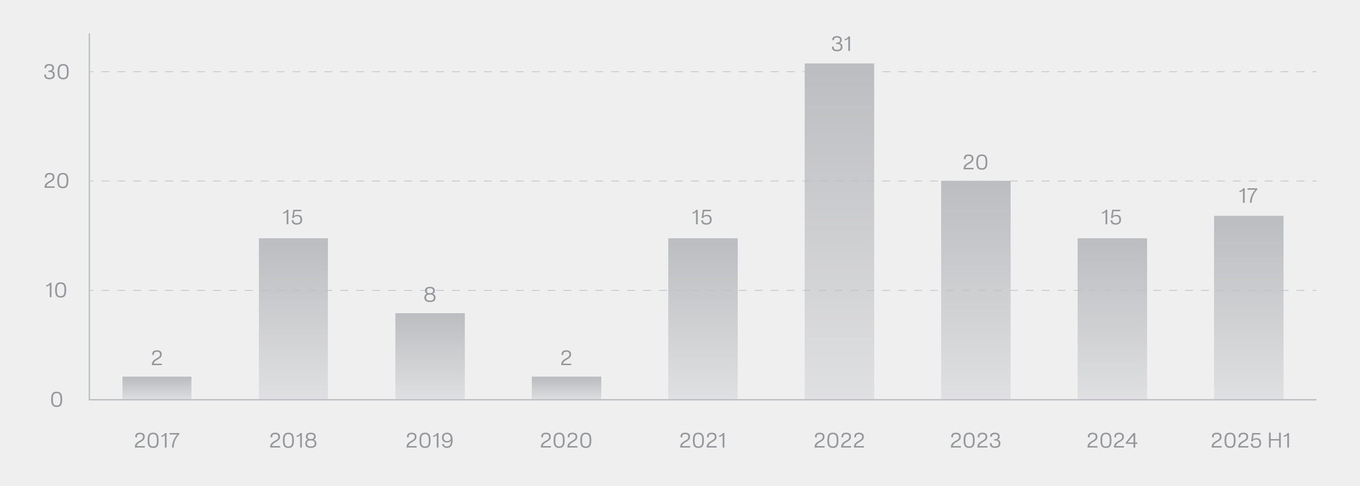


Figure 3: Statistics on Global Energy Storage Fire Incidents

Fire risks in energy storage systems span all levels, from battery and electrical components to the overall system, and persist throughout the entire lifecycle, including transportation, installation, commissioning, grid connection, and long-term operation.

Thermal runaway in batteries

2021—Energy storage plant fire incident in China

Arcing

2021—Energy storage plant fire incident in Australia

Fire suppression system defects

2024—Energy storage plant fire incident in the United States

Incident during transportation

2022—Energy storage container fire incident in China

Incident during commissioning

2025—Energy storage plant fire incident in the United Kingdom

Incident during operation

2024—PV-plus-storage plant fire incident in China

Figure 4: Energy Storage Safety Incident Cases

# 02

# Risk Landscape of Energy Storage Systems

As energy storage systems are deployed at scale, increasing system complexity has made safety risks more intricate. These risks are multi-dimensional. On the battery side, thermal abuse and control failures are the primary causes of thermal runaway. On the electrical side, short circuits and arcing faults pose risks to assets and personnel. On the system side, inadequate fault isolation and coordinated control can allow risks to escalate from localized incidents to system-wide failures. On the grid side, high penetration of renewable energy reduces system inertia and weakens disturbance tolerance. A clear recognition and in-depth analysis of these risks are essential to ensuring the safe operation of energy storage systems.

## 2.1 Battery Level: Potential Thermal Runaway Risks

In 2024, the Electric Power Research Institute (EPRI) released the world's first root cause analysis of energy storage plant incidents, Insights from the Battery Energy Storage System Failure Incident Database: Analysis of Failure Root Cause. The report shows that control issues, including battery management, are the primary cause of energy storage safety incidents, accounting for 46% of cases. Among these, electrical abuse, mechanical abuse, and thermal abuse of batteries are the main causes of thermal runaway. Effective battery management and proper operation are therefore critical to mitigating battery safety risks.

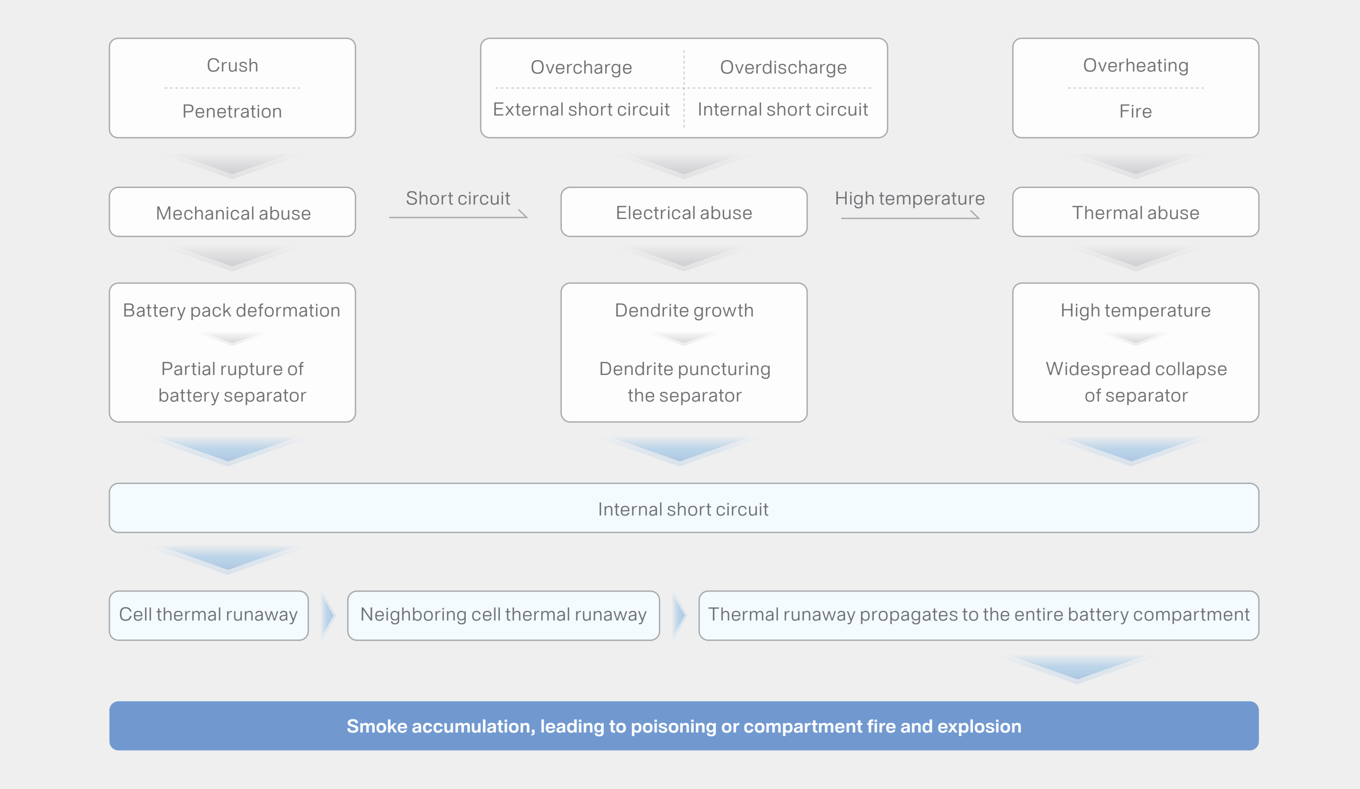


Figure 5: Schematic Diagram of Battery Thermal Runaway Triggers

## 2.2 Electrical Level: Arcing and Insulation Failure

As energy storage systems scale up, the growing number of electrical connection points increases engineering complexity and challenges effective management. Analyses of incident cases and industry reports show that short circuits and arcing faults resulting from non-compliant installation practices, such as loose connections and exposed conductors, have become major contributors to energy storage safety incidents. These faults may cause equipment damage or, in severe cases, trigger fires, posing risks to both personnel and assets.

Figure 6: Analysis of causes of ESS fire accident

## 2.3 System Level: Weak Fault Isolation and Coordination

In some industry projects, inadequate professionalism in system integration design, equipment matching, and engineering implementation has led to the propagation of failures and the loss of system-level response capability. When a cell enters thermal runaway, the absence of effective system-level isolation and coordination can allow the failure to escalate from a localized event into a system-wide catastrophe.

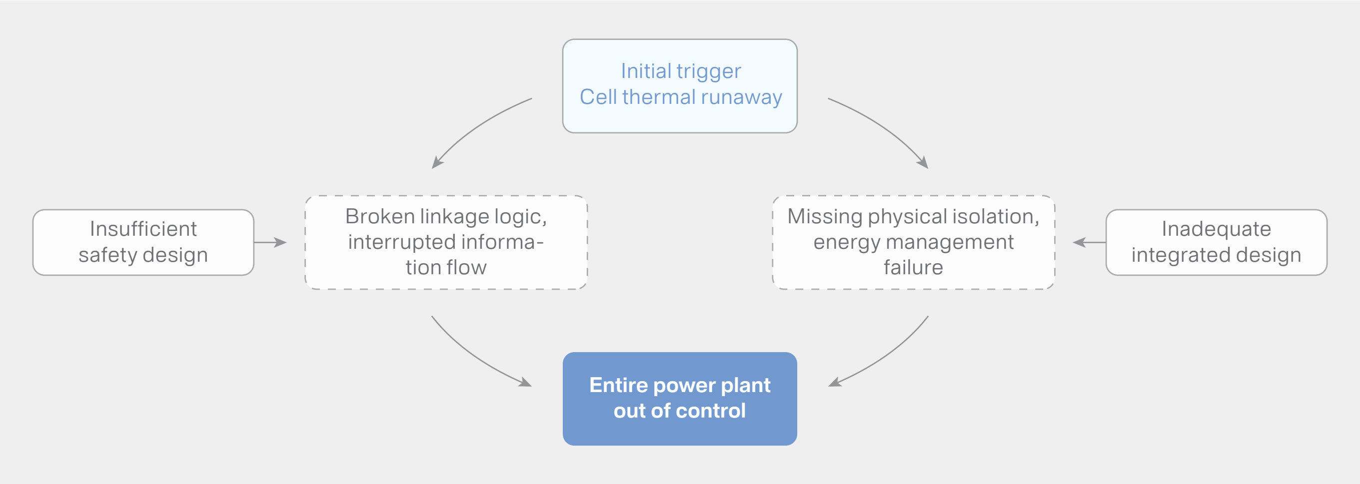


Figure 7: Deficiencies in System-Level Isolation and Coordinated Control

## 2.4 Grid Level: Insufficient Stability and Support Capability

As renewable penetration increases, power systems exhibit lower inertia, reduced damping, and weaker voltage support, making them more vulnerable to disturbances. Under extreme weather or equipment failures, these conditions can easily trigger cascading blackouts—for example, the 2016 South Australia blackout and the 2019 UK blackout—exposing grid instability under high renewable penetration scenarios.

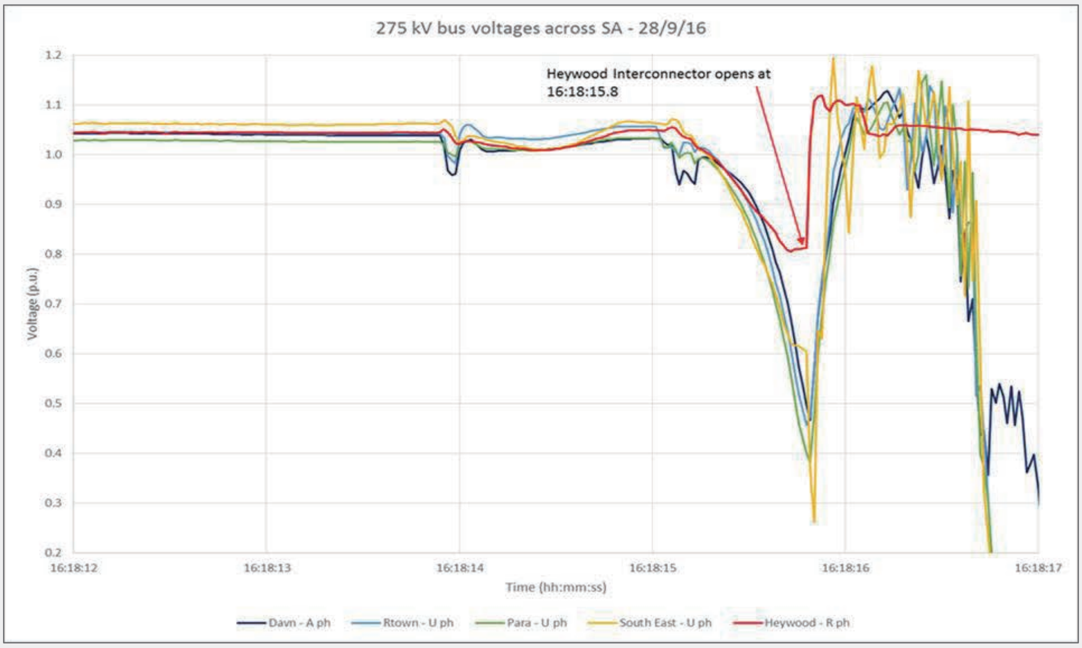


Figure 8: Voltage Drop (275 kV Bus Voltage) Before Grid Separation in the 2016 South Australia Blackout

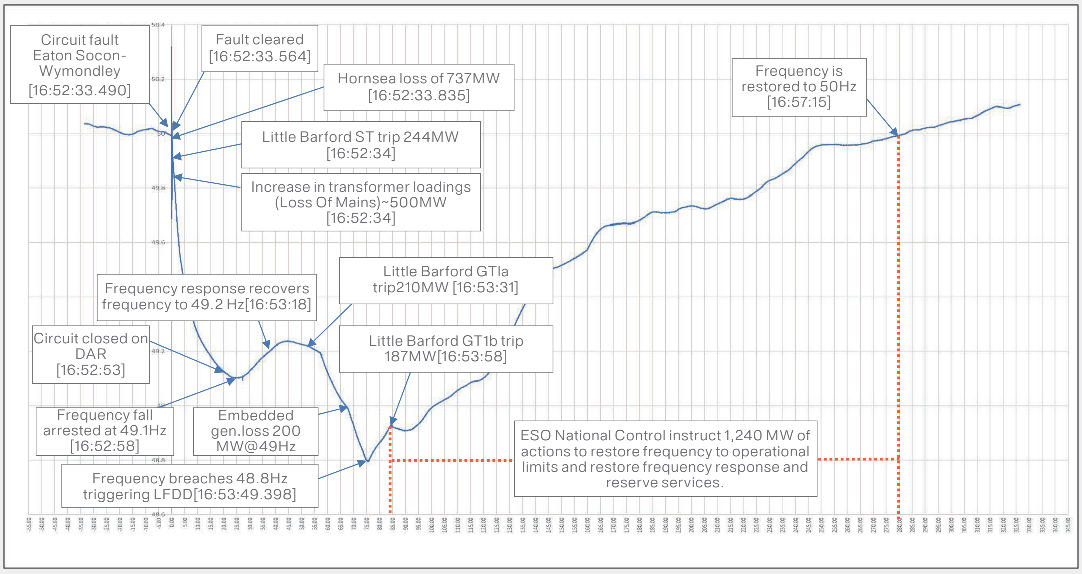


Figure 9: Frequency Tracking Record During the 2019 UK Blackout

Energy storage safety is a complex system challenge involving multiple risk sources across the entire lifecycle.

From a spatial perspective, risks arise at multiple levels, including battery thermal runaway, electrical short circuits and arcing, system-level fault propagation, and insufficient inertia support on the grid side—placing pressure on multiple layers of protection.

From a temporal perspective, these risks span the full lifecycle, from transportation, installation, and commissioning to operation and end-of-life. A gap at any stage may lead to equipment damage or even serious safety incidents.

Therefore, energy storage safety cannot rely on isolated, single-point protection. Instead, it requires a system-level approach based on comprehensive risk identification, lifecycle management, and coordinated protection across all layers. By integrating battery management, electrical protection, system integration, and grid compatibility, establishing risk management framework spanning generation, grid, load, and storage, the industry can build a solid safety foundation for energy storage deployment.

# 03

## Energy Storage All-Dimensional Safety Architecture

Based on the deep integration of electrochemistry, power electronics, and grid technologies, Sungrow has established a comprehensive safety system that covers all levels of energy storage systems across their full lifecycle. Leveraging cutting-edge technologies and rigorous standards, Sungrow delivers the highest level of uncompromised safety to every customer.

Spatially, all levels of energy storage systems, from cells to plants, are protected. We move beyond the traditional component-level approach to deliver comprehensive protection across all levels, from cells and packs to racks, battery compartments, and entire plants. By integrating electrochemistry technologies (for cell safety), power electronics technologies (for power conversion safety), and grid technologies (for grid forming support), we ensure that risks at every level are visible and controllable, completely eliminating the threat of a single-point failure triggering a systemic disaster.

Temporally, the full lifecycle from design to decommissioning is protected. Driven by the core philosophy of safety-by-design, we embed risk prevention into the entire product lifecycle from R&D to manufacturing, transport, installation, O&M, decommissioning, and recycling. We apply a "zero-compromise" standard across every phase, such as anti-collision measures during transport, anti-accidental touch during installation, overcharge protection during operation, and pollution prevention during decommissioning, shifting safety protection from passive response to proactive design.

Ultimately, we propose a holistic approach to energy storage safety. Rather than focusing on single-point improvements, this approach establishes a systematic framework built on comprehensive risk identification, full-lifecycle management, and coordinated protection across all levels. It rejects tiered safety standards in favor of a single principle: the same high standard of protection for every customer. Through this comprehensive safety architecture, Sungrow builds an all-dimensional safety architecture from cell to plant and across the entire lifecycle, ensuring that every kilowatt-hour stored and delivered is supported by reliable and consistent safety protection.

Figure 10: Energy Storage All-Dimensional Safety Architecture

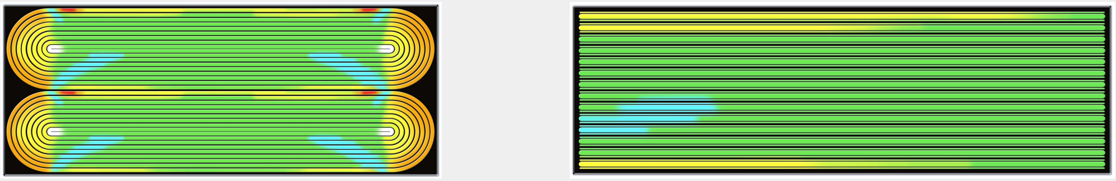
## 3.1 Battery-Level Safety Architecture

As energy storage facilities scale up, both battery containers and cells are evolving toward higher capacity and energy density. In large-scale applications, designing a safer cell technology is just the first step. The true foundation of long-term safety lies in robust system integration and effective cell management. Therefore, from a comprehensive safety perspective, high-capacity cells are just the beginning; proper cell management is the key to battery layer safety.

## 1 Quality Cell Design

- ### Stacked Cells: A Safer Choice

When cell capacity exceeds 500 Ah, cell width increases, and stress concentrates at the corners. After multiple charge-discharge cycles, unreleased internal stress may lead to cracking, causing active material shedding, lithium dendrite growth, or even internal short circuits, which can trigger thermal runaway. For cells above 600 Ah, Sungrow, in collaboration with cell partners, has developed a 684 Ah short-blade stacked cell based on system requirements. This design adopts planar stacked electrodes with a corner-free layout, ensuring uniform stress during electrode expansion and contraction. By avoiding microcracks and material detachment common in wound designs, this approach stabilizes the charge-discharge structure of high-capacity cells and reduces safety risks.



Cross-Section Diagram of 500 Ah+ Wound Cell

Cross-Section Diagram of 600 Ah+ Stacked Cell

Figure 11: Internal Structure and Stress Distribution (Darker Colors Indicate Higher Stress)

- ### Thermal-Electric Separation: A Safer Design

In conventional battery designs, the vent valve and the tabs are typically on the same side of each cell; within a pack, cells are aligned in the same direction, with vent valves located near the tabs of adjacent cells. When a single cell undergoes thermal runaway, the gas-liquid-solid mixture expelled from the vent valve can spread to neighboring healthy cells, potentially triggering a cascading failure.

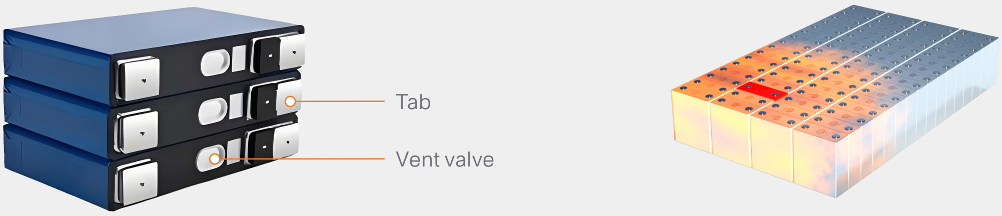


Figure 12: Cell Level—Traditional Design with Vent Valve and Tabs on the Same Side (Left);
Pack Level—In Traditional Design, Thermal Runaway of a Single Cell, High-Temperature Gas Rapidly Affecting Adjacent Cells (Right)

To address this issue, Sungrow has innovatively separated the cell tabs and vent valve, placing them on opposite sides. Within the pack, cells are arranged symmetrically in two rows, creating spatial separation between the thermal runaway vent area and the tabs. This design ensures that in the event of a single cell thermal runaway, high-temperature gas will not directly affect the tabs of adjacent cells, thus preventing cascading failures and ensuring module-level safety by design.

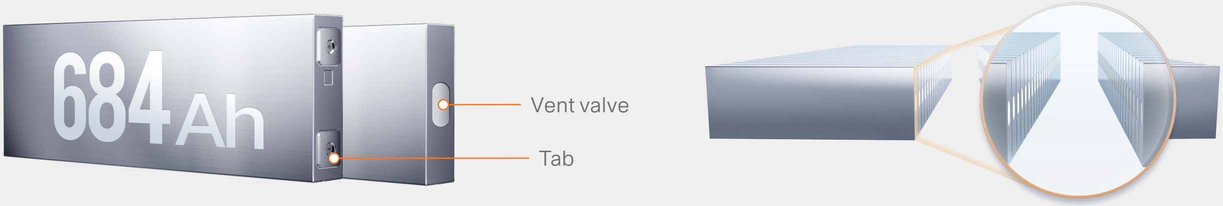


Figure 13: Cell Level—Thermal-Electric Separation Design (Left); Pack Level—Back-to-Back Cell Arrangement

## 2 Effective Cell Management

In energy storage systems, designing the right cells is fundamental. However, over the course of their entire lifecycle, factors such as uneven charge/discharge, misuse, and environmental temperature fluctuations can lead to cell degradation and thermal runaway, even if the cells initially exhibit good consistency. Therefore, "managing cells effectively" is key to safety throughout the entire lifecycle. The main challenges currently facing the industry focus on inaccurate battery state estimation and poor system interconnectivity.

Estimating the State of Charge (SOC) and State of Health (SOH) of lithium iron phosphate batteries remains a common industry challenge due to material properties, environmental factors, operating conditions, and algorithm limitations. Errors typically range from 5% to 8%. In energy storage systems operating under partial charge/discharge conditions, SOC and SOH are not regularly calibrated. As a result, cumulative errors are further amplified, which can lead to overcharging and ultimately trigger thermal runaway.

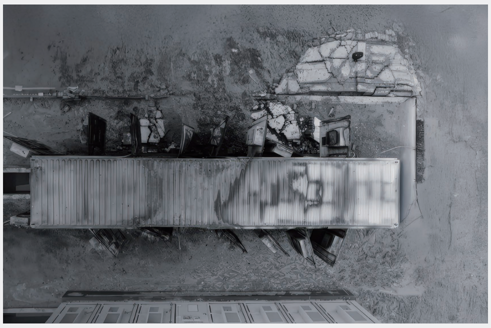
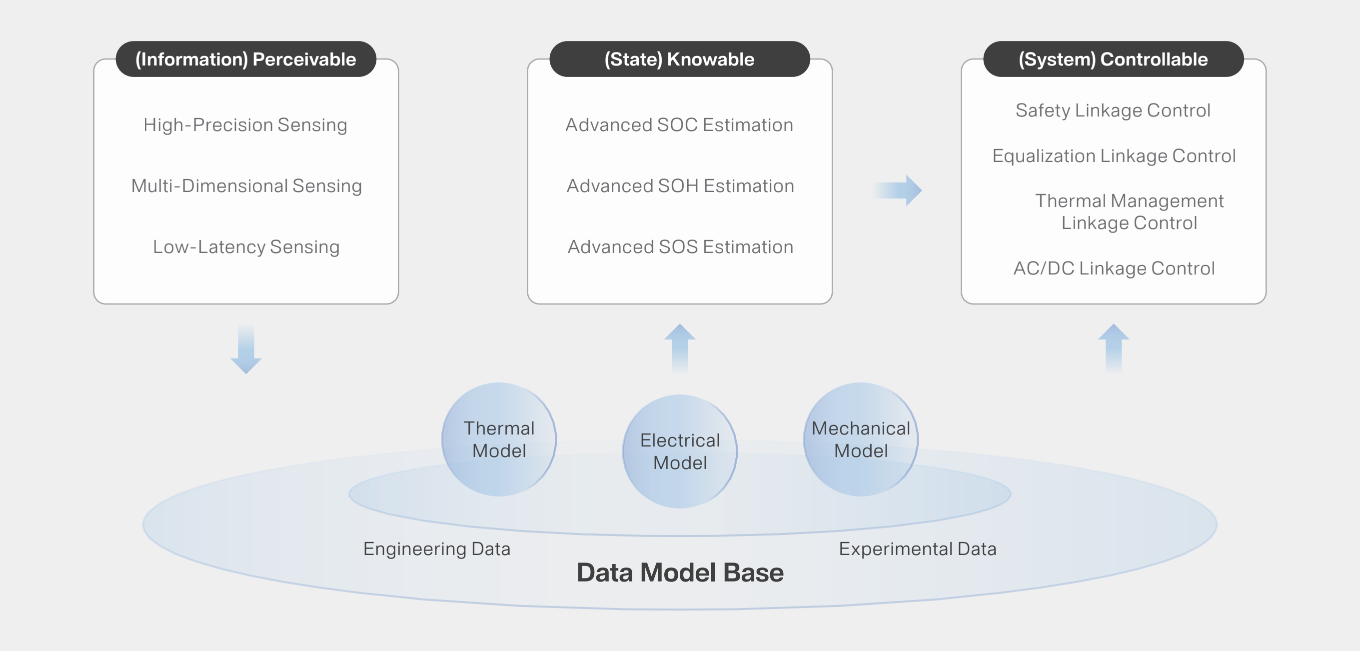


Figure 14: Thermal Runaway Fire Caused by Overcharging Due to 66% SOC Estimation Error at a 20 MWh Energy Storage Station in 2023

Energy storage systems consist of multiple subsystems, including Battery Management System (BMS), DC/AC Power Converter Unit, and Energy Management System (EMS). When energy storage systems involve multiple vendors, non-standard interfaces, and incompatible protocols, data silos can occur. In some cases, different units such as EMS, DC/AC Power Converter Unit, Thermal Management System (TMS), and Fire Suppression System (FSS) may obtain real-time battery status data, but this information is not effectively used as the basis for coordinated control. As a result, the value of battery management data cannot be fully utilized within the system.

In addition, the control architecture of an energy storage system typically involves multiple hierarchical layers. Independent control logic at different levels and a lack of coordination between devices can lead to issues like load disconnection or delayed tripping. A single fault response failure can cause local system failure due to excessive electrical or thermal stress, resulting in damage to the energy storage system.

To address the industry challenges of inaccurate estimation and poor interconnectivity, Sungrow leverages its full-stack proprietary system advantage. Through BM$^2$T (Battery Monitoring & Management Technology), Sungrow has developed a three-tier battery management architecture that ensures signal sensing, state awareness, and coordinated control, aiming to achieve safe, efficient, and long-lasting energy storage systems.



**(Information) Perceivable**

High-Precision Sensing

Multi-Dimensional Sensing

Low-Latency Sensing

**(State) Knowable**

Advanced SOC Estimation

Advanced SOH Estimation

Advanced SOS Estimation

**(System) Controllable**

Safety Linkage Control

Equalization Linkage Control

Thermal Management Linkage Control

AC/DC Linkage Control

Figure 15: BM$^2$T Architecture

- ## Multidimensional Sensing

Leveraging a TB-level battery lifecycle database, Sungrow analyzes the signal parameter changes during normal aging and thermal runaway stages. The study focuses on signals such as voltage, temperature, impedance, force, gas, light, and sound, tracking their evolution during changes in the battery's safety state. This has enabled engineering applications of multidimensional sensing technologies, such as tracking cell expansion force. By continuously tracking the expansion force of individual cells and its trends, and leveraging the "dual-peak breathing effect" along with the significantly enhanced regular pattern of expansion force during aging, Sungrow has developed SOC/SOH estimation algorithms, achieving an SOH estimation error of < 2% at the cell level, < 3% at the rack level, and an SOC estimation error of ≤ 3%.

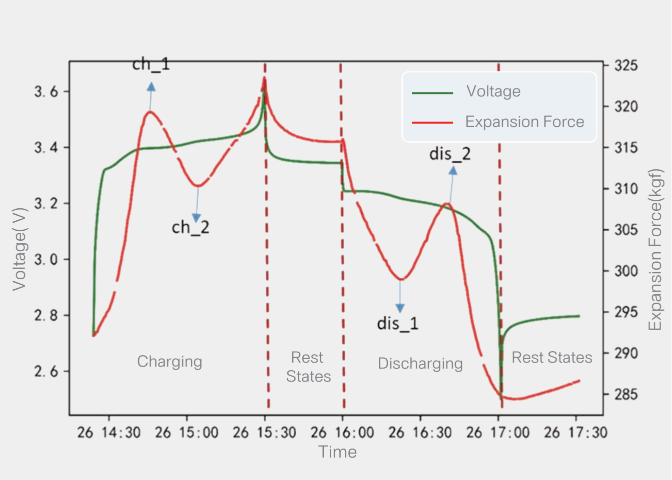


Figure 16: Battery Charge/Discharge Dual-Peak Breathing Effect Diagram

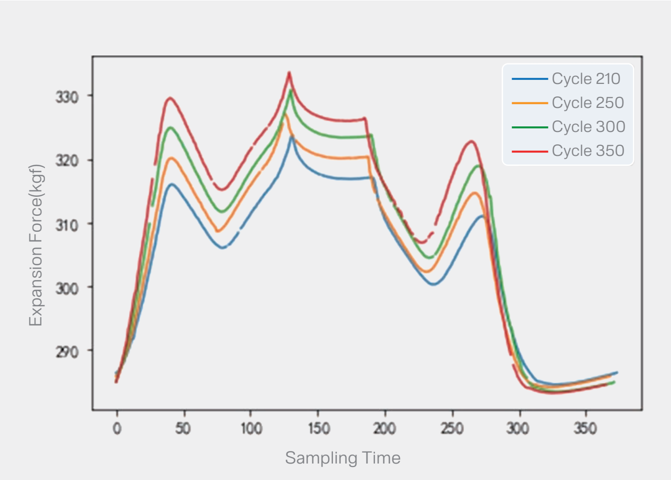


Figure 17: Battery Expansion Force Increases Gradually with Aging

- ## Accurate State Awareness

In complex operating environments, relying on a single parameter to assess battery status is insufficient. Based on electrochemical mechanisms and multi-physics field coupling modeling, Sungrow has developed a comprehensive State of Safety (SOS) evaluation system, covering everything from lithium plating to thermal runaway. This system is the core of achieving precise state awareness.

### ① Lithium Plating Early Warning Accuracy ≥ 95%

By analyzing the voltage–capacity curve characteristics of cells during operation and rest, Sungrow has developed a lithium plating feature dynamics model, focusing on abnormal voltage fluctuations at the end of charge and during rest relaxation. Using high-precision data acquisition and signal processing algorithms, early-stage lithium plating can be effectively detected, achieving a diagnostic accuracy of over 95%. This enables the prevention of internal short-circuit risks caused by lithium dendrite growth.

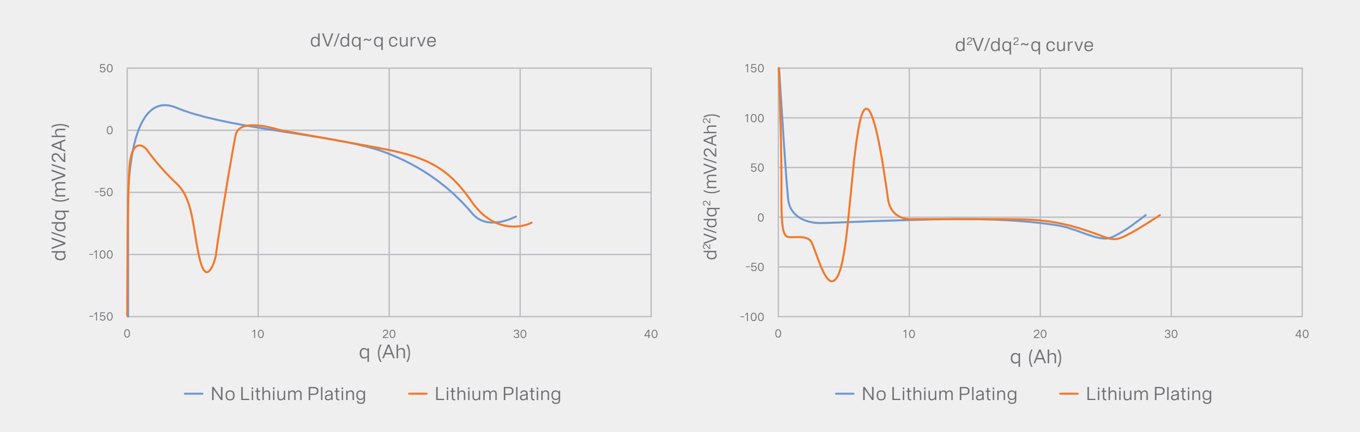
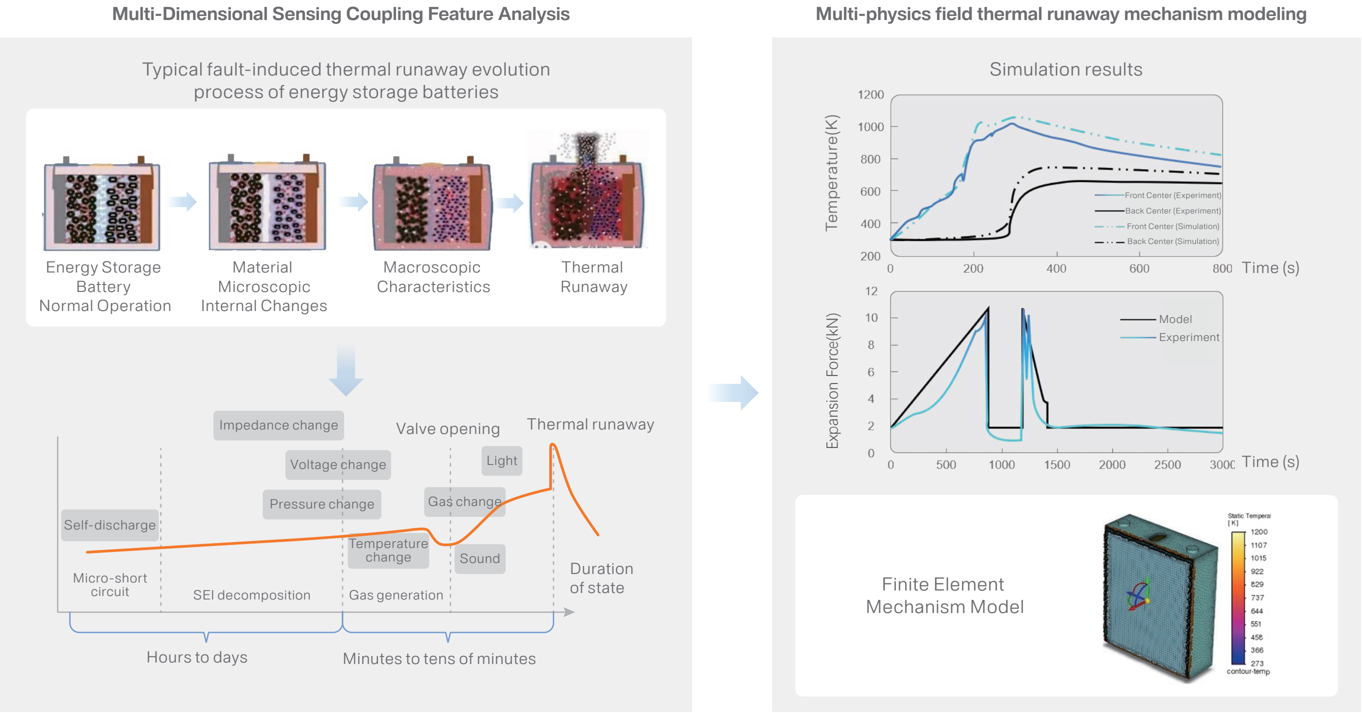


Figure 18: Principle of Lithium Plating Detection Using Second Order Differential of Voltage–Capacity Curve

### ② Thermal Runaway Early Warning Accuracy ≥ 99%

By analyzing the coupled evolution of multidimensional signals—mechanical, electrical, thermal, and force—under extreme conditions, Sungrow has established a dynamic modeling approach. Through multi-parameter integrated analysis, the system overcomes the limitations of single-dimensional assessment, enabling timely detection of early-stage thermal runaway. This technology can provide an early warning 5 minutes in advance with ≥ 99% accuracy, and 10 minutes in advance with ≥ 95% accuracy, significantly reducing false alarms and unplanned shutdowns.



**Multi-Dimensional Sensing Coupling Feature Analysis**

**Multi-physics field thermal runaway mechanism modeling**

Figure 19: Thermal Runaway Early Warning Mechanism Modeling

## • Coordinated and Controllable System-Level Operation

The ultimate goal of enhanced sensing and diagnostics is to enable efficient system-level coordinated control, allowing the energy storage system to operate as an integrated whole.

### ① Multi-Level Coordinated Safety Control

Through a multi-layer redundant protection architecture spanning the rack, battery stack, medium-voltage, and module levels, the system can respond promptly to faults while enabling controlled soft shutdown. Electrical circuits can be reliably and rapidly isolated, preventing fault escalation.

### ② Multi-Level Coordinated Balancing Control

To address SOC inconsistency among cells, conventional cell-level balancing provides limited effectiveness. The advanced management system establishes a data pathway from the cell level to the plant level, enabling coordinated multi-level balancing. Passive balancing is applied within racks, while active balancing operates at the pack level. At the block and plant levels, data-driven strategies enable inter-rack and inter-block dynamic power allocation and balancing. This systematic approach improves overall energy efficiency, extends battery lifecycle, and enhances plant safety.

# 3.2 Electrical-Level Safety Architecture

Based on statistics of energy storage fire incidents from 2017 to 2023 (as shown in Figure 20), electrical failures have been identified as one of the primary triggers of system-level thermal runaway, mainly occurring in the form of short circuits and arcing. Specifically, liquid ingress, condensation, or insulation degradation may lead to short circuits, resulting in high-current surges and localized overheating. In addition, sustained arcing caused by connector failures can generate high-temperature heat sources and trigger fire ignition. As short circuits and arcing constitute the primary pathways by which electrical faults escalate into fires, this white paper focuses on these two critical mechanisms and presents systematic electrical safety control strategies.

| Energy Storage Incident | Cause |
|---|---|
| 2017/3/7 Fire at AGC Frequency Regulation Project in Shanxi, China | Arcing at connection points |
| 2018/6/15 Fire at 19 MWh Energy Storage Project in Gunsan, Jeollabuk-do, South Korea | Insulation degradation due to water ingress |
| 2018/8/3 Fire at Demand-Side Energy Storage Project in Jiangsu, China | Overcharging of rack caused by reverse connection |
| 2018/12/22 Fire at 2.662 MWh Energy Storage Project in South Korea | Battery leakage |
| 2021/4/16 Fire at Dahongmen Energy Storage Project in Beijing, China | Internal battery short circuit |
| 2021/7/30 Fire at 450 MWh Energy Storage Project in Australia | Leakage and short circuit |
| 2022/9/20 Fire at 730 MWh Energy Storage Project in California, USA | Rainwater ingress and short circuit |
| 2023/4/26 Explosion at Uncommissioned Energy Storage Container in Gothenburg, Sweden | Leakage and short circuit |
| 2023/6/26 Fire at 36 MWh Energy Storage Project in New York, USA | Rainwater ingress and short circuit |
| ... | |

Figure 20: Statistics of Fire Incidents Caused by Electrical Failures

## 1 Short Circuit Risk Control

Liquid-cooled energy storage systems feature densely packed coolant pipelines and complex joints, and are often exposed to harsh outdoor conditions, including large temperature fluctuations, high humidity, and extreme weather such as rain and snow. These factors increase the risk of coolant leakage, water ingress, and condensation, creating significant challenges for maintenance and safety management. Such risks have been key contributors to past short-circuit fire incidents in energy storage systems.

### • Internal Leakage Risk Control

Throughout the energy storage system's lifecycle, improper handling or degraded sealing can lead to liquid leakage, allowing fluids to enter electrical areas and causing short circuits or arcing. In severe cases, this can trigger thermal runaway and present fire risks.

To mitigate these risks, energy storage systems can use multiple layers of protection on liquid cooling terminals and internal structures. The "no-leakage—liquid isolation—leakage alarm" closed-loop design effectively reduces short circuit risks and enhances overall safety and control.

Figure 21: Maintenance Personnel Performing Coolant Replenishment

#### ① Self-Sealing Liquid Cooling Terminals with No Leakage During Insertion and Removal

Energy storage system features a patented self-sealing structure for liquid cooling terminals. This design allows the liquid path to automatically seal during refilling operations, preventing coolant leakage and minimizing the risk of leakage caused by improper handling. Thanks to this design, the system has maintained a zero-leakage record across hundreds of thousands of installations, fully validating its reliability.

### ② Liquid-Electrical Separation Without Short Circuits from Leakage

To further reduce the risk of leakage and electrical hazards caused by improper handling, energy storage system features a patented liquid-electrical separation design. This design re-engineers the internal structure of the liquid-cooled pack and DC/AC Power Converter Unit, ensuring complete separation between the liquid circuit and the electrical circuit. This reduces the risk of coolant contacting live electrical components, achieving both efficient heat dissipation and electrical safety in a compact space.

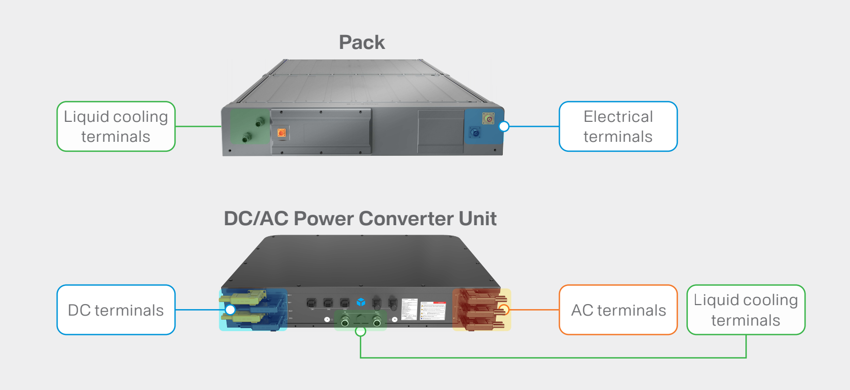


Figure 22: PowerTitan 3.0 Pack & DC/AC Power Converter Unit Liquid-Electrical Separation Design

In the event of leakage, the energy storage system implements directed drainage and electrical risk isolation using IP65 aviation connectors for electrical connections, ensuring high protection for the pack's electrical areas. Additionally, drainage channels, liquid collection chambers, and drainage outlets are integrated at the bottom of the storage cabinet, creating a dedicated path for liquid drainage. This design ensures that any leaked liquid quickly and safely exits the system, preventing it from reaching electrical areas, reducing the risk of short circuits, and enhancing the system's emergency leak management capabilities.

### ③ Risk Sensing for Early Leakage Detection

To further reduce uncertainties in the operation of liquid-cooled energy storage systems and enable early leakage detection and response, Sungrow has implemented leakage tracking technology across the entire energy storage battery and DC/AC Power Converter Unit. This technology utilizes a three-dimensional collaborative sensing approach to track liquid level, flow rate, and pressure. It instantly detects abnormalities in the cooling circuit, triggering immediate proactive alarms or individual device shutdowns. This helps prevent fault escalation, ensuring higher stability and reliability in the liquid cooling environment.

## • External Erosion Risk Defense

Throughout the lifecycle of an energy storage system, it faces complex and variable environmental challenges. Insufficient sealing or poor design can allow external rainwater, moisture-laden air, and condensation to infiltrate the electrical areas, potentially causing terminal short circuits and triggering thermal runaway and fires. A typical case is the December 2025 fire at an energy storage plant in the United States. Official investigations confirmed that the incident was caused by a manufacturing defect that allowed water infiltration, eventually leading to a short-circuit fire.

Figure 23: Fire at an Energy Storage Plant in the United States Due to Water Ingress and Short Circuit (Image Source: Mainstream Media Reports)

To address the risks of insulation failure, internal short circuits, thermal runaway, and potential fires or explosions caused by rainwater infiltration, condensation, and moisture accumulation, Sungrow has implemented a comprehensive design focusing on waterproofing, condensation resistance, and moisture control.

The system adopts IP55-rated full-unit sealing and IP67-rated protection for terminals and connection points, effectively preventing rainwater ingress and mitigating moisture-induced risks such as electrical short circuits and thermal runaway. The enclosure is constructed with high-performance thermal insulation materials to resist external environmental fluctuations and prevent internal condensation. A "one-enclosure,

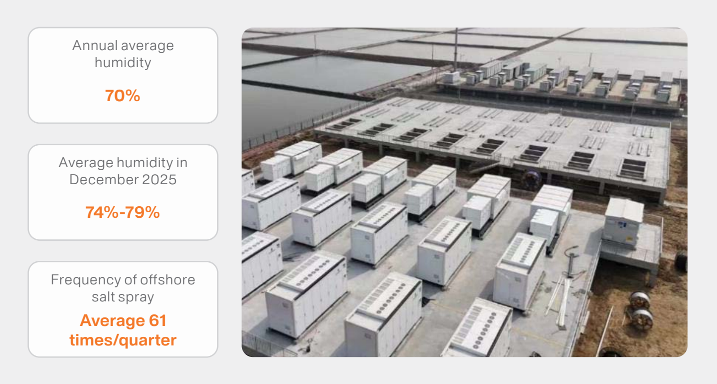


Figure 24: Offshore Energy Storage Project in Weifang, China (28 MW/56 MWh), Operating Reliably and Efficiently

dual-dehumidifier" design enables zonal dehumidification, ensuring rapid humidity reduction. Even after container opening during maintenance, residual moisture is quickly removed upon closure, maintaining long-term operational stability.

## 2 Arcing Risk Control

Arcing occurs in both AC and DC power systems, typically at electrical equipment connections and switch locations. It is mainly caused by poor contact at connection points, aging or damaged insulation materials, or sudden circuit disconnections.

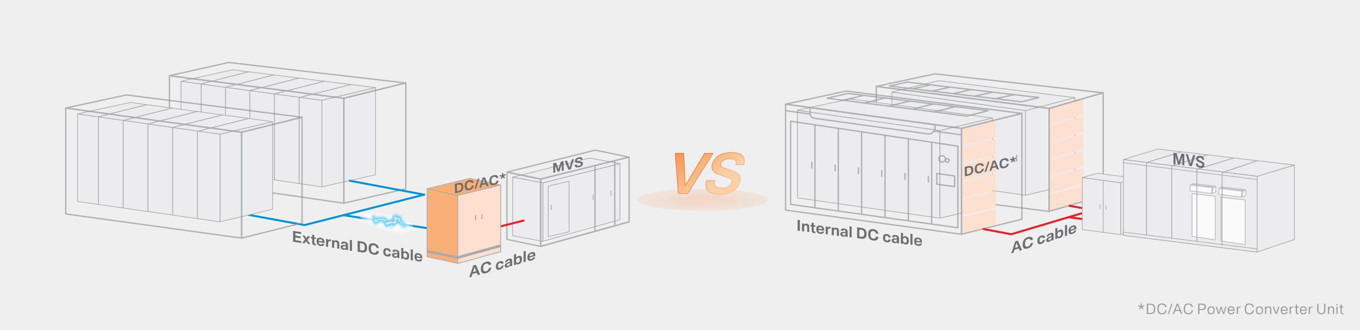
Unlike AC arcs, which naturally extinguish when the current passes through zero, DC arcs lack a zero-crossing point. The continuous current keeps supplying energy to the arc, making it difficult to extinguish and significantly increasing the risk of fires in flammable components like batteries and cables. As energy storage system capacities grow and the number of connection points increases, the number of potential fault points on the DC side and higher energy levels further exacerbate the risks. If a DC arcing fault occurs, the potential hazards and severity of the incident can escalate significantly.

### • Comprehensive Arc Prevention

**① Component-Level Source Prevention**

Based on conservative estimates from engineering practices, for every 10 meters of external DC cable, 3 to 5 additional potential connection or installation defects are introduced, increasing the likelihood of external arcing faults. Additionally, DC cables exposed to the environment are more susceptible to erosion and damage from foreign objects. If a fault occurs, it can quickly lead to fires or equipment damage.

To tackle the issue of exposed DC cables, which is common in traditional energy storage systems, Sungrow has introduced an innovative AC storage architecture. This solution not only ensures exceptional efficiency and precision but also mitigates the safety risk of DC cable arcing. By embedding the DC/AC Power Converter Unit inside the battery container, the design keeps the DC circuits contained, reducing cable lengths and significantly minimizing external exposure, thereby effectively preventing insulation arcing due to environmental factors. To address the risk of internal arcing, Sungrow's energy storage system strengthens insulation, improves connection point stability, and employs copper busbar isolation in the busbar area, reducing the likelihood of DC arcing and its spread.



*DC/AC Power Converter Unit

Figure 25: External DC Cables vs. DC Cables Staying Inside the Battery Container

Additionally, to ensure on-site safety, Sungrow's energy storage system pre-installs all DC-side wiring and connections at the factory, eliminating potential on-site assembly errors, reducing the number of DC connection points, and ensuring long-term reliability. This approach enhances both system safety and operational reliability for projects.

**② Full-Link Hazard Isolation**

To mitigate the risks of high-voltage short circuits during transportation and installation, as well as overcurrent hazards during operation, Sungrow has developed a comprehensive tiered overcurrent protection system. This system covers the pack, rack, and both AC and DC sides of the DC/AC Power Converter Unit, ensuring that fault energy is quickly isolated at the source. It effectively contains the chain reaction from short-circuit currents, significantly reducing the risk of fire caused by arcing.

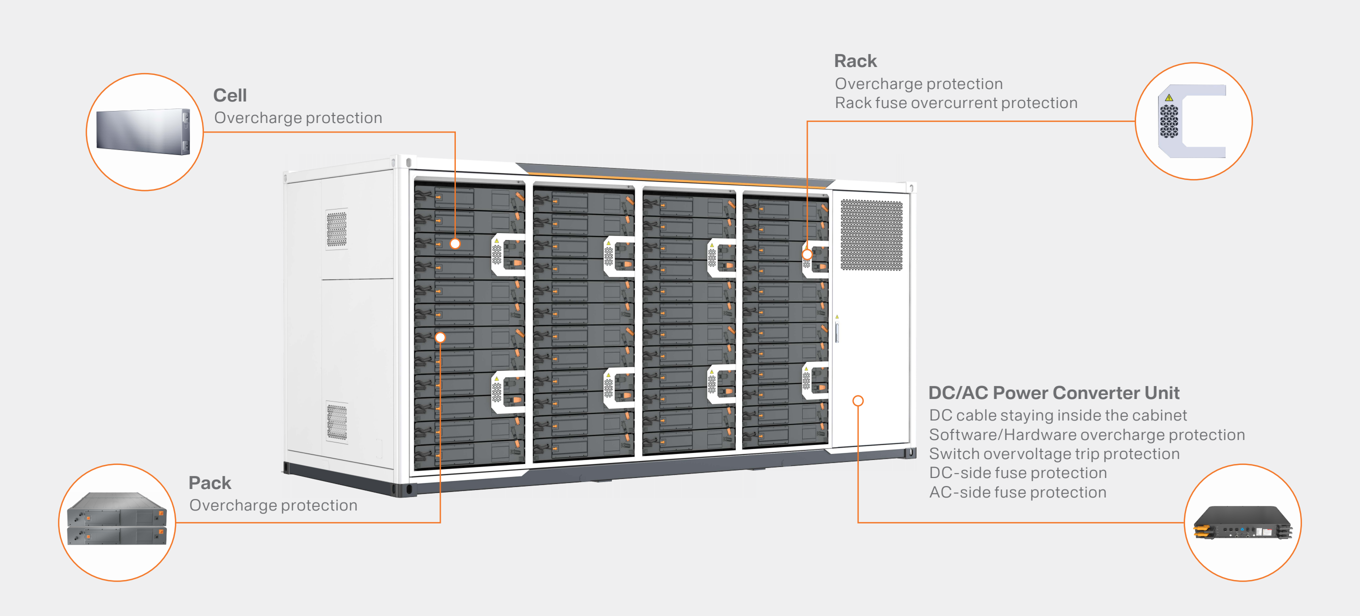


Figure 26: Full-Link Tiered Overcurrent Protection System

### ③ 24h Insulation Risk Early Warning

Energy storage stations typically operate for 15 to 20 years. Over long-term operation, electrical equipment and cables are consistently exposed to heat, mechanical, and environmental stresses, which cause the insulation materials to degrade and age. Once this degradation reaches a critical point, it can easily lead to severe arcing faults.

To address the hidden risks of insulation degradation on both the AC and DC sides, electrical insulation tracking is essential to create a safety loop for arc prevention. Sungrow's energy storage system features 24-hour AC/DC insulation tracking. Before startup, it performs DC-side impedance testing, and during operation, it continuously tracks AC-side insulation. The system submits and analyzes the data in real time, providing early warnings for any insulation issues to prevent them from evolving into arcing risks, thereby significantly enhancing overall system safety and reliability.

## • Active Arc Extinction

Energy storage systems face unpredictable extreme events throughout their lifecycle, such as rodent or insect damage, foreign object intrusion, or sudden impacts, making risk prevention challenging. As a result, the system must be equipped with active arc control capabilities.

The ArcDefender DC arcing suppression technology was specifically developed to mitigate these risks. Leveraging core technologies such as Tunnel Magnetoresistance (TMR) sensors, data tracking, and dynamic arcing detection algorithms, this technology accurately identifies and rapidly extinguishes arcs. It ensures the safe and stable operation of energy storage systems in high-voltage, high-current, and complex environments.

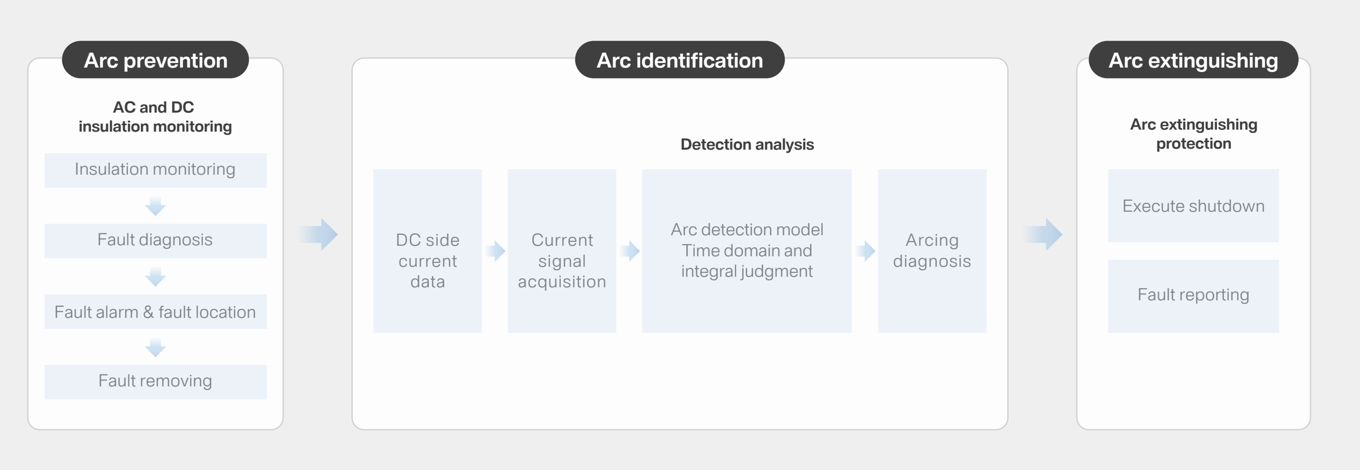


Figure 27: ArcDefender DC Arcing Solution for Energy Storage

### Multi-Scenario

100% high-precision detection in grid-following and grid-forming scenarios

### Wide Current Range

Covers arc currents from the mA level to 500 A

### Rapid Suppression

Identifies and extinguishes arcs within 0.1 seconds, instantly suppressing the spread of risks

TÜV Rheinland (Shanghai) Co., Ltd.
Member of TÜV Rheinland Group

Sungrow Power Supply Co., Ltd.

Date : 7 June, 2024
Our ref. : 326028263

No. 1699, Xiyou Road, New & High Technology Industrial
Development Zone, Hefei, Anhui 230088, P.R. CHINA

Dear Mr. Guangqiang Li,

We herewith notify that the product: **Energy Storage Converter**
Type designation: **SC210HX, SC125HX, SC105HX-FM**

has been type-tested against the following requirement(s)
Test requirement: **White Paper for DC Arc Detection and Interruption Performance**

and were found to meet the requirements of the prescribed specifications.

We appreciate your valued support and would like to offer our assistance and varied services in the approval of your products in the future.

With kind regards,

TÜV Rheinland (Shanghai) Co., Ltd.

Xingxin Tian

Xingxin Tian (Section Manager)
Solar & Commercial Products

TÜV Rheinland (Shanghai) Co., Ltd. 10-15/F, Huatsing Building, No. 88, Lane 777, West Guangzhong Road, 200072 Shanghai, P.R. China
Tel.: (+86) 21-6108 1188
Fax: (+86) 21-6108 1199
E-mail: info@shg.chn.tuv.com
Website: www.chn.tuv.com

QMA30.105.11SHG_7.1 Format of Notification of Test Result (Documentation incomplete) / Revision date: 2008-05-14

Figure 28: TÜV Technical Advancement Certification

In summary, through architectural innovation, risk tracking, and active protection, Sungrow's energy storage system achieves early detection, controlled processes, and rapid isolation in the event of short circuits or arcing risks. This significantly reduces the probability and scope of electrical faults, further enhancing the overall safety of the system.

For more details on DC arc safety technology, please refer to the ESS ArcDefender$^{TM}$ DC Technology White Paper.

Leading Innovation in ESS Arc Safety

ESS ArcDefender Technology White Paper

# 3.3 System-Level Safety Architecture

As energy storage systems scale up, safety risks increasingly exhibit system-level characteristics, making traditional isolated, component-level safety measures insufficient. Sungrow adopts a system-level safety standard to ensure the reliable protection of energy storage plants.

## 1 System-Level Functional Safety Verification

- **Industry-First IEC 61508 Certification**

As energy storage technology advances towards higher integration and larger capacities, system complexity increases, presenting more stringent challenges to system-level safety. Relying solely on equipment reliability is no longer sufficient to mitigate potential risks. A system-level functional safety design is essential to ensure that, even if a single component fails or the system encounters an anomaly, the risk of escalation can be effectively contained, preventing secondary disasters like thermal runaway. In line with this rigorous safety philosophy, Sungrow's energy storage system has undergone a comprehensive evaluation against international standards, becoming the first in the industry to achieve IEC 61508 certification and receive the highest SIL 2 rating.

Achieving this certification not only demonstrates the reliability of the components but also confirms the system's leading-edge performance in software architecture, fault diagnosis, redundancy design, and resistance to interference. It ensures that the system has robust failure protection capabilities, minimizing the likelihood of risks when confronted with potential faults.

FUNCTIONAL SAFETY CERTIFICATE

This is to certify that the

*Battery controller for battery rack R0893AL-AMCA(4H) and R0893AL-AMGA(8H)*
manufactured by

*SUNGROW POWER SUPPLY CO., LTD.*
No 1699 Xiyou Road,
New & High Technology District,
Hefei, P.R.China

have been assessed by CSA Group Testing UK Ltd with reference to the CASS methodologies and found to meet the requirements of

**IEC 61508-2:2010, IEC 61508-3:2010**
**Routes $1_H$ & $1_S$**
**Systematic Capability (SC 2)**

as a subsystem suitable for use in safety related systems performing safety function up to and including
**SIL 2, capable with HFT=0 (1oo1)***

when used in accordance with the scope and conditions of this certificate.

* This certificate does not waive the need for further functional safety verification to establish the achieved Safety Integrity Level (SIL) of the safety related system

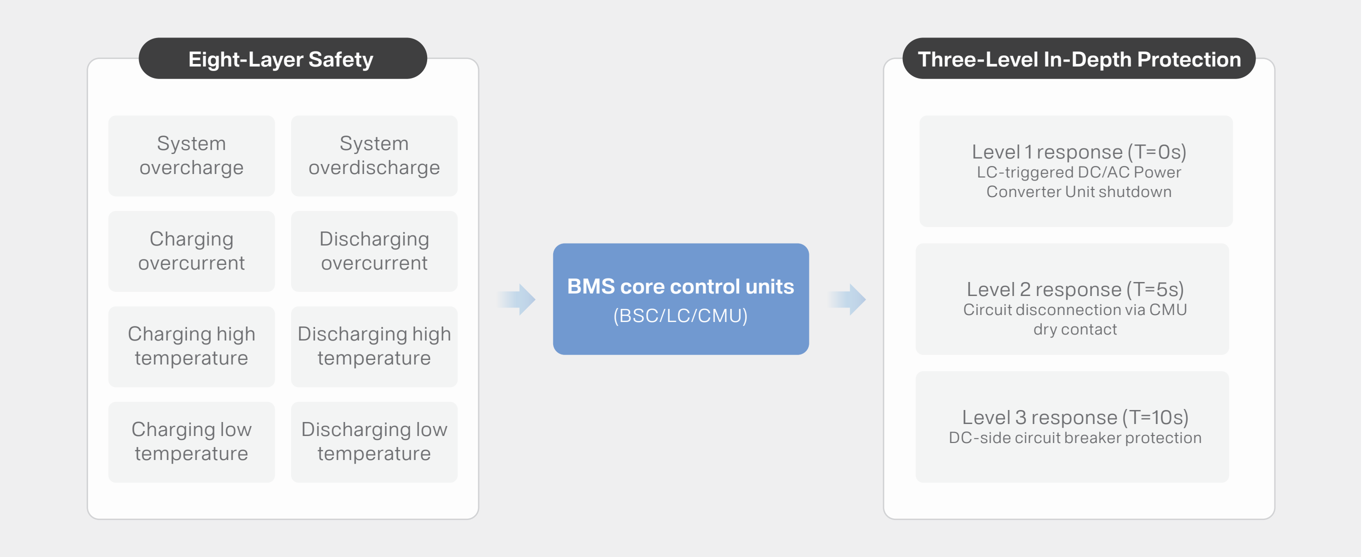
This certificate may only be reproduced in its entirety, without any change.

CSA Group Testing UK Ltd

Figure 29: IEC 61508 Certification Report

### ② Eight-Layer System Safety Protection Framework

In line with the IEC 61508 standard, Sungrow has developed an **"Eight-Layer System Safety Protection Framework"** that covers the three core elements: voltage, current, and temperature. This framework enables millisecond-level real-time tracking of both the cell and system status. Even under extreme scenarios such as communication failure or control command malfunction, the system automatically enters a fail-safe state through hardware-enforced circuit disconnection, ensuring protection against overcharge, overdischarge, overcurrent, and overtemperature, thereby preventing thermal runaway.



## 2 Integrated Fire Suppression System

Battery fires are complex incidents involving the combined release of chemical and electrical energy, making them significantly more challenging to extinguish than traditional electrical fires. Currently, most energy storage systems rely on passive response mechanisms, lacking advanced coordination and full-cycle assessment.

To address this industry challenge, Sungrow has developed the integrated fire suppression system, designed with a system-level approach to create a safety barrier that ensures "extreme thermal runaway does not result in fire". The system strictly complies with stringent international standards such as UL 9540A and NFPA 855/69/68/13, offering comprehensive safety protection from cells to entire container-level systems.

This system adopts a five-layer protection framework covering isolation, detection, exhaust, deflagration, and suppression, combining proactive prevention with rapid response to ensure comprehensive fire safety.

### ① Isolation

The battery and integrated compartments are independently designed, with the battery compartment walls made of nanometer-level flame-retardant materials. This effectively delays heat transfer between adjacent compartments, and the walls are fire-resistant for over 2 hours.

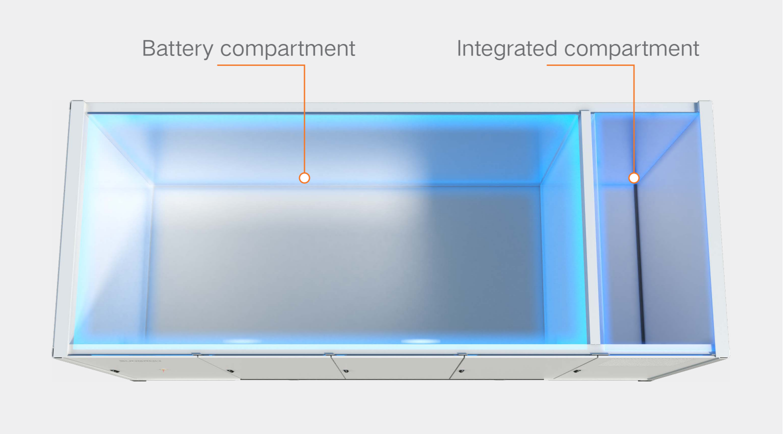


Figure 30: Isolated Design of Battery Compartment and Integrated Compartment

### ② Detection

The system integrates smoke, temperature, and gas detection technologies. Multiple detection signals trigger graded alarms through the control system, reducing the risk of false positives or missed alerts from individual sensors. When any critical parameter exceeds its threshold—such as smoke particles, temperature values or rates, gas concentration levels or rates, or when multiple parameters show abnormal trends simultaneously—the system quickly identifies the issue and gives an alarm for early detection of abnormalities.

Figure 31: Triple Detection System

### ③ Exhaust

The battery energy storage system container features multiple strategically placed ventilation openings, with the internal airflow structure optimized for efficiency. Air flows in from the left side of the cabinet and exits through the top, creating a gas channel that establishes a clear and controllable path for releasing gases. This system continuously expels combustible gases, ensuring the concentration of flammable gases inside the container remains below the lower explosive limit.

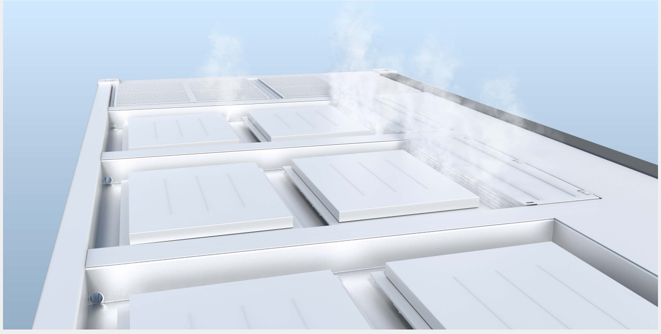


Figure 32: Exhaust System

### ④ Deflagration

The system features a top-directed deflagration design, utilizing a self-sensing venting device for active and controllable pressure release. During thermal runaway, battery cells generate substantial combustible gas. If ignition conditions are met, the combustible gas ignites, causing pressure to rise within the compartment. The deflagration device activates automatically once the preset pressure threshold is reached, opening a directed channel to release the flammable gas and impact energy upward. This prevents pressure buildup and protects the container structure from rupture.

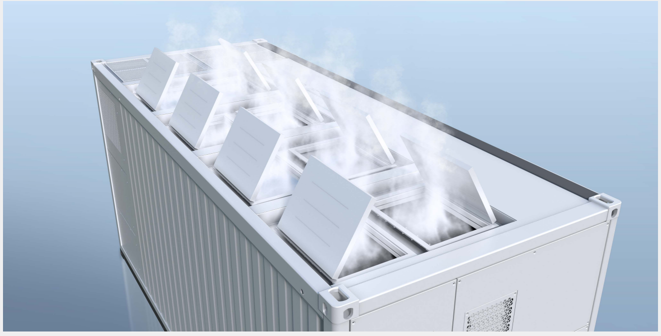


Figure 33: Pressure and Explosion Venting System

### ⑤ Suppression

The system employs a composite fire extinguishing strategy, combining gas (aerosol/gas cylinders) and water-based fire suppression. It integrates an automatic fire extinguishing device for rapid response in the early stages of fire formation, ensuring precise firefighting.

**Gas Fire Suppression:**

Once the detection system identifies thermal runaway or early combustion signs, the gas fire extinguishing device activates, releasing extinguishing agents. These agents suppress free radical reactions and disrupt the combustion chain reaction to contain fire spread. This stage focuses on incipient fires and localized runaway areas, providing critical time for subsequent water-based fire suppression.

**Water-Based Fire Suppression System:**

The system features 12 nozzles for three-dimensional spray coverage inside the battery compartment. When the fire spreads or the temperature exceeds a set threshold, the water-based fire suppression system automatically activates, cooling the area and absorbing heat to reduce the temperature, preventing re-ignition and heat transfer to adjacent compartments. The nozzle layout is optimized for uniform coverage of critical heat sources, ensuring no blind spots for firefighting.

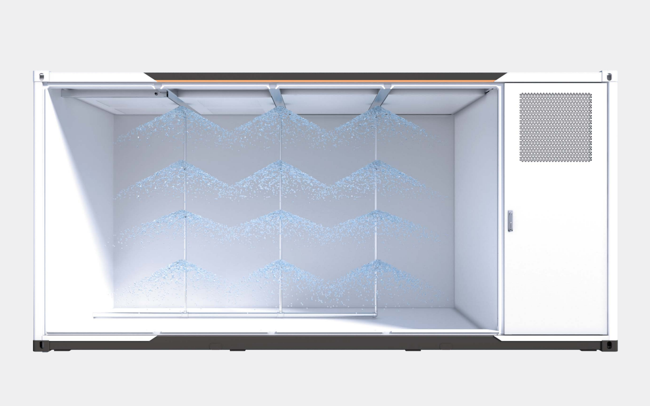


Figure 34: Water-Based Fire Suppression

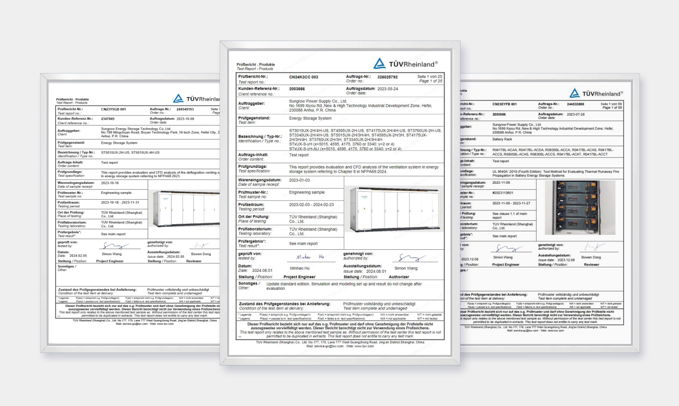


Figure 35: NFPA 68/NFPA 69/UL 9540A

## 3.4 Plant-Level Safety Architecture

Energy storage projects are operated as plants, not as individual containers or isolated systems. Safety measures applied only at the container or system level can address local faults, but they are not sufficient to manage risks that may spread across the plant—for example, when thermal events propagate from a single rack to the whole plant. A plant-level safety approach is therefore essential to ensure asset protection and stable operation.

Sungrow addresses this by designing safety from the plant level down, coordinating the functions of containers, subsystems, and control systems as part of an integrated architecture. This approach goes beyond basic equipment compliance and focuses on maintaining reliable plant operation. By managing safety at the plant level, energy storage assets can operate more predictably and with greater operational confidence.

### 1 Large-Scale Burn Test

Safety validation for energy storage systems has traditionally focused on individual components such as battery packs or racks. This approach does not fully address the risk of thermal propagation at the plant level. To better manage these risks and protect assets, personnel, and long-term investment value, Sungrow has extended its safety validation from equipment-level testing to plant-scale scenarios.

Rather than testing individual cabinets in isolation, Sungrow conducts large-scale burn tests that replicate extreme conditions across a full installation. These tests evaluate whether a thermal event originating in a single rack can be contained without spreading to the rest of the plant.

In collaboration with DNV, Sungrow has carried out two of the largest burn tests conducted for energy storage systems. The results provide practical evidence of the effectiveness of plant-level safety design and contribute to advancing safety practices across the industry.

- **Test Conditions**

A 20 MWh real-world energy storage plant scenario was created, with four PowerTitan 2.0 energy storage systems. Containers A and B were arranged back-to-back with a 15 cm gap, without firewalls. The system was fully charged at 100% SOC. The ambient wind speed was 3.3 m/s. To simulate a real thermal runaway scenario, all fire protection systems were deliberately disabled during the test. Furthermore, 52 cells in Container A were subjected to destructive heating and ignition to induce thermal runaway, enabling an assessment of the system's safety protection capabilities.

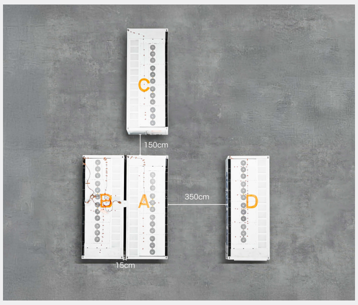
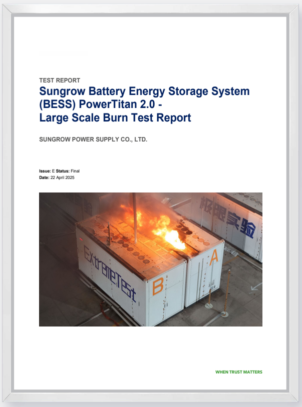


Figure 36: Test Layout Diagram

Figure 37: On-Site Large-Scale Burn Test of PowerTitan

## Test Results

- **Structural integrity and directional pressure relief:** The deflagration panel activated automatically, ensuring precise pressure relief and deflagration. The container structure remained intact, without deformation or flying debris.
- **No thermal runaway propagation:** The test lasted for 14 hours, with the fire reaching its peak. The maximum temperature in Container A was 1385°C, while the temperature in the adjacent Container B reached 42°C. There was no thermal runaway propagation to Containers B, C, or D, and no thermal runaway risk was observed.
- **The fire burned out without burn-through, and no re-ignition was observed:** After 26 hours of continuous combustion, Container A did not reignite, and its structure remained free from burn-through. Containers B, C, and D remained undamaged.



TEST REPORT

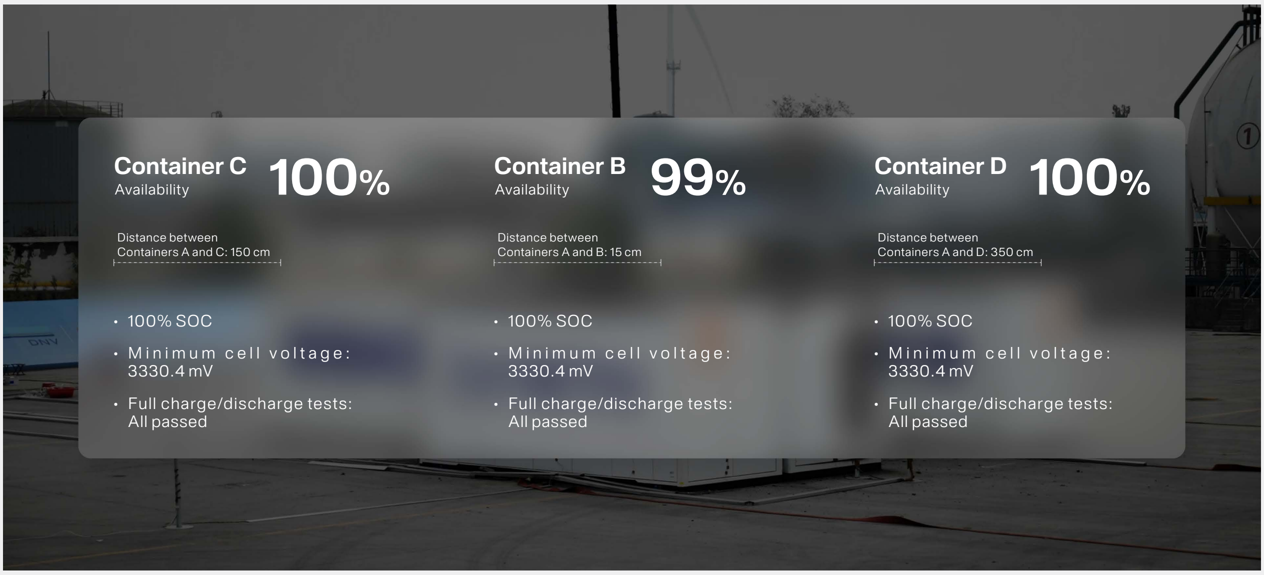
Sungrow Battery Energy Storage System
(BESS) PowerTitan 2.0 -
Large Scale Burn Test Report

SUNGROW POWER SUPPLY CO., LTD.

**Issue:** E **Status:** Final
**Date:** 22 April 2025

WHEN TRUST MATTERS

Figure 38: PowerTitan Large-Scale Burn Test Report



**Container C** 100%
Availability

Distance between
Containers A and C: 150 cm

- 100% SOC
- Minimum cell voltage: 3330.4 mV
- Full charge/discharge tests: All passed

**Container B** 99%
Availability

Distance between
Containers A and B: 15 cm

- 100% SOC
- Minimum cell voltage: 3330.4 mV
- Full charge/discharge tests: All passed

**Container D** 100%
Availability

Distance between
Containers A and D: 350 cm

- 100% SOC
- Minimum cell voltage: 3330.4 mV
- Full charge/discharge tests: All passed

Figure 39: After the test, Container B's availability was 99%, Container C's availability was 100%, and Container D's availability was 100%

# 3.5 Grid-Level Safety Architecture

As the global energy mix shifts toward low-carbon sources, the share of renewable energy in power systems is rising rapidly. With the large-scale integration of renewable energy sources, primarily through power electronic interfaces, system inertia and natural damping levels are decreasing, altering grid operation characteristics and introducing new challenges in frequency, voltage, power angle, and wide-frequency stability.

However, grid safety depends not only on the regulation capabilities of the DC/AC Power Converter Unit but also on deep collaboration between the AC and DC sides. Sungrow's "Stem-Cell Grid-Forming Technology" is designed to meet the evolving demands of next-generation power systems. It ensures safe and efficient charging and discharging of DC-side batteries across various grid conditions, while also providing stable energy support to the AC side. Through system-level collaboration, this technology maintains full-spectrum stability in frequency, voltage, and power angle, while effectively suppressing broadband oscillations, ensuring safe and stable grid operation.

## 1 Frequency Stability

As system inertia continues to decline in new power systems, active power support becomes weaker, leading to larger frequency fluctuations and frequency deviations beyond acceptable limits. In severe cases, this may trigger large-scale blackouts, threatening grid security and power supply reliability.

Sungrow's flexible frequency control technology addresses this challenge by tracking the rate of frequency change to assess disturbance intensity. The system dynamically adjusts virtual inertia: increasing it during strong disturbances and reducing it during weaker ones. This enables rapid active power response across a grid strength range of SCR 1–40, effectively stabilizing frequency. On December 23, 2023, the sudden tripping of a high-voltage transmission line between the UK and France caused an instantaneous loss of 1 GW of power in the UK grid. System frequency dropped sharply from 50 Hz to 49.3 Hz. The Sungrow energy storage plant in Minety responded within 1 second, helping restore grid frequency within 5 minutes.

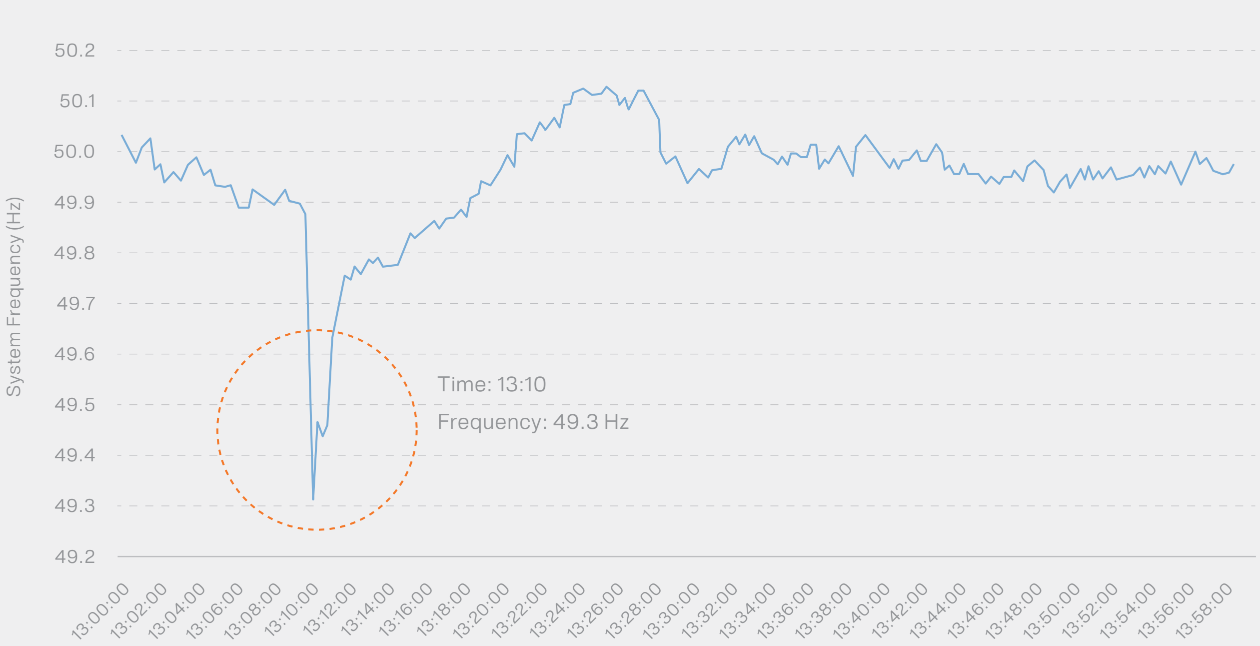


Figure 40: UK Grid Frequency Drop Event on December 23, 2023

## 2 Voltage Stability

Power-electronics-dominated power systems face growing challenges in maintaining voltage stability. Commutation failures in voltage source converter-based high voltage direct current (VSC-HVDC) transmission systems or abrupt reductions in wind and solar output can trigger voltage instability if reactive power compensation is insufficient. Meanwhile, renewable energy generation units generally lack the inherent reactive power support of conventional synchronous generators, constraining their ability to regulate grid voltage. On September 28, 2016, a severe storm struck South Australia, destroyed over 20 transmission towers, causing voltage dips that triggered a "System Black"" event. Due to insufficient low-voltage ride-through capability, large numbers of wind turbines disconnected in succession, ultimately resulting in a statewide blackout that took more than 50 hours to fully restore.

Sungrow's wide-SCR transient adaptation technology enables smooth transitions between strong and weak grids across an SCR range of 1–40. The DC/AC Power Converter Unit rapidly adjusts power output to compensate for power imbalances caused by changes in grid strength, while effectively suppressing voltage fluctuations. In addition, the voltage-source-enhanced continuous high/low voltage ride-through technology enables the system to withstand multiple consecutive extreme faults without disconnecting. During voltage sags, it rapidly injects reactive power to aid voltage recovery; during voltage swells, it promptly absorbs excess reactive power to mitigate overvoltage. With a reactive power response time of under 20 milliseconds, it supports voltage recovery at the point of connection (POC).

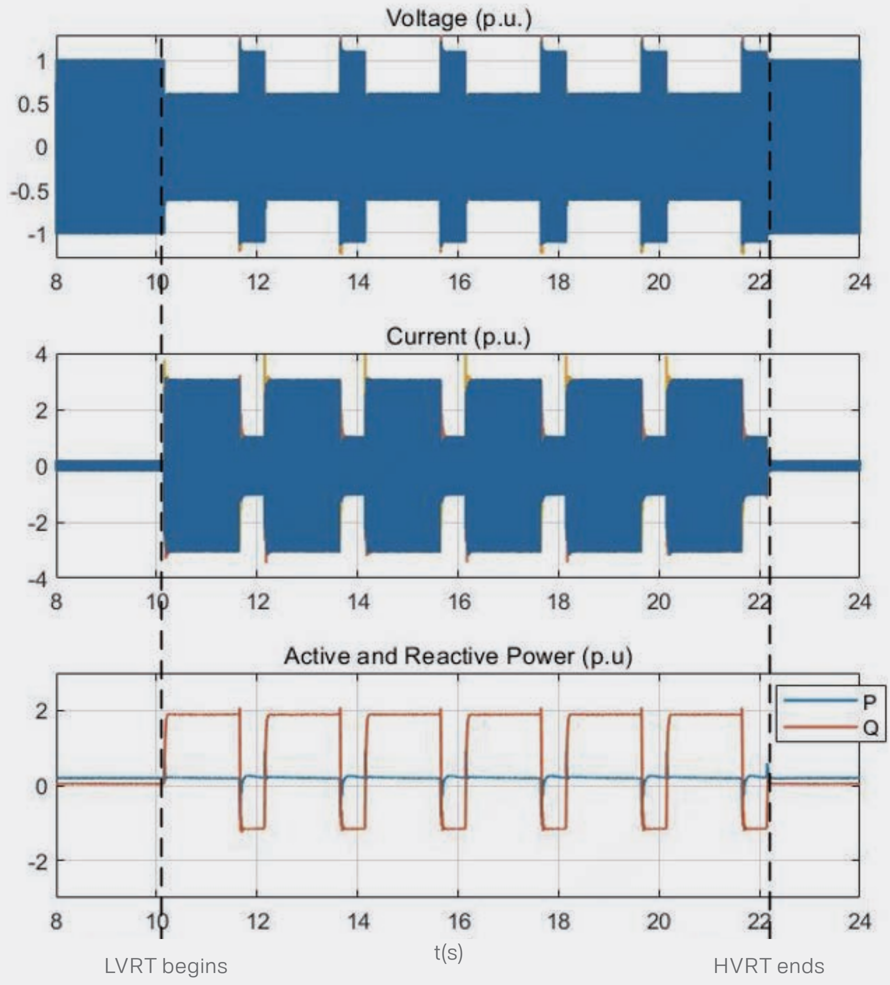


Figure 41: Waveforms of Six Consecutive Grid Voltage Dip-Rise Ride-Through Events

During the 35 kV artificial short-circuit test at the Nêdong Caipeng project in China, 192 units of string DC/AC Power Converter Units from Sungrow were connected in parallel. Under both full-charge and full-discharge conditions, the system successfully delivered an instantaneous short-circuit current three times the rated value and achieved millisecond-level voltage recovery after the fault. All units maintained stable consistency, current sharing, and coordinated control throughout the test.

Figure 42: 35 kV Artificial Short-Circuit Test at the Nêdong Caipeng Project in China

## 3 Power Angle Stability

In conventional power systems, synchronous generators maintain synchronous operation through electromechanical coupling, ensuring power angle stability. With a high penetration of renewable energy, power electronic devices increasingly replace synchronous generators, reducing system inertia and weakening synchronization capability. When the system experiences disturbances, such as sudden load changes or grid faults, low-inertia renewable units cannot provide enough synchronizing power support. This leads to increased power angle deviations between generators, which can result in loss of synchronism or system separation.

On January 8, 2021, the Ernestinovo 400 kV substation in Croatia experienced a bus tie breaker overload trip, causing multiple transmission lines to disconnect within 20 seconds. This event split the European continental grid into northwest and southeast sections. The system experienced an instantaneous power imbalance of approximately 5.8 GW, resulting in severe frequency fluctuations. Generators lost synchronism, leading to power angle instability, widespread load shedding, and their disconnection from the grid.

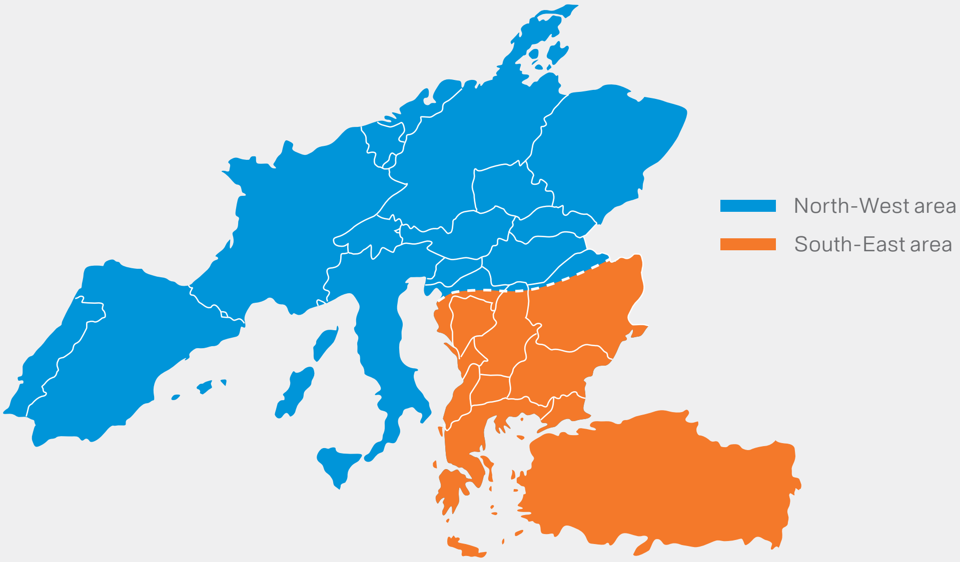
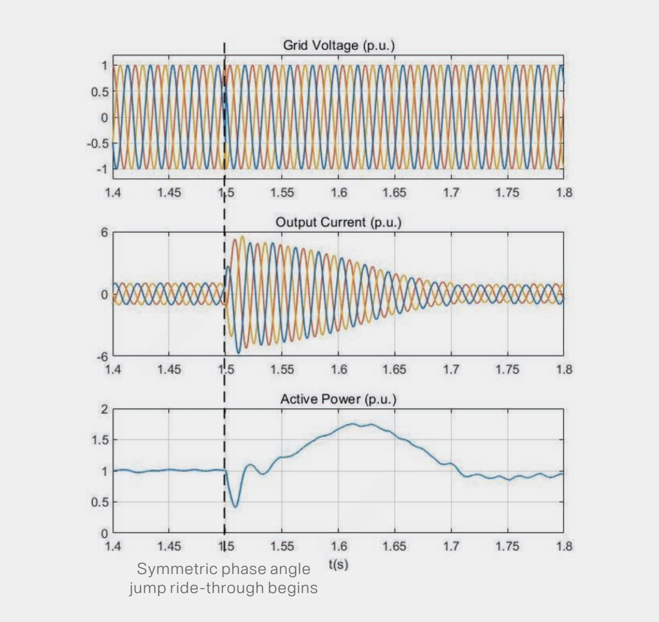


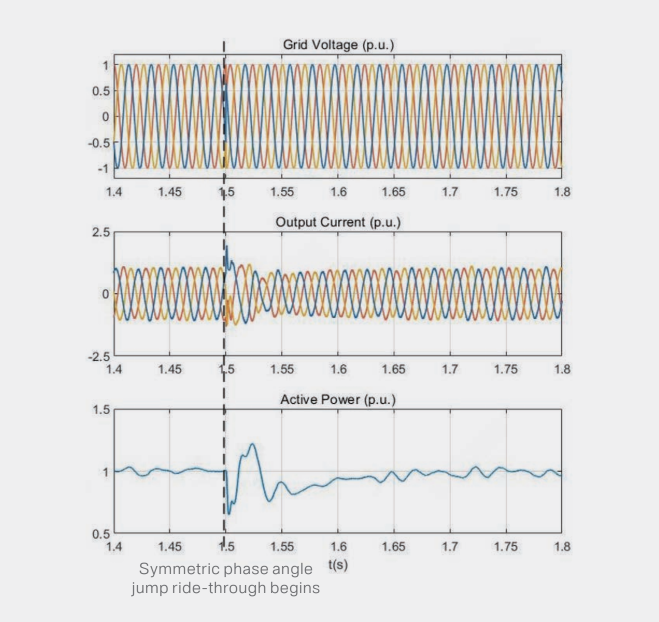
Figure 43: The Synchronous Area of Continental Europe Was Separated into Two Parts on January 8, 2021

Sungrow has developed an **adaptive phase-angle jump ride-through technology** that fully supports ±90° symmetric and asymmetric phase-angle jumps. Under wide-range phase-angle jump conditions, the system anticipates grid phase variations and rapidly adjusts the internal electromotive force frequency of the DC/AC Power Converter Unit, accelerating the virtual rotor dynamics to maintain power angle stability. For small-range phase-angle jumps, the function automatically reduces its intervention, allowing the DC/AC Power Converter Unit to fully utilize its frequency support capability. When asymmetric phase-angle jumps occur in the grid, the DC/AC Power Converter Unit generates negative-sequence voltage to support the faulted phase. This enables a transition from passive adaptation to unbalanced grid conditions to active voltage support for the grid.



Symmetric phase angle jump ride-through begins

Figure 44: Symmetric Phase-Angle Jump Ride-Through Waveforms (90°, without optimization technology)



Symmetric phase angle jump ride-through begins

Figure 45: Symmetric Phase-Angle Jump Ride-Through Waveforms (90°, with optimization technology)

## 4 Broadband Oscillations

Renewable energy generation units connect to the grid through power electronic devices. Under weak grid conditions, the coupling resonance between power electronics, grid impedance, and control loops can be easily amplified, resulting in multi-frequency oscillations spanning from low to high frequencies. Wide-frequency oscillations can damage renewable energy generation units, degrade power quality, and cause grid voltage or current to exceed limits. This may trigger protection mechanisms, potentially leading to the disconnection of renewable or conventional generation units.

On July 1, 2015, a subsynchronous oscillation occurred at a wind farm in northwest China, causing torsional oscillation protection on a thermal power generator located over 300 kilometers away. This led to a shutdown of the thermal power generator. It was a typical case of grid power oscillations caused by the propagation of subsynchronous oscillation components across multiple levels of the power grid.

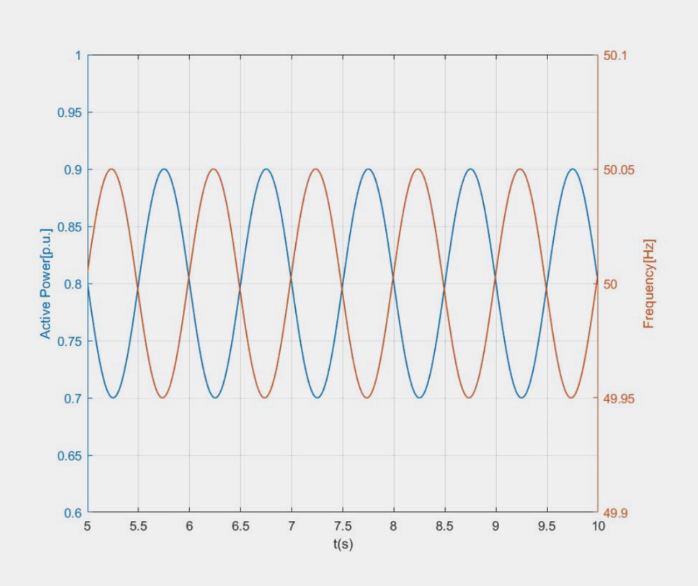


Figure 46: 1 Hz Oscillation Suppression Effect

Sungrow has adopted **power oscillation damping technology and multi-frequency oscillation suppression technology**. By real-time tracking of voltage and power information across various frequency bands, the system activates corresponding suppression measures for each frequency range. This enables resonance suppression in the 0.1 Hz–2.4 kHz frequency band, improving the grid robustness.

Significant regional differences in grid structure, load characteristics, renewable energy penetration, and application scenarios limit the effectiveness of single DC/AC Power Converter Units or PV inverters. To address the complexity and variability of modern power systems, a full-chain, system-level grid-forming capability covering all grid conditions and application scenarios is required for wind-solar-storage integration.

Built on the "Stem-Cell Grid-Forming Technology", Sungrow leverages multi-dimensional algorithmic coordination to ensure reliable grid forming under complex and extreme conditions. Its full-scenario grid-forming capabilities for wind, solar, and storage support flexible AC- and DC-coupling, meeting diverse grid configurations and application requirements.

Furthermore, grid-forming capability should not be confined to the DC/AC Power Converter Unit alone, but reflect the integrated performance of the entire energy storage system. Leveraging full-stack AC and DC development, Sungrow avoids system mismatches and integration issues caused by assembling components from multiple vendors. Its proprietary battery SOC management technology precisely supports the energy and power responses required for AC-side grid forming operation. In addition, pioneering DC arc suppression technology, combined with thermal management control, provides early warning of thermal runaway and ensures safe grid-forming operation.

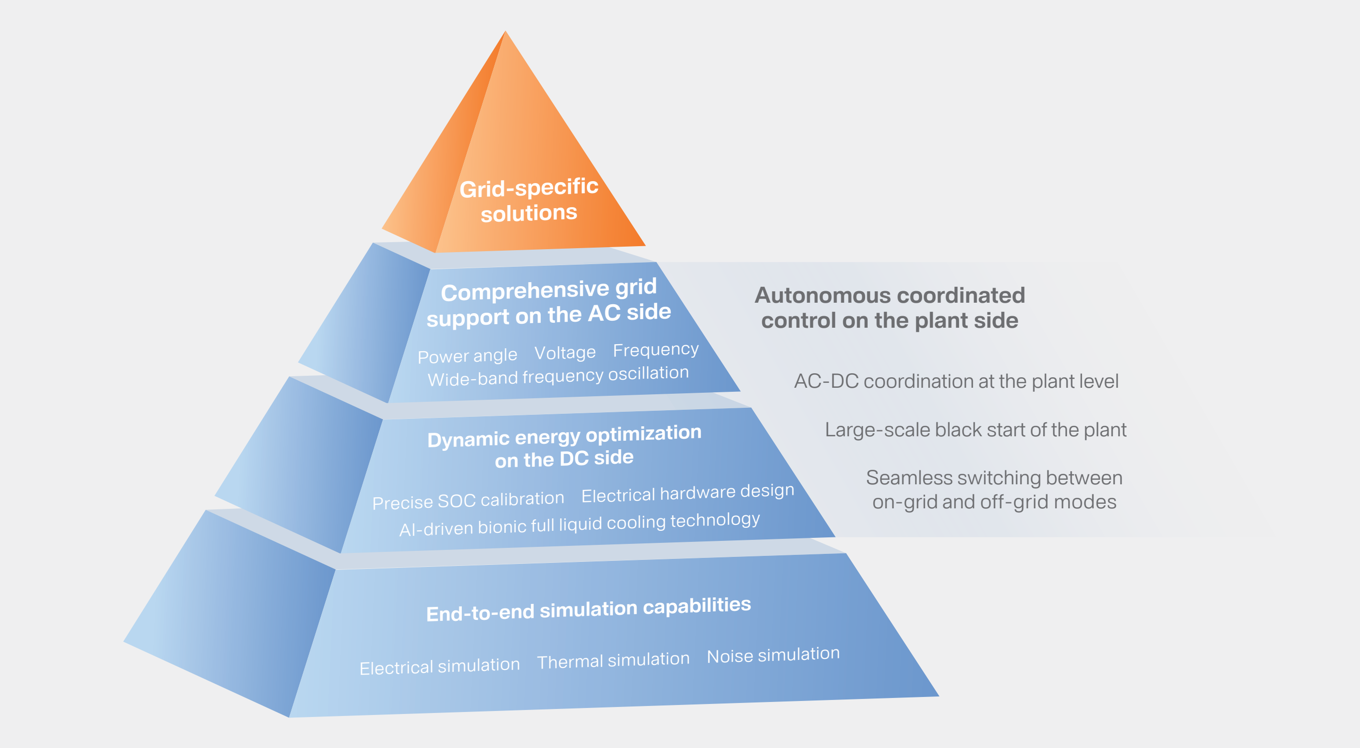
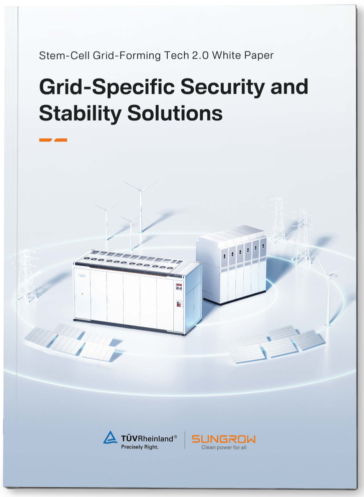


Figure 47: Stem-Cell Grid-Forming Technology 2.0 Architecture Diagram

For more details about grid-forming technology, please refer to the Stem-Cell Grid-Forming Tech 2.0 White Paper.


Stem-Cell Grid-Forming Tech 2.0 White Paper

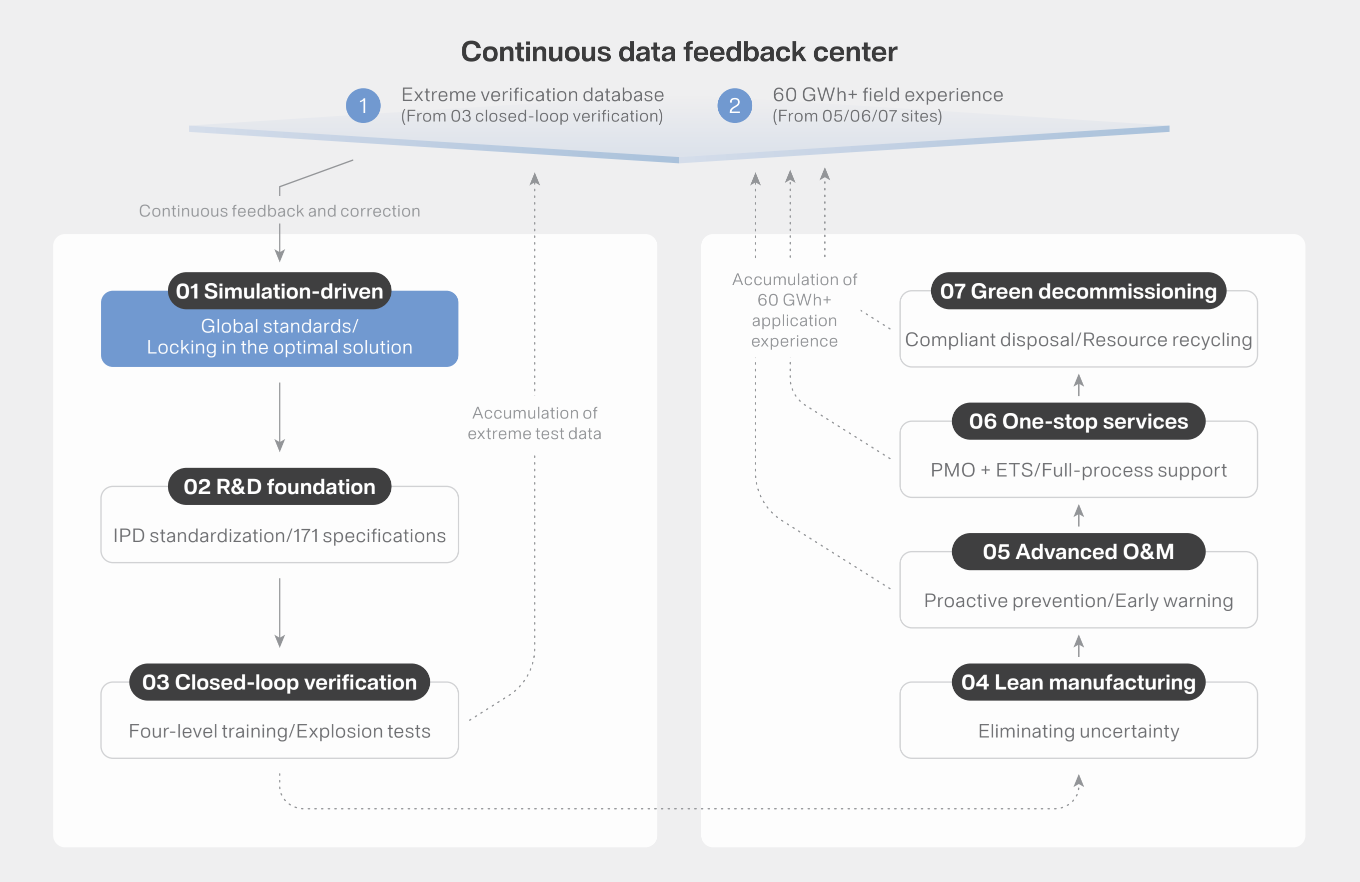
Grid-Specific Security and Stability Solutions

TÜVRheinland®
Precisely Right.
SUNGROW
Clean power for all

# 3.6 Full Lifecycle Safety Support System

Safety risks in energy storage not only exist spatially at multiple levels but also span the entire lifecycle from transportation and installation to operation and decommissioning. Therefore, full lifecycle safety is not an optional add-on, but the foundation that ensures the reliable operation of energy storage assets from inception to retirement. Only by embedding risk prevention and control into every single phase can we achieve full-lifecycle protection in the holistic safety philosophy.

The full-lifecycle safety of energy storage systems is far more than a simple aggregation of safety measures at each stage. Instead, Sungrow follows the core principle that "safety originates from design, and verification precedes manufacturing" and has established a full-lifecycle safety defense system covering simulation-driven design, R&D foundation, closed-loop verification, lean manufacturing, advanced operation and maintenance, one-stop services, and green decommissioning. This approach ensures that energy storage assets remain controllable, visible, and secure at every stage of their lifecycle. This represents the ultimate realization of full-lifecycle protection in our holistic safety philosophy.



## 1 Simulation-Driven Design

**Safety is not achieved through post-event management, but rather through simulation-driven design from the outset.** With top-tier simulation labs, high-performance computing hardware, a professional simulation team, and core databases, Sungrow conducts full-link safety simulations in the virtual world before finalizing the design.

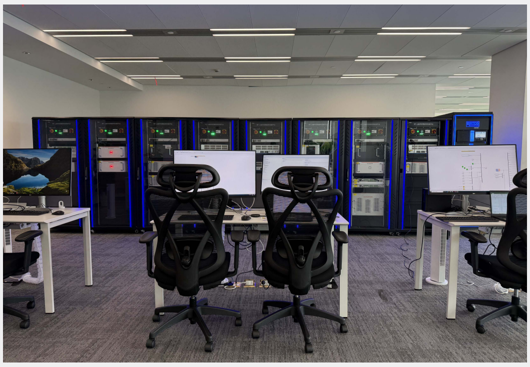


Figure 48: Hardware-in-the-Loop Simulation Laboratory

- **Top-tier simulation resources:** Leveraging advanced hardware and a highly skilled team, we operate the world's largest simulation platform, offering end-to-end capabilities in structural, mechanical, electrical, thermal, grid connection, and hardware-in-the-loop simulations. It enables high-fidelity virtual reproduction of extreme operating conditions and faults, supporting the validation and optimization of design solutions.
- **Global grid standard coverage:** Sungrow continuously tracks and collects global grid standards, building the industry's largest grid code database. This ensures that products meet stringent requirements across all major regions worldwide, including IEEE 2800, IEEE 1547, UL 1741, and PRC-028/029.
- **Core databases enabling mutual validation:** Based on **60 GWh+ global project experience** and **extreme destructive experimental data**, the simulation models are continuously refined, ensuring that simulations closely align with real-world physical boundaries.

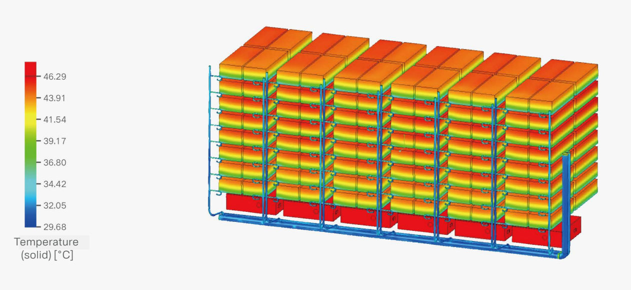


Figure 49: Battery System Thermal Simulation

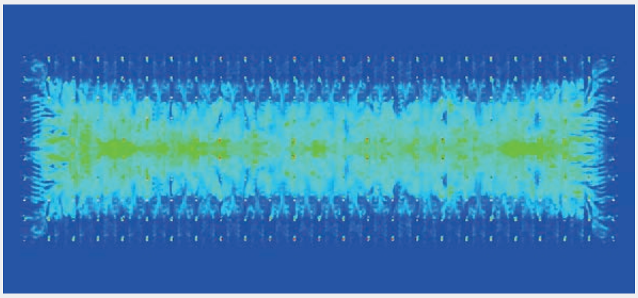


Figure 50: GWh-Level Plant Thermal Simulation

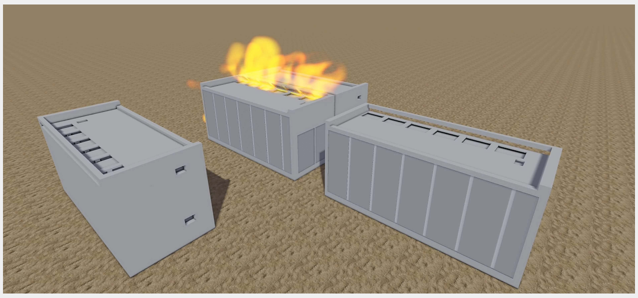


Figure 51: Energy Storage System Explosion Venting Simulation

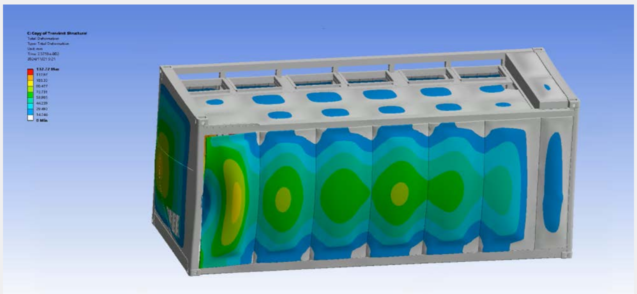


Figure 52: Door Panel Deformation Transient Simulation

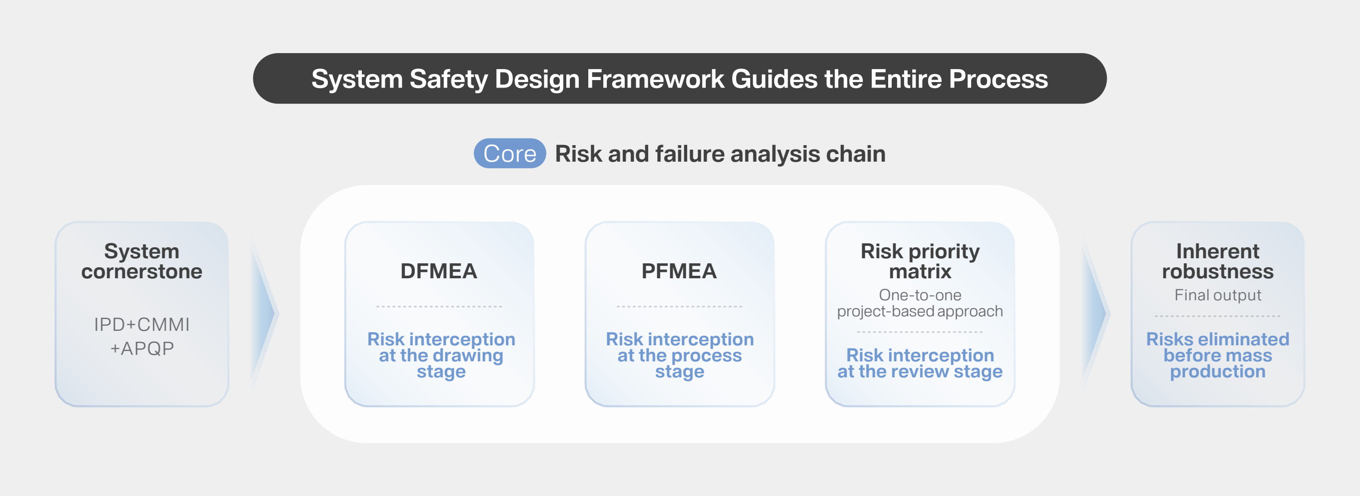
- **Extreme condition simulation:** The simulation system predefines thousands of extreme scenarios, including short circuits, thermal runaway, extreme high and low temperatures, and grid disturbances. This allows repeated testing and validation of technical solutions entirely in software, eliminating the need for physical trial and error.
- **Optimal solution selection:** Through an iterative "simulate–optimize–resimulate" closed loop, potential risk scenarios are identified and eliminated early in the R&D stage, enabling the selection of the system's safest configuration. This approach guides subsequent engineering development, ensuring that intent is realized and safety is achieved.

## 2 R&D Foundation

After establishing the optimal solution through simulation, Sungrow rigorously applies the Integrated Product Development (IPD) process to translate safety standards into engineering practice, deeply integrating Capability Maturity Model Integration (CMMI) and Advanced Product Quality Planning (APQP) standards to build a robust R&D quality system.

- **Full-chain risk interception:** Sungrow is an industry pioneer in **applying Failure Mode and Effects Analysis (FMEA) risk management to 100% of its core products**, establishing a complete defense chain from Design Failure Mode and Effects Analysis (DFMEA) to Process Failure Mode and Effects Analysis (PFMEA).
- **Proactive hazard elimination:** Through a full-cycle "one-to-one project-based" approach combined with a risk priority matrix model, potential risks are identified and mitigated at the concept stage, eliminating quality hazards at the design level and ensuring the product's intrinsic safety.

- **Comprehensive proactive design guidance:** A system-level safety design framework has been established, consisting of 171 safety design specifications and a 255-point checklist. These standards are fully integrated into the IPD process. By implementing Safety-by-Design from the outset of R&D, with standardized design inputs and rigorous stage-gate reviews, safety and reliability are translated into actionable, quantifiable engineering standards. This approach systematically eliminates development blind spots and mitigates potential risks.



**System Safety Design Framework Guides the Entire Process**

Core **Risk and failure analysis chain**

**System cornerstone**
IPD+CMMI
+APQP

**DFMEA**
Risk interception at the drawing stage

**PFMEA**
Risk interception at the process stage

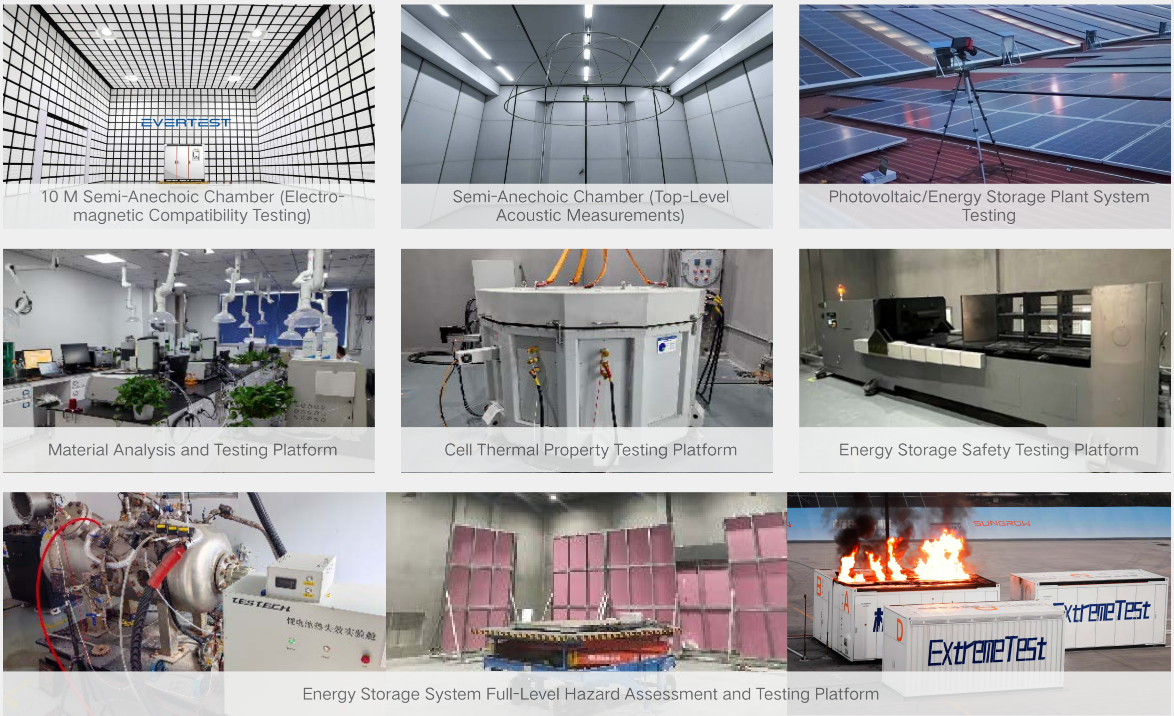
**Risk priority matrix**
One-to-one project-based approach
Risk interception at the review stage

**Inherent robustness**
Final output
Risks eliminated before mass production

Figure 53: R&D Risk Control Flowchart

## 3 Closed-Loop Verification

Physical verification is a crucial step in assessing design quality. Sungrow leverages **industry-leading laboratory capabilities**, with witness laboratory qualifications recognized by globally renowned authorities such as CNAS, UL, and TÜV. With a comprehensive testing range—from microscopic material analysis to large-scale system-level fire testing—it can replicate extreme environmental conditions (such as extreme cold, humid heat, and salt spray) and complex operating scenarios around the world. The testing platform covers all levels from cell, pack, and rack to the system, while evaluating electrical performance, electromagnetic compatibility, and environmental reliability, providing a solid foundation for comprehensive safety verification.



10 M Semi-Anechoic Chamber (Electromagnetic Compatibility Testing)

Semi-Anechoic Chamber (Top-Level Acoustic Measurements)

Photovoltaic/Energy Storage Plant System Testing

Material Analysis and Testing Platform

Cell Thermal Property Testing Platform

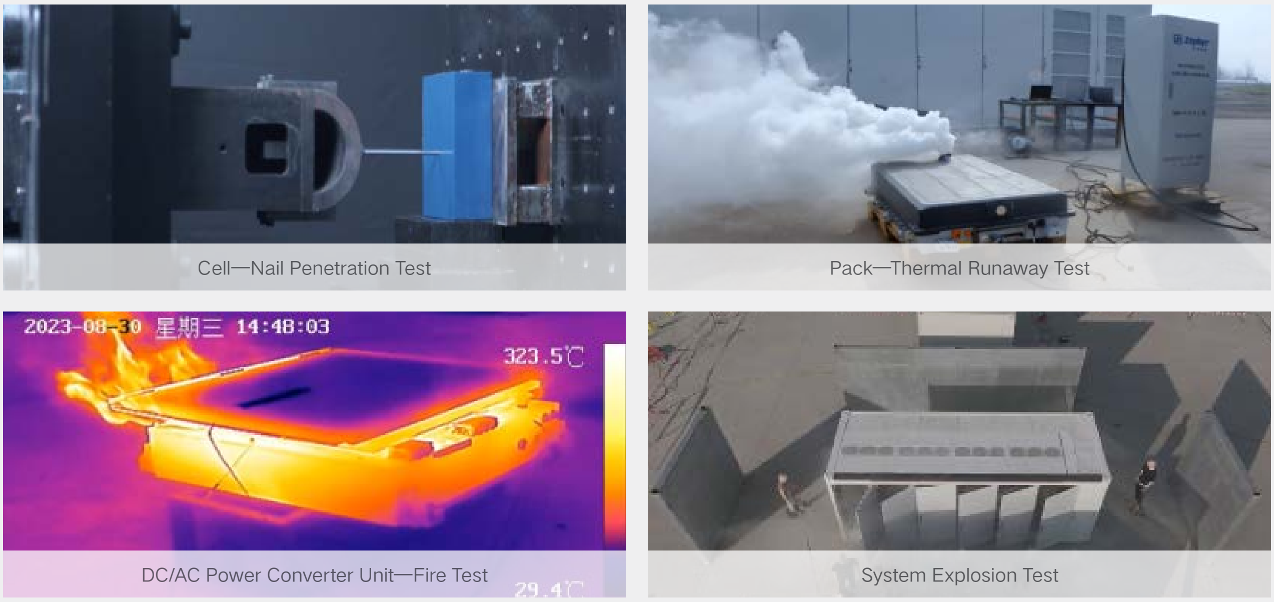
Energy Storage Safety Testing Platform

Energy Storage System Full-Level Hazard Assessment and Testing Platform

Figure 54: R&D Risk Control Flowchart

With its state-of-the-art laboratories, Sungrow rigorously tests energy storage systems under the harshest conditions to ensure maximum safety. From abuse tests on individual cells to full-system fire test, each test is designed to push the system to its limits, confirming reliability even in the most extreme operating environments.

| Level | Key Test Items (Examples) |
|---|---|
| **Cell** | UL 9540A, thermal runaway (heating/overcharging), fire jetting, cycle life, etc. |
| **Pack** | Thermal runaway propagation, crush/dropping, short circuit, mechanical impact, salt spray/condensation, etc. |
| **DC/AC Power Converter Unit** | Short circuit protection test, thermal/electrical stress test, high/low temperature cycling, aging test, etc. |
| **System** | Explosion test, liquid cooling reliability, transport vibration, fault injection test, etc. |


Cell—Nail Penetration Test

Pack—Thermal Runaway Test

DC/AC Power Converter Unit—Fire Test

System Explosion Test

Figure 55: Extreme Test

## 4 Lean Manufacturing

To address the challenges of large-scale production and delivery, Sungrow leverages digital technologies and automated production lines to minimize process variability, ensuring consistent and high-quality product output.

### ① Strict Supply Chain Control

Sungrow enforces a stringent supply chain management system, conducting 100% inspections of key raw materials like cells. This ensures that defective materials never enter production, and that every component, from screws to cells, meets strict safety and quality standards.

### ② Digitalized Manufacturing

With over 80% of production processes digitally integrated and 90% of key operations automated, Sungrow integrates systems such as Enterprise Resource Planning (ERP), Manufacturing Operations Management (MOM), and the Industrial Internet of Things (IIoT), achieving full transparency and traceability across the production process.

- **Global delivery capacity:** Sungrow operates with a capacity of 465 GW and 75 GWh, plus an additional 35 GWh modular production line under construction. With a 90% production line compatibility rate, Sungrow ensures agile global delivery.

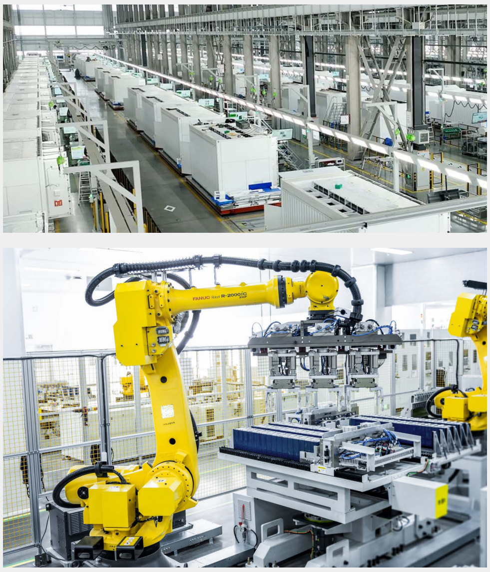


Figure 56: Automated Factory

- **Rigorous quality control:** Functional testing integration covers 100% of products, with over 500 fully automated inspection items and a roll throughput yield of 99.4%, ensuring that each delivered unit meets the highest reliability standards.

## 5 Advanced Operation and Maintenance

To address common challenges in large-scale energy storage plant operations—such as maintenance blind spots, slow inspections, and difficulty in fault localization—Sungrow has innovatively applied optimized algorithms to transition plant maintenance from passive handling to proactive prevention.

### • Device-Level

With embedded self-diagnostic algorithms, the device can sense and diagnose itself, preventing issues before they occur and enabling early-stage maintenance.

#### ① Early Warning

The equipment incorporates optimized algorithms that are self-learning and self-evolving. It proactively provides warnings for five common fault types—voltage, temperature, capacity, resistance, and SOC—along with over 30 other common fault risks. This ensures early warning and intervention, preventing unplanned downtime.

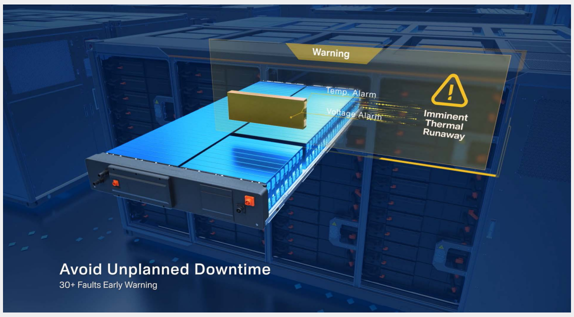


Figure 57: Early Fault Warning

#### ② Root Cause Localization

For fault issues, the system achieves a root cause localization accuracy of ≥ 99%, eliminating the need for experts to manually inspect the site.

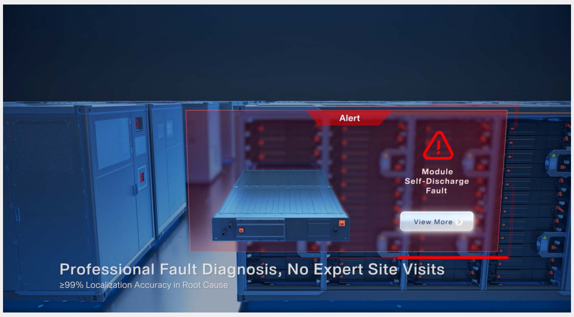


Figure 58: Root Cause Localization

### • Plant-Level

Equipped with PowerDoctor, the system provides maintenance recommendations for potential issues.

#### ① Full-Plant Check

Comprehensive professional checks across five dimensions, with a report generated in just **10 minutes**, offering a clear overview of the system's health trends.

#### ② O&M Assistant

In-depth analysis, proactive recommendation of O&M guidance, and helping operators make quick decisions and ensuring issues are fully resolved.

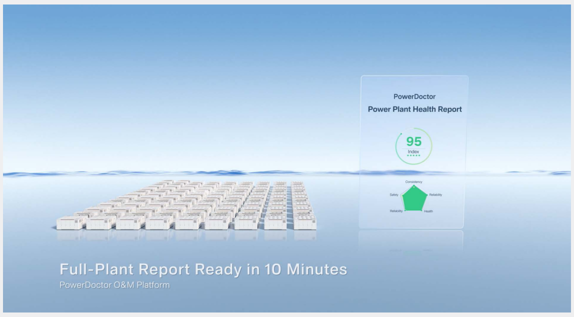


Figure 59: PowerDoctor Full-Plant Check

## 6 One-Stop Services

To tackle the challenges of “complex O&M” and “slow response” in energy storage plants, Sungrow breaks traditional service boundaries with a comprehensive, integrated PMO + ETS service system.

Figure 60: Long-Term O&M Support

### ① Project Management Office (PMO) (Delivery Phase)

A dedicated PMO team is engaged from contract signing, overseeing the entire process from production and transportation to installation, commissioning, and grid connection. This management approach ensures rapid issue resolution, while integrated certification advantages enable exemptions from certain on-site tests across multiple global regions, significantly reducing delivery time.

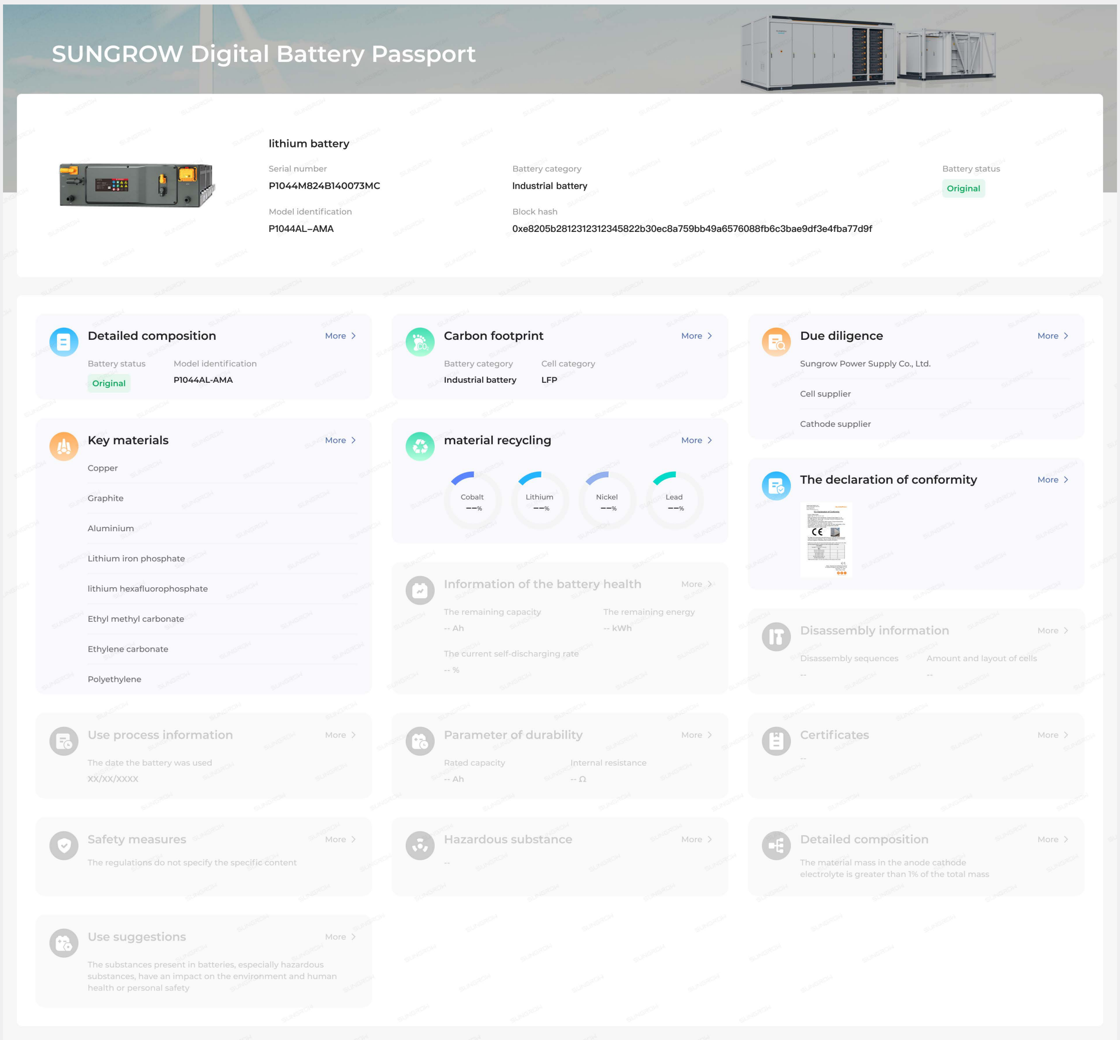
### ② Engineering and Technical Service (ETS) Full Lifecycle O&M (Operational Phase)

- **Rapid response:** Leveraging a global service network and a 24/7 contact center, Sungrow establishes a three-tiered technical expert resource pool for on-demand support, quickly containing any risks.
- **Proactive defense:** Moving beyond reactive repairs, experienced electrical and thermal management experts provide regular health checks and safety reinforcement recommendations, identifying potential issues before they escalate.
- **Transparency and control:** A fully digitized O&M management system is built, ensuring that safety is visible, risks are controllable, and issues are traceable.

## 7 Green Decommissioning

The end of an energy storage system's lifecycle does not mark the end of safety responsibility; rather, it represents the final line of defense for ecological security. In response to increasingly stringent environmental regulations (such as the EU's Batteries Regulation), partnering with global third-party organizations to create a compliant recycling and disposal network can effectively eliminate the safety risks associated with improper handling.

- **Safe de-energization:** Employing specialized techniques to deeply discharge and passivate retired batteries, fully eliminating residual energy and preventing self-ignition risks during disposal.
- **Targeted material recovery:** Using advanced technologies such as physical crushing and hydrometallurgical processing, retired batteries are broken down to extract valuable metals like nickel, cobalt, and lithium. These materials are then returned as pure "raw materials" to the upstream supply chain. This not only ensures resource conservation but also prevents the diversion of retired batteries to informal channels, reducing quality and safety risks.



SUNGROW Digital Battery Passport

**lithium battery**

Serial number: P1044M824B140073MC

Battery category: Industrial battery

Battery status: Original

Model identification: P1044AL–AMA

Block hash: 0xe8205b2812312312345822b30ec8a759bb49a6576088fb6c3bae9df3e4fba77d9f

**Detailed composition**

Battery status: Original

Model identification: P1044AL-AMA

**Carbon footprint**

Battery category: Industrial battery

Cell category: LFP

**Due diligence**

Sungrow Power Supply Co., Ltd.

Cell supplier

Cathode supplier

**Key materials**

- Copper
- Graphite
- Aluminium
- Lithium iron phosphate
- lithium hexafluorophosphate
- Ethyl methyl carbonate
- Ethylene carbonate
- Polyethylene

**material recycling**

Cobalt ––%

Lithium ––%

Nickel ––%

Lead ––%

**The declaration of conformity**

**Information of the battery health**

The remaining capacity: -- Ah

The remaining energy: -- kWh

The current self-discharging rate: -- %

**Disassembly information**

Disassembly sequences: --

Amount and layout of cells: --

**Use process information**

The date the battery was used: XX/XX/XXXX

**Parameter of durability**

Rated capacity: -- Ah

Internal resistance: -- Ω

**Certificates**

--

**Safety measures**

The regulations do not specify the specific content

**Hazardous substance**

--

**Detailed composition**

The material mass in the anode cathode electrolyte is greater than 1% of the total mass

**Use suggestions**

The substances present in batteries, especially hazardous substances, have an impact on the environment and human health or personal safety

Figure 61: Battery Passport Interface

Green decommissioning helps clients avoid legal risks and potential fines associated with environmental pollution after a system is retired, while also supporting their ESG commitments. It ensures that the final stage of the energy storage asset's lifecycle remains safe, compliant, and environmentally responsible.

Sungrow's full-lifecycle safety framework ensures comprehensive protection across every phase, eliminating risk-control blind spots through a closed-loop approach: simulation-based risk prediction, safety-by-design in R&D, closed-loop verification, lean manufacturing, advanced O&M for proactive prevention, one-stop services for end-to-end support, and green decommissioning. This is the core essence of full-lifecycle safety protection in the holistic safety philosophy—ensuring that energy storage systems are not only functional but also dependable, durable, and fundamentally safe.

In addition, energy storage safety extends beyond physical protection and environmental resilience—it's fundamentally about maintaining stability under dynamic, real-world operating conditions. The holistic safety approach supports safety across a wide range of applications—from utility-scale to commercial and industrial deployments—while seamlessly adapting to complex grid architectures, including source-grid-load-storage microgrids and off-grid islanded systems. It is also engineered to meet demanding requirements, including grid services. As a result, energy storage assets are safeguarded with consistent and predictable reliability across all scenarios.

# C4

# Conclusion

The future of energy storage safety lies in the transition from reactive protection to proactive risk management. Instead of relying on isolated safeguards, safety must be built into the entire system. As electrochemistry, power electronics, and grid technologies become more closely integrated, energy storage systems will increasingly be able to track their own condition, detect issues across the lifecycle, and adapt to different operating scenarios. In this way, safety risks can become more predictable, measurable, and manageable.

Guided by its holistic safety framework, Sungrow embeds safety across all system levels and throughout the entire lifecycle. This approach ensures that energy storage systems are not only capable of performing their function, but are also reliable and trustworthy—forming a dependable foundation for the energy transition.

Clean power for all

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IEC version