Jointly released by Huawei Digital Power
and TÜV Rheinland

C&I ESS C2C Dual-link Safety White Paper

Comprehensive Safety from Cell to Consumption

PREFACE

As carbon neutrality has become a shared mission of the world, investment is accelerating global low-carbon energy transformation. In 2023, global investment in this sector grew by 17%, reaching an annual record of USD1.77 trillion. Additionally, carbon taxes and subsidy policies have further driven companies towards low-carbon energy transformation[1]. Up to now,17 provinces and cities in China have issued subsidy policies for energy storage. With rising electricity prices and declining costs of PV systems and energy storage systems (ESSs), the deployment of PV+ESS has created business value, and the return on investment (ROI) of C&I ESS projects increases significantly. In 2023, the global demand for C&I ESSs experienced explosive growth. The installed capacity growth rate of C&I ESSs surpassed those of utility-scale and residential ESSs, doubling in scale[2].

However, with the explosive growth of global C&I ESS requirements, the frequency of safety accidents also increases sharply. According to the incomplete statistics of the industry database of the Energy Storage Application Branch (CESA) of the China Chemical and Physical Power Industry Association, 117 energy storage accidents have occurred worldwide since November 2009. Among them, 61 accidents occurred in the past three years, accounting for more than half of the total accidents.1 In addition, the accident occurrence frequency is still rising. The number of energy storage accidents in the first 10 months of 2024 has surpassed the total for 2023[3]. The percentage of C&I ESS accidents reaches three quarters. Accidents frequently occur because of companies sacrificing product quality and safety standards for price competition, cross-industry participation of non-professional integrators in projects, and lack of strict safety regulations and standards in the industry.

Compared with utility-scale ESSs, C&I ESSs are applied in more complex scenarios such as factories, hospitals, malls, and campuses, where fire safety is more challenging and population and assets are denser, making safety demands particularly critical. To avoid frequent safety accidents in the industry and steer the industry towards higher safety standards, Huawei Digital Power and TÜV Rheinland jointly released the C&I ESS C2C Dual-link Safety White Paper. This white paper emphasizes the importance of safety design for battery cells and systems in constructing C&I ESSs. It highlights the current shortcomings in industry safety standards while offering forward-looking innovative technological concepts and directions for the industry's reference.

1-Data source: <https://energy.pku.edu.cn/tzgg/yjyxw/da500e29ab3e40a49e3aff9aee3fa7ae.htm>

2-Data source: China Energy Storage Alliance https:<//www.cnesa.org/information/detail/?column_id=1&id=6708>

3-Data source: <https://www.escn.com.cn/news/show-2066389.html; https://www.desn.com.cn/news/show-1616404.html>

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Safety is the Cornerstone of C&I ESS Development

01

1.1 Rapid Growth of the C&I ESS Market

Since 2023, the global demand for C&I ESSs has experienced explosive growth. The installed capacity growth rate of C&I ESSs surpassed those of utility-scale and residential ESSs, doubling in scale. The ESS price directly impacts the total investment and economic viability of C&I ESS projects. Since 2023, lithium carbonate prices have declined significantly, coupled with a rapid increase in the number of market players and heightened competition. These factors have driven down the prices of various ESSs by over 50%, significantly enhancing the ROI of C&I ESS projects. Initially, the primary demand for C&I ESSs revolved around emergency backup power. Over time, this demand has evolved into diverse and mature business scenarios, such as C&I energy saving and emissions reduction, energy consumption cost reduction, and PV+ESS+charger integration.

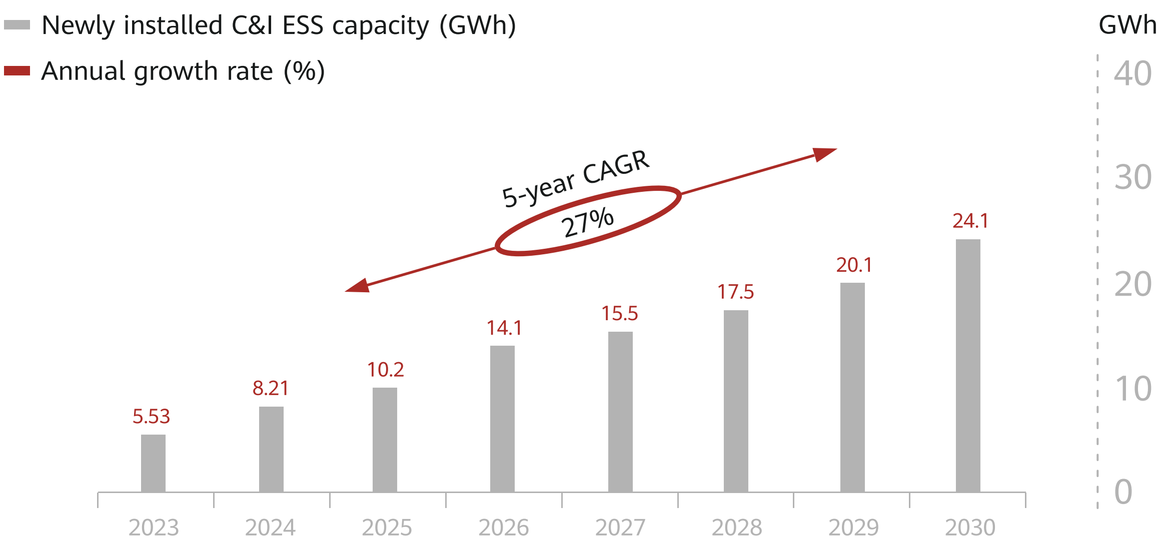


Figure 1 C&I ESS growth data in recent years[4]

4-Data source: China Energy Storage Network (https://finance.sina.cn/2024-11-19/detail-incwqkxu2986592.d.html, 2024-11-19), and Wood Mackenzie, 2024

By 2025, the cumulative installed capacity of global C&I ESSs is expected to reach 11.5 GW, with China and Europe accounting for over 50% of the global capacity[5].

This is attributed to their advanced C&I sectors and the strong policy support for C&I ESSs. Additionally, the decreasing costs of PV modules and shortened ROI for PV+ESS systems have stimulated the growth of distributed PV+ESS systems, which in turn drives an increase in the newly installed capacity of C&I ESSs. For instance, the European Union (EU)'s Fit for 55 and REPowerEU Plan have set ambitious renewable energy targets, aiming for 45% renewable electricity generation by 2030. From 2026 onward, all new public and commercial buildings with a roof area exceeding 250 m2 shall install rooftop PV systems, directly boosting energy storage demands[6]. In the past two years, China's C&I ESS policies feature a combination of national-level strategic planning and localized innovations. Measures such as electricity price reforms, financial subsidies, market access improvements, and technical standardizations are accelerating the transition from pilot demonstrations to large-scale deployment.

Between January and April 2024, China's National Development and Reform Commission and National Energy Administration released four policies for ESSs. These include the Guidelines for Strengthening the Construction of Peak-Shaving ESS and Intelligent Scheduling Capabilities,

Notice on Establishing and Improving the Market Price Mechanism for Electric Power Auxiliary Services, Guidelines for Energy Work in 2024, and Notice on Promoting the Grid Connection and Dispatching of New ESSs, improving the time-of-use (TOU) electricity price mechanism and encouraging companies to build distributed energy and energy storage facilities. Since 2022, over 40 direct subsidy policies for C&I ESSs have been rolled out , including Zhejiang, Guangdong, Jiangsu, Chongqing, Anhui, and Tianjin, driving project implementation[7].

Moreover, with increasing energy price volatility, continuous advancements in battery technologies, and cost reductions, it has become more economical for C&I sectors to adopt ESSs. In Europe, many companies in countries like Germany, the UK, and Netherlands, have begun integrating ESSs to promote the electrification of production processes. More and more small- and medium-sized companies and industrial plants are progressively moving towards energy self-sufficiency.

5-Data source: 2023 China C&I ESS Development White Paper released by the China Industrial Association of Power Sources

6-Data source: <https://www.consilium.europa.eu/en/infographics/fit-for-55-making-buildings-in-the-eu-greener/>

7-Data source: <https://www.escn.com.cn/news/show-2066389.html; https://www.desn.com.cn/news/show-1616404.html>

1.2 Importance of C&I ESS Safety

1.2.1 ESS Safety Becomes the Industry's Concern

According to a follow-up survey conducted by TÜV Rheinland, the past five years have seen a significant increase in concerns about ESS safety issues and the lack of industry standards[9].

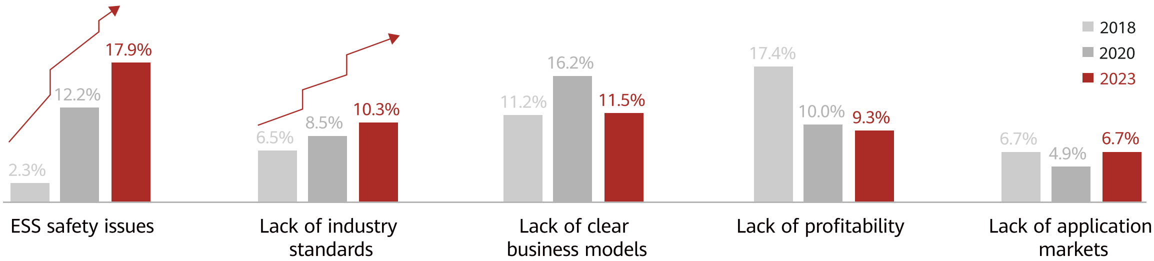


Figure 2 Key constraints on ESS development

1.2.2 ESS Products Pose High Safety Risks

ESSs inherently pose high safety risks due to the characteristics of their batteries. Currently, most ESSs use lithium iron phosphate (LFP) cells. Because lithium ions are highly active, if internal or external factors trigger a violent reaction between the positive and negative materials within the battery cells, the resulting thermal runaway is extremely difficult to control. This risk is further magnified in ESSs composed of numerous battery cells, which feature large capacity and high voltage. The destructive potential of thermal runaway makes the safety risks of ESSs particularly critical.

9-Data source: Dadong Times, Community of Battery Enterprise Advancement (cbea.com), and Global Energy Storage Industry Trend Prediction Report 2024 (released on December 2023)

1.2.3 C&I ESSs Face Greater Safety Challenges

Compared with conventional utility-scale ESSs, C&I ESSs are applied in complexer scenarios, where fire safety is more challenging and population and assets are denser. ESSs are typically positioned closer to people and assets, and their usage frequency is higher. As a result, when safety risks arise, the potential damage and societal impacts can be far greater. Key features and challenges of C&I ESS construction include:

01 Complex Environment

C&I ESSs are applied in various electricity usage scenarios such as factories, hospitals, shopping malls, and campuses. The deployment locations of ESSs differ across these scenarios. Some are situated in spaces with limited surrounding areas, obstructed and winding fire apparatus access roads, or adjacent to high-value assets. These conditions make firefighting more challenging.

02 Dense Population

Compared to grid-side ESS plants located in sparsely populated areas, C&I ESSs are typically much closer to places where people live and work. This increases the importance of minimizing the frequency of accidents and the severity of potential hazards to ensure the safety of personnel around the facility.

03 Intensive Assets

C&I ESSs are closely tied to a company's core assets and operations. In asset-intensive areas, any failure in ESSs poses significant risks — not only endangering personal safety but also potentially leading to substantial economic losses. Such areas often include precision manufacturing facilities and charging stations.

1.3 Global ESS Safety Accident Analysis

According to the CESA, since November 2009, there have been 117 ESS-related accidents globally, with approximately three-quarters occurring in C&I ESSs.

In September 2024 alone, within just half a month, eight ESS safety accidents were reported in countries including Australia, France, Germany, and Austria. These ranged from fires at lithium battery production facilities to data center fires. Earlier accidents include a fire and secondary explosion at Germany's Nemours commercial area, injuring two firefighters, and a factory accident in South Korea that tragically resulted in 23 fatalities.

Analysis of these accidents reveals that they were primarily caused by factors such as electrical insulation failure and the spread of short circuits. Inadequate thermal runaway suppression and fire suppression measures exacerbated these accidents, leading to larger-scale damages, and even casualties.

Figure 3 Two firefighters injured by the door explosion of ESSs in Nemours commercial area, Germany5

Figure 4 Explosion at a chicken farm in Saint-Esprit, France, causing an asset loss of millions of euros6

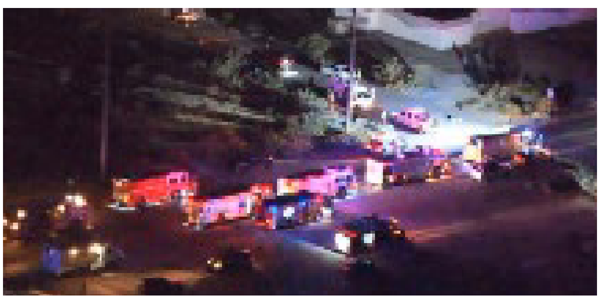


Figure 5 An accident of a 2 MW/2.47 MWh ESS station in McMicken, Arizona, USA6

Figure 6 An ESS fire at a PV plant in Chungcheong-namdo, South Korea7

10-11-Data source:Energy Storage China Network News Center
12-Data source: FOX News
13-Data source: National Fire Agency of South Korea

Table 1 Statistics of major ESS safety accidents in recent years[14]

Accident Time	Accident Location	Accident Name	Impact	Cause
March 9, 2025	South Jeolla Province, South Korea	Gangjin-gun	More than 500 square meters of ESS facilities and 3852 ESS modules were burnt, causing a property loss of about CNY50 million.	The short circuit inside a battery pack spread and the battery pack was overheated continuously. The cell was short-circuited to the ground and a fire occurred quickly.
September 29, 2024	Fujian, China	Fire at an ESS battery production base	About 50,000 square meters of buildings were damaged, and the estimated asset loss exceeded CNY300 million.	Battery spontaneous combustion occurred due to overcharging and overdischarging.
September 10, 2024	Singapore	Explosion of lithium batteries in a data center	The fire lasted for more than 36 hours, severely affecting the normal services of technology companies.	The internal insulation failure of the battery caused thermal runaway and explosion, leading to fire spreading and high temperature.
June 24, 2024	South Korea Hwaseong, Gyeonggi-do	Explosion at Aricell Lithium Battery Factory	The explosion resulted in 23 fatalities and 8 injuries.	Short circuits in lithium batteries caused a fire due to thermal runaway, and some of the 35,000 lithium batteries stored on the second floor of the factory exploded.
May 15, 2024	Saint-Esprit, France	Fire and explosion at a PV+ESS chicken farm	The explosion severely damaged the windows of more than 300 houses nearby, causing economic losses of more than EUR1 million.	Fault warning was unavailable. The faulty battery was not disconnected in a timely manner. As a result, the fault spread to surrounding batteries, causing a large amount of combustible gases to accumulate. An explosion occurred due to electric sparks.
April 27, 2024	Bremen, Germany	ESS fire and explosion accident in Nemours commercial area	Two firefighters were injured, Caused economic loss of 500,000 euros	After the lithium battery heats out of control, the battery pack is damaged and the internal combustible gas leaks, causing a secondary explosion and the cabinet door bursts open.
September 20, 2021	Victoria, Australia	Fire at the Victorian Big Battery project	The loss amounted to USD38 million.	After thermal runaway of lithium batteries, the battery pack was damaged, and the internal combustible gases were released. As a result, a secondary explosion occurred and the cabinet door exploded.
April 16, 2021	Beijing, China	Fire and explosion in a PV+ESS+Charger integrated project of Full Service	The accident resulted in one electrician losing his life, two firefighters sacrificing themselves, and one firefighter sustaining injuries. The direct property damage exceeded CNY16 million.	The liquid cooling system leaked, causing electric arcs and sparks between electric devices. As a result, the system experienced thermal runaway, causing a fire to spread.
April 19, 2019	Arizona, USA	Explosion at APS ESS plant	The ESS was damaged, and four fire firefighters were injured.	A short circuit inside a battery caused thermal runaway. As a result, a large amount of combustible gases were released and accumulated. The propagation of combustible gases caused a secondary explosion.

These cases of ESS accidents often involved products that had undergone standard testing and certification, with some even meeting current European or North American standards. Yet, accidents still occurred, which indicates that existing standards in the ESS market are inadequate to fully meet the safety requirements of ESS facilities. There is significant room for improvement and further refinement.

14-Data source: American Electric Power Research Institute (EPRI)'s BESS Failure Incident Database

C&I ESS Safety Risk Analysis and Challenges 02

2.1 Safety Risk Sources and Thermal Runaway Mechanisms

2.1.1 ESS Safety Risk Sources

The risks of thermal runaway in ESSs can be categorized into three main types based on their underlying mechanisms: mechanical abuse, electrical abuse, and thermal abuse.

Mechanical abuse: During manufacturing, transportation, or installation, external mechanical forces such as dropping, vibration, collision, crushing, or penetration can damage the battery structure or create internal defects. These may result in deformation of cell enclosure, separator damage, or electrolyte leakage.

Electrical abuse: Improper electrical operations or circuit faults, including the overcharging, overdischarging, insulation failure, control failure, or external short circuit, can lead to internal short circuits in batteries.

Thermal abuse: External high-temperature environments or internal thermal diffusion can cause abnormally high temperatures within batteries, leading to thermal runaway risks.

Table 2 ESS safety risk source analysis

Mechanical Abuse	Electrical Abuse	Thermal Abuse
Pack sealing defect	Lightning energy injection	Heat due to current flow/Connection fault
Falling during transportation/installation	High-voltage loop fault	High ambient temperature
Vibration/Impact/Collision during transportation	Electrical link insulation damage	External fire source/abnormal high temperature
Weak pack structure	Abnormal external high voltage/current	Thermal diffusion in the pack

2.1.2 ESS Thermal Runaway Mechanisms

01 Short Circuits: The Root Cause of Thermal Runaway

Electrical link faults such as short circuits are the root cause of safety risks in ESSs. Short circuits can occur at any link, including battery cells, battery packs, internal system circuits, or external circuits. Once a short circuit happens, it has the potential to spread and ultimately trigger thermal runaway.

Short circuits usually occur due to external and environmental risks, electrical risks, internal defects, and control failures. For example, internal short circuits within battery cells caused by collision, overcharging, or overdischarging, as well as manufacturing defects, can lead to pack-level internal or external short circuits, or even escalate into ESS failures (such as BMS failures, functional safety failures, and misoperations).

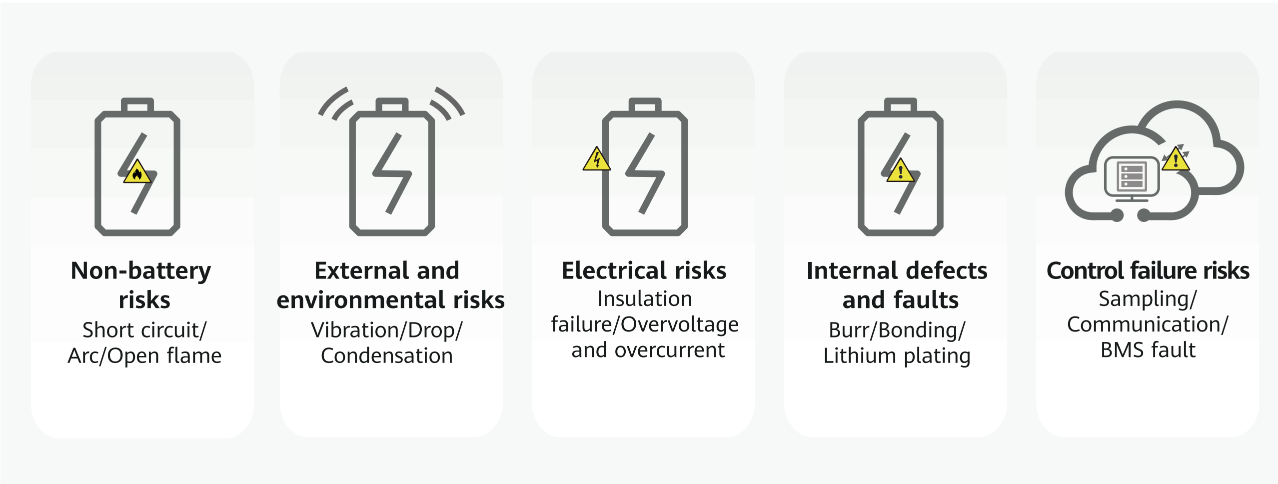


Figure 7 Causes of electrical short circuits

02 Thermal Runaway Diffusion: Escalating ESS Safety Risks

Thermal runaway propagation represents the escalation of safety risks in ESSs. Typically, thermal runaway begins at the cell level, which gradually spreads to a broader area, potentially causing battery pack fires, combustion or explosions within ESS cabinets, and even spreading among cabinets. This can severely impact surrounding assets and personnel.

Lithium battery thermal runaway involves intense exothermic reactions, accelerating thermal runaway. On average, a battery pack contains about 60–100 cells, which are densely packed. Once a cell experiences thermal runaway, the heat spreads rapidly to neighboring cells, triggering further thermal runaway and extending to the entire battery pack and even the whole ESS. The reaction is both violent and fast, with heat generation driving battery temperatures to soar quickly to between 400°C and 1000°C. Additionally, the thermal runaway process produces a large volume of combustible gases (such as CO and H_2). When these gases mix with O2 in the air and reach the explosive limit, they can ignite upon exposure to high temperatures or open flames, resulting in explosions and fire spread.

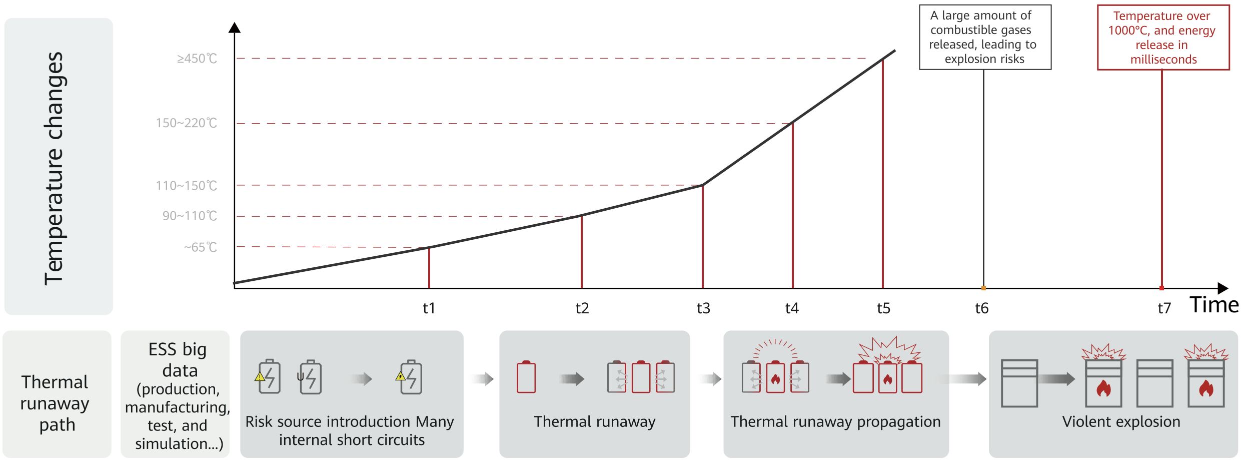


Figure 8 Thermal runaway propagation

2.2 Shortcomings and Challenges of Conventional Safety Design

C&I ESSs are highly complex, posing stringent requirements on system integration design. As battery cell technologies become increasingly mature, ESS safety now relies more heavily on system integration design. Shortcomings in system design, such as electrical short-circuit protection for electrical links and thermal runaway suppression measures for thermal links, are the main reasons for the generation and escalation of safety risks in ESSs. They are also the pain points and challenges faced by C&I ESS safety design.

2.2.1 Shortcomings and Challenges of Short-Circuit Protection Design for Electrical Links

Currently, conventional ESSs in the industry have the following pain points and problems in short−circuit protection:

01 Precise Detection and Warning for Internal Short Circuits in Battery Cells: Addressing Weaknesses in Data Analysis and Fault Warning of Conventional Solutions

ESS thermal runaway is generally caused by a short circuit in the cell. Internal cell short circuits are likely to occur due to cell enclosure damage, dendrite penetration, or electrolyte leakage. Internal cell short circuits are mainly reflected by abnormal cell parameters.

Identifying and warning cell internal short circuits requires extensive data collection and analysis across numerous battery cells. The precision and speed of this data collection depend heavily on the capabilities of data collection chips. However, conventional data collection chips currently used in ESSs often face limitations such as low data collection capacity and significant errors.

Additionally, conventional board-level warning algorithms used for cell abnormalities have notable drawbacks, including high error margins, slow speed, and low capability upper limit. These factors restrict the ability to effectively identify and warn battery cell faults in advance.

02 Insulation Failure in Packs Leading to Internal Short Circuits: Vulnerability of Common Insulation Materials Resulting in Leakage and Insulation Failure

At the battery pack level, if pack insulation fails or the insulation isolation range is inadequate, electrical contact may occur between cells in the pack or between cells and pack enclosure, causing internal short circuits of a battery pack.

In the ESS design, the insulation protection of battery packs is critical. The insulation design needs to be enhanced to prevent insulation failure and enhance the protection effect.

Conventional battery pack insulation design often focuses solely on external enclosure insulation, neglecting the insulation between battery cells and modules within the pack. As a result, electrical faults such as short circuits due to abnormal connections, arcs, and short circuits may occur, which may spread and cause ESS electrical failure. In addition, common insulation materials fail to provide adequate protection during cell thermal runaway. If cell thermal runaway occurs, the high temperatures and corrosive electrolytes can severely damage insulation materials, leading to insulation failure.

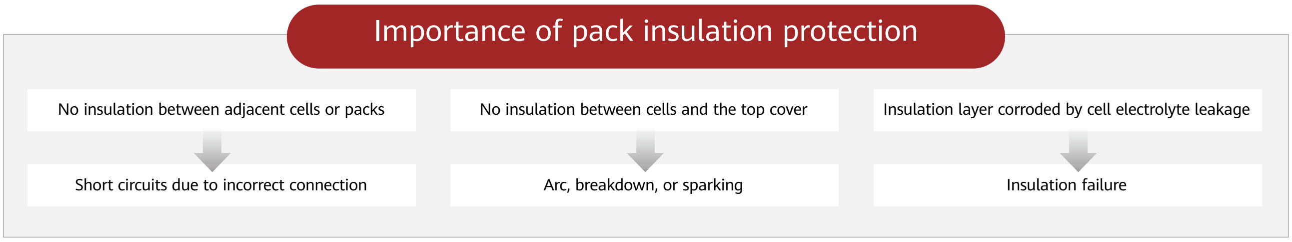


Figure 9 Importance of battery pack insulation protection

Defects of Conventional Pack Insulation Design:

1)Conventional battery packs often focus solely on insulation between the bottom and the enclosure, overlooking insulation between adjacent cells, adjacent modules, and between cells and the top cover.

2)Generally, leaked cell electrolyte continuously corrodes the insulation layer. However, due to the slow process, the corrosion may not be detected in time. Continuous corrosion due to exposure to electrolyte can lead to carbonization and bubbling of the insulation layer, ultimately resulting in insulation failure and system damage. Conventional battery packs use common insulation paint with poor resistance to electrolyte corrosion, which can withstand electrolyte corrosion for only seven days.

3)Conventional battery packs use plastic enclosure, which is prone to melting under high temperatures caused by thermal runaway. This compromises the insulation layer further and can result in large-scale insulation failure.

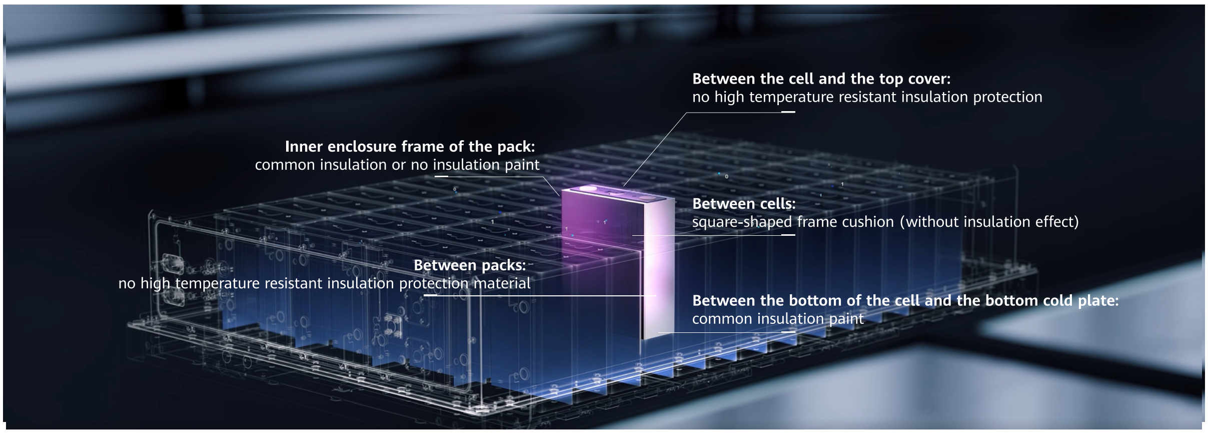
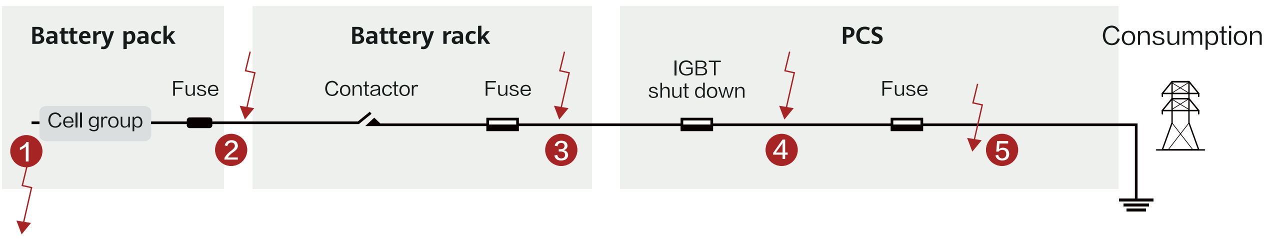


Figure 10 Internal insulation design of a conventional battery pack

03 Risk of Fire Due to High-Current Short Circuits Not Shut Down Rapidly: Addressing Vulnerabilities in ESS Components Across Multiple Phases

For the ESS, short circuits may occur on both DC and AC sides. In addition to the cell internal short circuit and pack internal short circuit due to incorrect connection, there are other short circuits caused by poor connection of different electrical components. Inside the ESS, short circuits of different types may occur due to incorrect cable connections of electrical components. For example, if ports or cables in different positions are damaged or connected incorrectly, short circuits may occur, such as short circuits between positive and negative DC buses, short circuits caused by internal component failures of a PCS, and high-current cell-to-ground short circuits. Problems such as poor electrical connection or component failure are usually caused by product defects, damage during transportation and installation, non-standard installation and maintenance, and components operating in poor working conditions for a long time.

Common short circuits are as follows.



	①	②	③	④	⑤
Fault Cause	Cell electrolyte leakage, causing insulation damage	Port damage and incorrect connection	Cable damage and incorrect connection	Short circuits due to capacitor/IGBT failure inside the PCS	Damaged cables on the PCS AC side, incorrect connection between the positive and negative buses, and damaged cable during installation
Fault Type	Cell-to-ground short circuit	Short circuit between the positive and negative buses at the front port of the battery rack controller	Short circuit between the positive and negative buses at the rear port of the battery rack controller	PCS internal short circuit	Short circuit between phases or to ground on the PCS AC side

Figure 11 Classification of ESS short circuits

Shortcomings of conventional protection solutions:

1)Protection blind spots

Conventional fuses and contactors have relatively limited protection ranges, leaving protection blind spots within the current range of 1.2–1.6 kA. The protection cannot be implemented within the external short-circuit resistance range of 0.4 Ω to 0.6 Ω (generally, the external short-circuit resistance ranges from 0.1 Ω to 1 Ω).

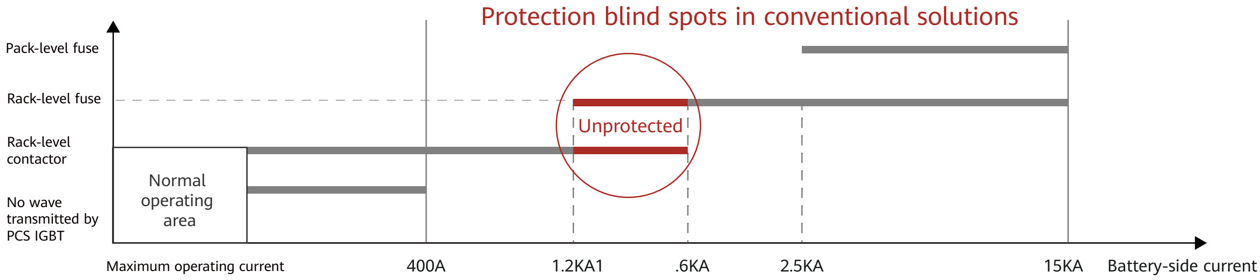


Figure 12 Protection blind spots for short-circuit current identification in conventional solutions

2)Failure to perform rapid shutdown for high current faults such as cell-to-ground short circuits

Conventional fuses take more than seconds to respond, resulting in slow shutdown. Conventional solutions can only detect and break abnormal differential-mode currents (short circuits between the positive and negative buses), which typically have relatively small currents and slower fire reaction. In such cases, conventional fuses can provide protection. However, for abnormal common-mode currents, such as a cell-to-ground short circuit caused by a cell blue film damage, a busbar-to-ground short circuit, or a cell enclosure-to-ground short circuit, the short-circuit current is high. Fires may occur within dozens of milliseconds, and conventional solutions cannot quickly detect and implement disconnection for protection.

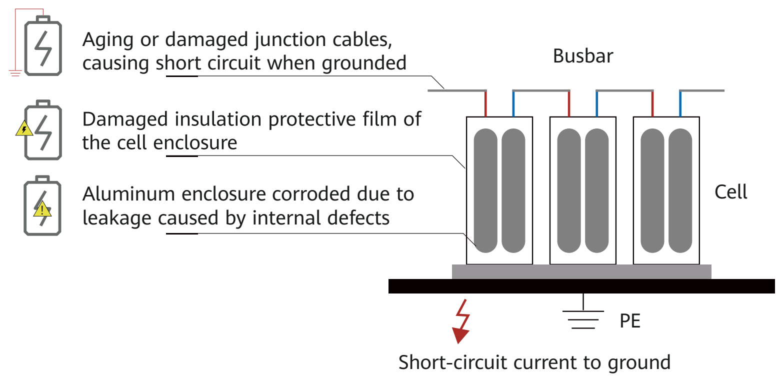


Figure 13 Cause analysis of the battery cell short circuit to ground

04 External cable damage and grounding causing leakage and injury: Limitations and Risks of Conventional Current Leakage Detection Methods

At the application layer, the ESS is connected to the external power distribution cabinet through cables. External cables are prone to damage caused by factors such as animal bites or water infiltration. These issues can result in incorrect cable connection or short circuits to the ground. Consequently, this may cause short circuits or current leakage on the external AC side or auxiliary power side of the cabinet. Also, it may cause electric shock injury and equipment damage.

Causes of Leakage Current	
Insulation failure and aging	Improper installation and maintenance
System design defects	Internal battery defects

Risks Due to Leakage Current	
Personal safety risks	Device damage risks
System operating stability risks	Electromagnetic interference risks

Figure 14 Cause and risk analysis of leakage currents

In most conventional solutions, the PCS is restarted to detect the ground insulation impedance or current leakage. However, only the DC side short circuit can be detected, and the AC side ground short circuit, ground current leakage, and auxiliary side current leakage cannot be effectively detected. Rapid shutdown cannot be performed for external current leakage and short circuits, which may cause electric shocks and damage to ESS components due to high currents

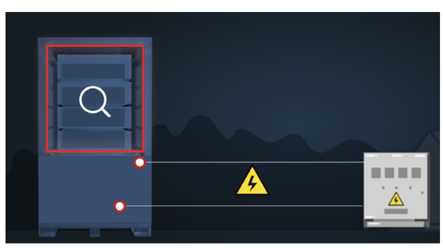


Figure 15 Risks of failing to monitor the leakage current in conventional solutions

2.2.2 Challenges of Thermal Runaway Suppression

01 Defects in Heat Insulation Design, Causing Thermal Diffusion Between Cells

Importance of cell heat insulation design:

In ESSs using lithium batteries, the heat insulation design between cells plays an important role. Once a defect occurs, serious consequences will be caused. Defective heat insulation design cannot effectively block heat spreading among cells, which is prone to cell thermal runaway propagation.

Under normal conditions, battery cells generate a specific amount of heat during charging and discharging. A well-designed insulation layer ensures that heat is confined to individual cells, preventing it from spreading to neighboring cells.

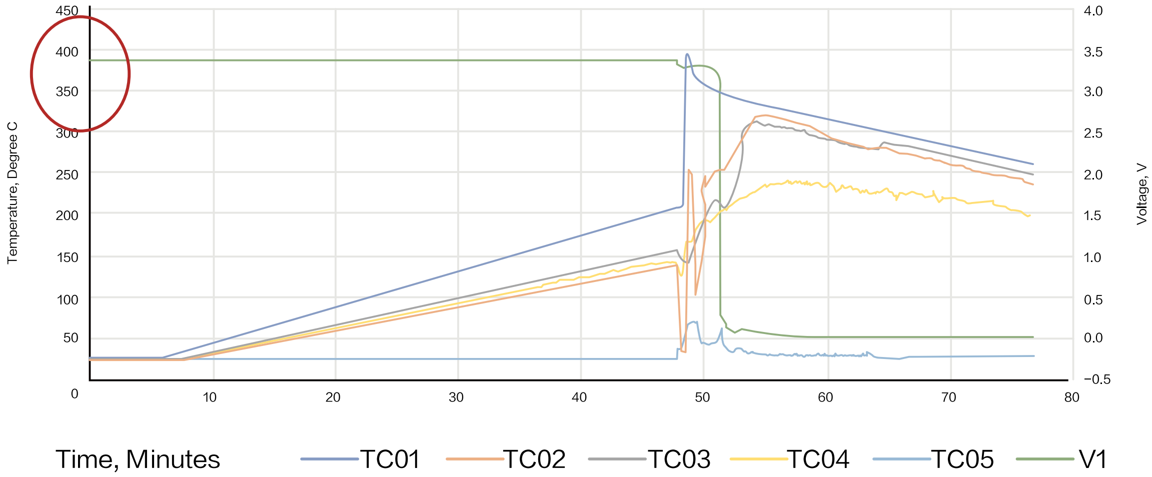


Figure 16 Temperature change of cells during thermal runaway

Defects in the heat insulation design of conventional solutions:

Conventional solutions often lack dedicated thermal insulation design for battery cells or rely on common heat insulation materials that fail to provide effective heat insulation. As a result, heat generated by one cell can quickly spread to surrounding cells. Additionally, there are design flaws in conventional heat insulation structures. For instance, as the gaps between battery cells are too small, the heat insulation materials filled in the gaps are inadequate, leaving cells in direct contact. This creates a short pathway for heat transfer, drastically shortening the time for heat to spread and accelerating the rate of thermal runaway diffusion.

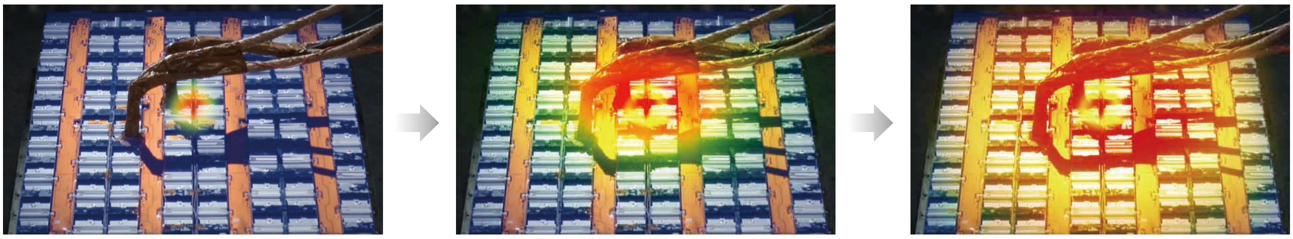


Figure 17 Pack melting due to thermal runaway

02 Thermal Runaway in Packs: O_2-Induced Rapid Ignition Within Battery Packs

When batteries burn, they release combustible gases such as H_2, C_2H_6, and C_2H_2. Under specific conditions, these gases can lead to explosions or combustion, posing significant threats to the processes of battery production and storage.

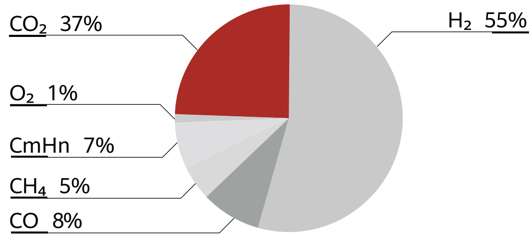


Figure 18 Composition of gases produced by cells and their explosive limits

The three key elements required for combustion are combustible gases, O_2, and combustion point. Combustion can only occur when these three elements are simultaneously present and interact. In fire prevention design, disrupting any one of these elements can effectively prevent combustion or extinguish a fire.

During the thermal runaway of LFP batteries, combustible gases are released. These gases typically include various organic compounds, such as C_2H_4 and CH_4, produced from the decomposition of the electrolyte due to heat. However, LFP batteries produce almost no O_2 during thermal runaway, which means that external air becomes the primary source of O_2.

When external air enters through gaps or damaged positions in a battery pack, combustible gases are mixed with O_2. In a high-temperature environment or in the presence of sparks from electrical system faults, this mixture can ignite, causing the battery pack to catch fire almost instantly.

Defects of conventional pack design:

Conventional solutions often use plastic enclosure with melting points below 400°C. Under high-temperature conditions, the enclosure is prone to melting, leading to seal failure. Once the seal fails, combustible gases can rapidly mix with external air. At this point, high-temperature hot spots, such as electrical sparks caused by battery short circuits, overheated components, or even micro-friction between adjacent parts, can easily ignite the gas-air mixture.

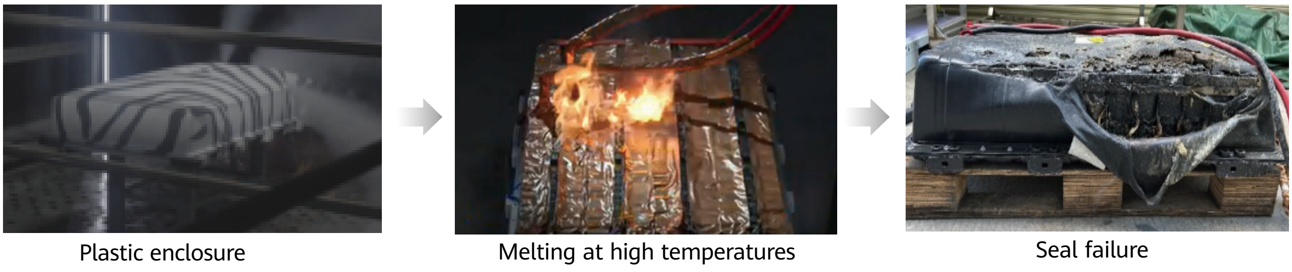


Figure 19 Pack melting due to thermal runaway

03 Thermal Runaway in Cabinets: Gases Not Exhausted from Cabinets and Increased Risks of Combustion and Explosion

When thermal runaway occurs in an ESS, it generates a significant amount of explosive and combustible gases. If these gases cannot be quickly vented, they can accumulate within the cabinet, reaching the explosive limit. Any ignition source or energy trigger can easily cause an explosion. Additionally, due to the dense arrangement of batteries, a fire or explosion in one area can trigger a chain reaction.

Defects in the design of conventional solutions:

Unprotected scenario: When thermal runaway occurs in battery cells within a battery pack, it continuously produces combustible gases. If exposed to high temperatures and O2, combustible gases will ignite.

Battery Pack pressure relief valve: Combustible gases are vented in the cabinet, and accumulated gases can quickly reach the explosive limits.

Cabinet-level venting: If combustible gases are not quickly exhausted from the cabinet, the thermal runaway can spread further.

Figure 20 Fast gas venting unavailable in conventional solutions

04 High Risks of Personal Injury Caused by ESS Explosion and Disintegration

If an ESS experiences an explosion and structural disintegration, the destructive force poses a significant safety threat, potentially causing severe harm to nearby individuals.

During the operation of the ESS, if internal batteries undergo thermal runaway, a large volume of high-temperature gases rapidly accumulates inside the cabinet. On one hand, combustible gases mix with air to form an explosive mixture. Upon reaching the explosive limits and encountering an ignition source, such as electrical sparks from battery short circuits or current leakage sparks due to aging wiring, the mixture can ignite instantly, causing a violent explosion. Additionally, vapor clouds of electrolyte released during thermal runaway can compromise the electrical insulation within the cabinet. Additionally, the cabinet structure, subjected to prolonged internal pressure shocks, experiences a gradual reduction in strength. When an explosion occurs, the cabinet may fail to withstand the immense force, leading to fragmentation.

The high-speed shrapnel from the cabinet can scatter widely, with enough force to penetrate the human body and cause severe injuries. Furthermore, the explosion's shockwave, carrying immense energy, can knock individuals off their feet.

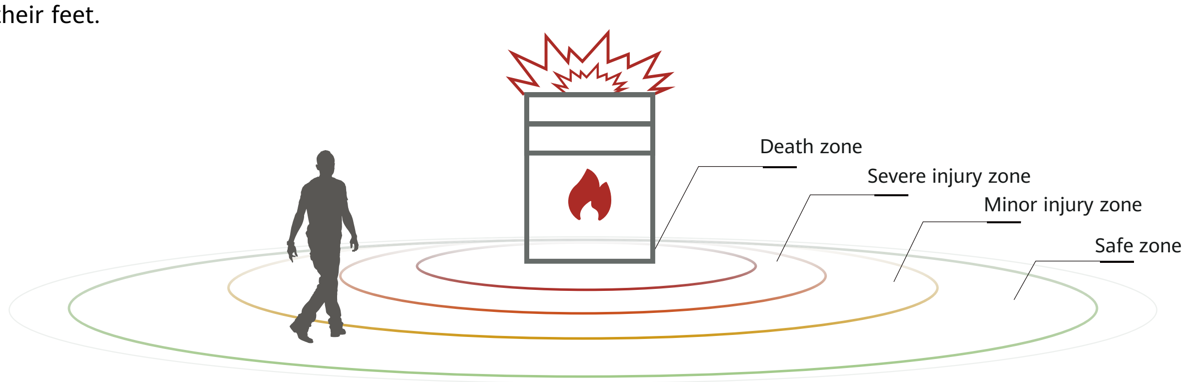


Figure 21 Explosion zones of an ESS

Defects of conventional ESS solutions:

1) In conventional solutions, the PCS and liquid cooling air conditioners are deployed at the top of the cabinet. This layout leaves no effective venting or pressure relief pathways when the cabinet faces a rapid increase in internal pressure, such as during a thermal runaway event that triggers an explosion risk. Given no path to vent gases, pressure continues to build inside the cabinet, significantly increasing the likelihood of cabinet explosion and disintegration.

2) Some solutions provide top-mounted pressure relief vents with limited explosion relief area. When the pressure inside the cabinet rises sharply due to various faults, the limited explosion relief area cannot exhaust high-pressure gases in a timely manner. As a result, the internal pressure accumulates continuously, making it nearly impossible to prevent cabinet explosion.

C2C Dual-link Safety Architecture

03

3.1 C2C Dual-link Safety Architecture: Born Safe, Life Safe

The two key links for thermal runaway in C&I ESSs are the electrical link and thermal link.

From the perspective of the electrical link, any short circuit that occurs in a cell, battery pack, internal bus circuit, or external circuit on the consumption side may spread, causing irreversible damage to the device. In addition, the impact of the short-circuit current may directly cause a cell short circuit, resulting in catastrophic thermal runaway and even electric shocks to onsite personnel.

From the perspective of the thermal link, thermal runaway spreading is the main process of exacerbating ESS risks. The thermal runaway usually begins at the cell level, which gradually spreads to a broader area, potentially causing battery pack fires, combustion or explosions within ESS cabinets, and even spreading among cabinets. This can severely impact surrounding assets and personnel.

Therefore, it is particularly important to ensure the safety of these two links. Huawei Digital Power innovatively proposes the C2C dual-link safety architecture (C2C: cell to consumption). The architecture integrates protective design at every stage along the electrical link and thermal link, reconstructing the DNA of electrical safety and thermal safety. It ensures comprehensive protection, starting from the battery cell level, to the pack and ESS levels, and finally extending to the consumption level, creating a holistic safety shield across the entire ESS.

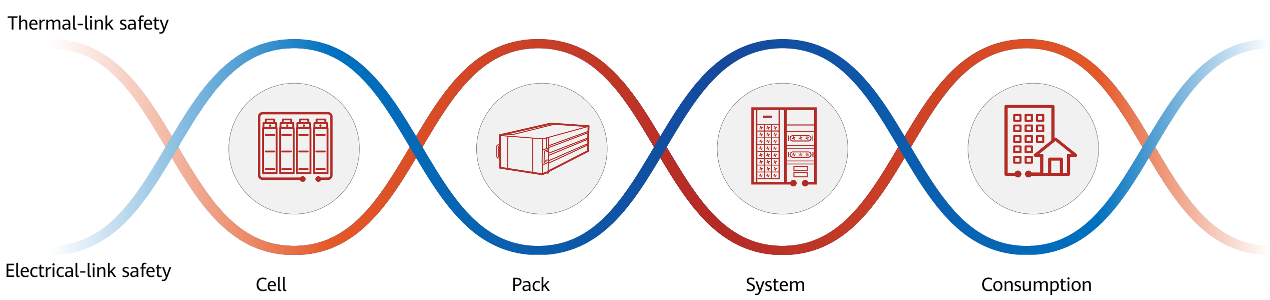


Figure 22 C2C dual-link safety architecture

3.2 Electrical-link: Short Circuit Prevention and Isolation

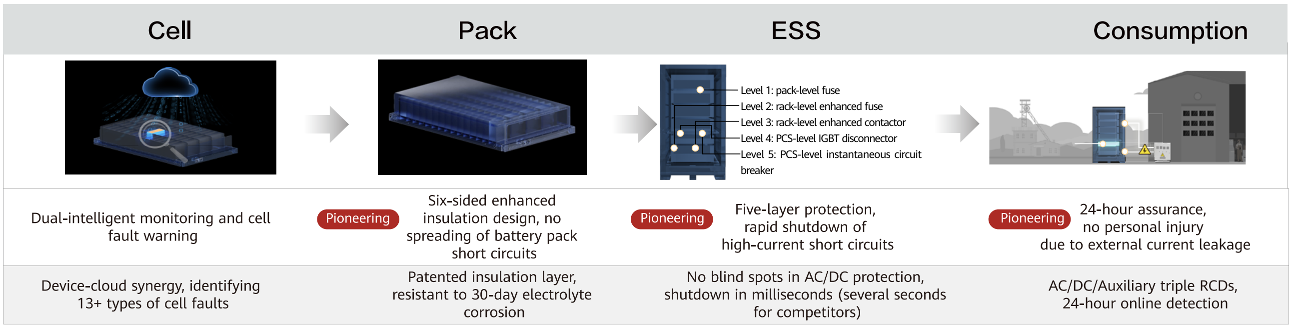


Figure 23 C2C dual-link safety: electrical-link safety architecture

In terms of electrical safety, Huawei Digital Power uses cutting-edge technologies and innovative concepts to reduce the possibility of short circuit risks through multi-level prevention and isolation design. This strict and interlocking multi-level prevention and isolation mechanism ensures the overall electrical safety.

01 Cell Level: Dual Intelligent Detection

Cell management chips and alarm algorithms affect the accuracy of cell status monitoring and safety risk identification.

To ensure cell safety and stability, Huawei Digital Power uses the device-cloud synergy mode. Automotive-grade battery management chips are used to monitor key cell parameters in real time and accurately. Additionally, the cell big data analysis and learning system collects massive cell running data, analyzes causes of typical faults, and detects and warns of more than 13 types of cell faults, such as abnormal internal resistance, abnormal temperature sampling, overcharging, and overdischarging.

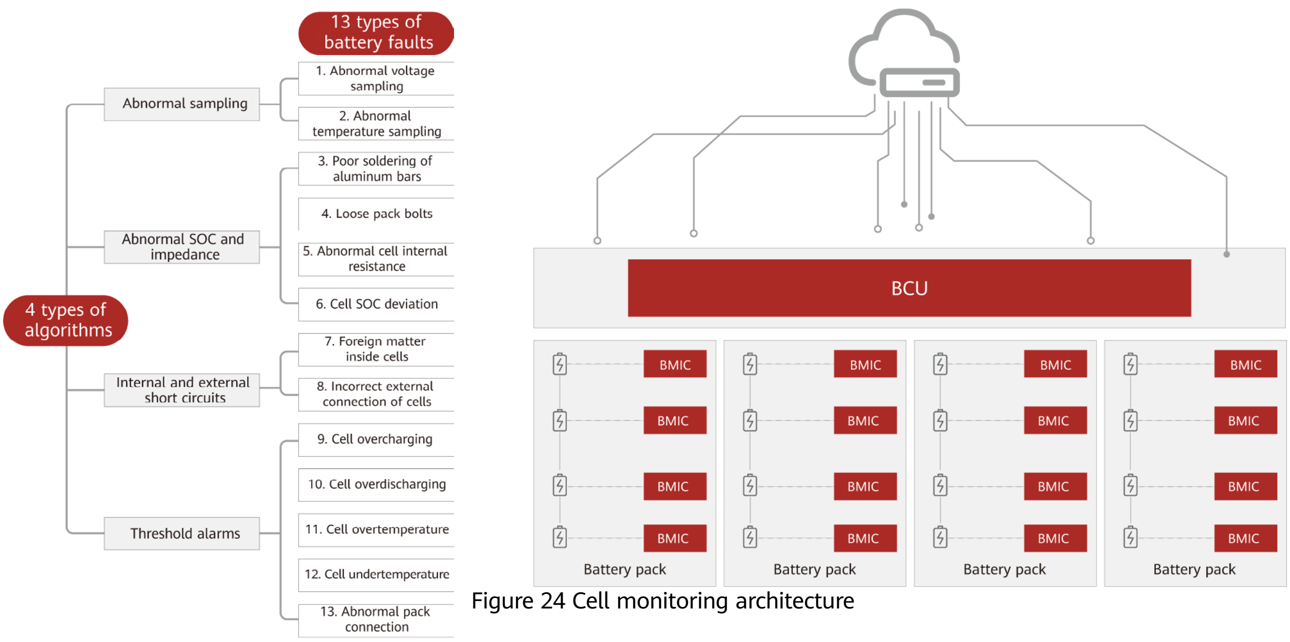


Figure 24 Cell monitoring architecture

02 Pack Level: Six-Sided Strong Insulation

A comprehensive and reliable insulation design is critical for electrical safety. The insulation shall be ensured between cells, between packs, and between the cell and the top cover, and between the cell and the bottom plate to ensure safe and stable operation of the ESS.

• Insulation on six sides of cells and battery packs

High-temperature-resistant insulation materials are between cells, between a cell and a top cover, between a cell and a bottom plate, and between packs. This prevents short circuits due to incorrect connection between adjacent cells and arcing, breakdown, and sparking between cells and battery pack enclosures.

Figure 25 Six-sided insulation for the battery pack

• Enhanced insulation paint: resistant to electrolyte corrosion

In addition, to solve the problem of poor corrosion resistance of traditional insulation materials, Huawei Digital Power developed a patented insulation paint with super corrosion resistance. The insulation paint can withstand electrolyte corrosion for more than 30 days, and no change is observed after being immersed for more than 1000 hours in actual tests.

Advantages of enhanced insulation paint
Corrosion resistance: 30-day electrolyte corrosion (no change after 1000 hours of immersion)
High temperature resistance: no change after 10 minutes at 350°C
High voltage resistance: 1500 V

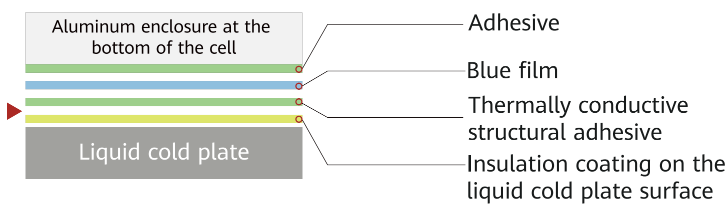


Figure 26 Reinforced insulation paint layer

• Metal enclosure: no sealing failure at high temperatures

To solve the problem that the conventional plastic enclosure is prone to insulation failure due to high temperature melting, Huawei Digital Power uses alloy metal enclosure. If the cell thermal runaway or high temperature occurs, the enclosure completeness and insulation is ensured.

03 System Level: Five-Level Full Protection

The key to preventing the spread of short-circuit faults in ESSs is to implement all-round and rapid shutdown for short circuits, especially the short circuit of high-current cell pairs.

• Five-level full protection: eliminating AC and DC blind spots

The conventional solution provides only three to four levels of protection, and there are protection blind spots. Five-level full protection measures are used to prevent short circuits in each phase of the system and implement rapid shutdown within 5 ms.

Therefore, Huawei Digital Power enhances the design of rack-level contactors and fuses to expand the protection range to cover the protection blind spot of 1.2 kA to 1.6 kA. The unique instantaneous circuit breaker is used. The five-level protection consists of the battery pack fuse, rack-level enhanced contactor, rack-level enhanced fuse, no wave transmitted by the PCS IGBT, and PCS instantaneous circuit breaker. This prevents electrical faults, such as cell-to-ground short circuits, short circuits of the positive and negative buses between the front and rear ports of the battery rack, short circuits inside the PCS, and short circuits between phases on the AC side, achieving full protection from the DC side to the AC side.

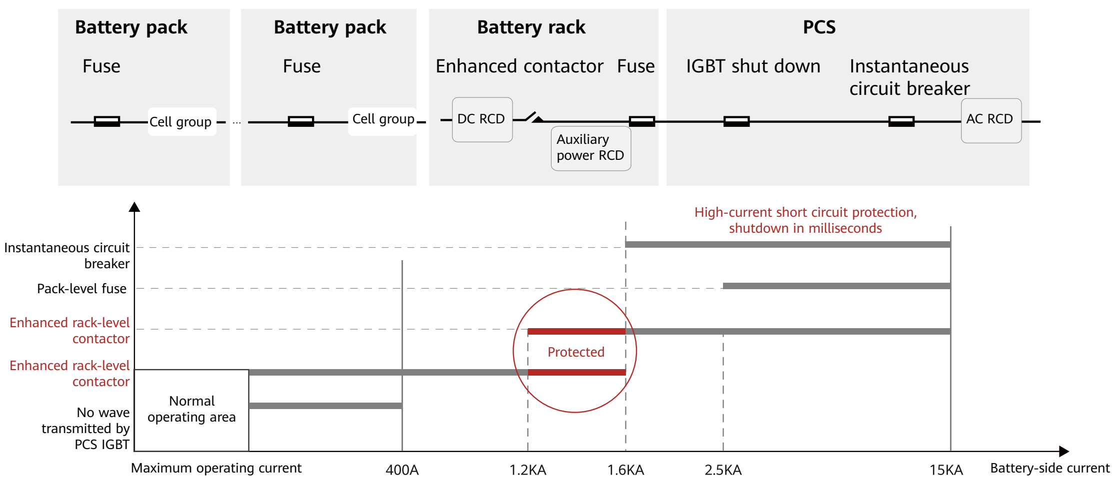


Figure 27 Five-level system protection

• Rapid shutdown for high-current cell-to-ground short circuits in milliseconds

Conventional fuses and contactors are mainly used to isolate short circuits between positive and negative electrodes. However, for a high-current short circuit to ground, a relatively long response time is required, which is usually in seconds. The unique instantaneous circuit breaker is used to implement millisecond-level rapid shutdown. It can effectively protect the PCS from internal short circuits and short circuits between phases on the PCS AC side to the ground. Additionally, for a high-current cell-to-ground short circuit that is more likely to catch fire, rapid shutdown can be performed within 5 ms. This solves the pain point that the cell-to-ground high-current short circuit cannot be protected in the industry.

04 Consumption Level: 24-Hour Protection, Preventing Electric Leakage from Hurting People

In terms of consumption, conventional ESSs in the industry usually monitor only the leakage current on the DC side, and ignore the leakage current on the AC side and auxiliary power side. The unique RCD of Huawei Digital Power provides comprehensive protection for AC, DC, and auxiliary power supplies, effectively preventing electric leakage of external circuits during operation. When current leakage occurs on the internal DC circuit of the ESS, the AC circuit between the ESS and the external power distribution cabinet, or the AC circuit between the ESS and the auxiliary power supply circuit, the residual current in the circuit can be quickly detected and the circuit is automatically disconnected in a very short time. This prevents electric shocks and ensures personal safety.

In addition, triple RCDs can protect devices in a timely manner. When current leakage occurs, the power supply is quickly disconnected to prevent further damage to devices, avoid safety accidents such as electrical fire caused by current leakage, prolong the service life of devices, and protect the electrical device and property safety.

Furthermore, when the insulation performance of the line deteriorates and slight current leakage occurs, RCDs can monitor the insulation status of the line and generate an alarm in a timely manner. This reduces the range and duration of power outage caused by faults such as current leakage and improves the reliability of power supply.

Figure 28 Triple RCD protection

3.3 Thermal-link Safety: Thermal Runaway Mitigation and Suppression

Fire mitigation and suppression measures are taken from cells to consumption, minimizing the impact of thermal runaway, which can achieve four goals: no diffusion of cell thermal runaway, no fire in battery packs, no explosion in the ESS, and no personal injury at the consumption side.

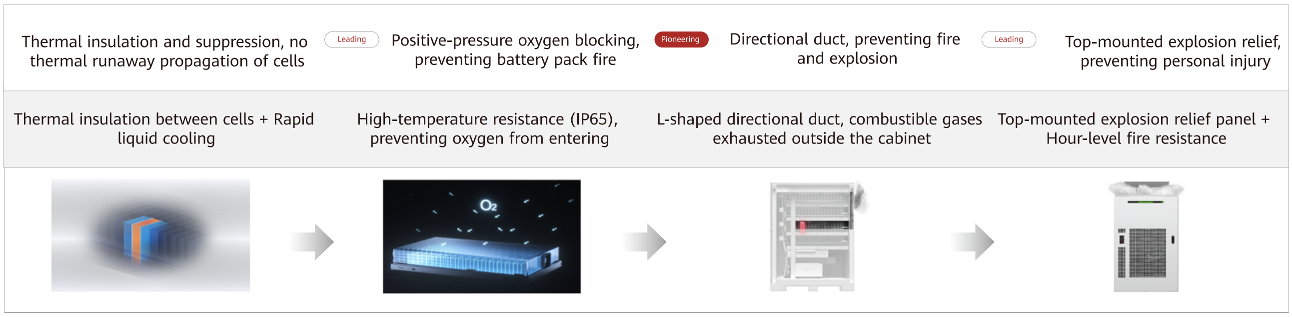


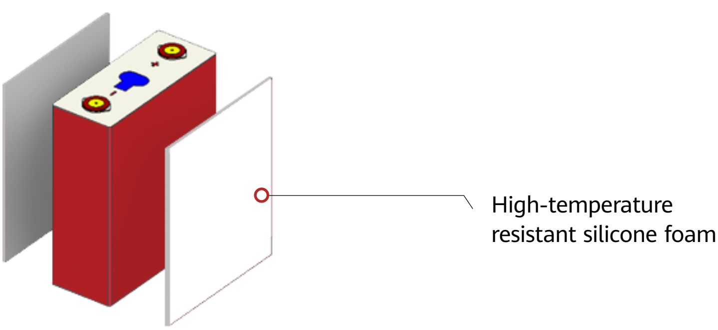
Figure 29 C2C dual-link safety: thermal-link safety architecture

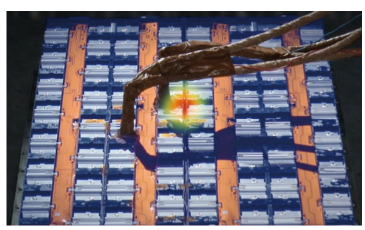
01 Cell Level: Heat Insulation and Suppression, Prevent Heat Diffusion Between Cells

In terms of cell-level thermal runaway suppression, Huawei Digital Power uses the cell heat insulation design and rapid liquid cooling technology to effectively control the cell temperature and ensure that the thermal runaway of a single cell does not propagate.

• Cell−level heat insulation design

Cell heat insulation is an important technical measure to suppress the thermal runaway propagation of cells and ensure ESS safety. Huawei Digital Power uses advanced high-temperature-resistant insulation materials with temperature resistance > 350°C and thermal conductivity ≤ 0.1 W/ (m·K). The thickness and materials of the insulation layer are optimized based on the ESS for a physical barrier between cells. The insulation layer blocks thermal runaway propagation based on three basic heat transfer modes: heat conduction, heat convection, and heat radiation. This prevents cell thermal runaway from affecting neighboring cells and causing thermal runaway chain reactions.





Heat insulation between cells, preventing thermal runaway propagation in a long time

Figure 30 Heat insulation between cells

- **Rapid cooling of the liquid cold plate**

In the C&I scenario, loads vary greatly. During the production period at the daytime, the demand for electricity increases sharply, and ESSs are continuously charged and discharge at high power. As a result, the electrochemical reaction inside cells intensifies, and heat accumulates rapidly.

The liquid cold plate at the bottom of cells adopts the dual-loop heat dissipation design to ensure the heat dissipation effect for cells. If the cell temperature is too high, the liquid thermal management system (LTMS) works in maximum output mode to quickly take away the cell heat, which effectively slows down and suppresses the thermal runaway of cells.

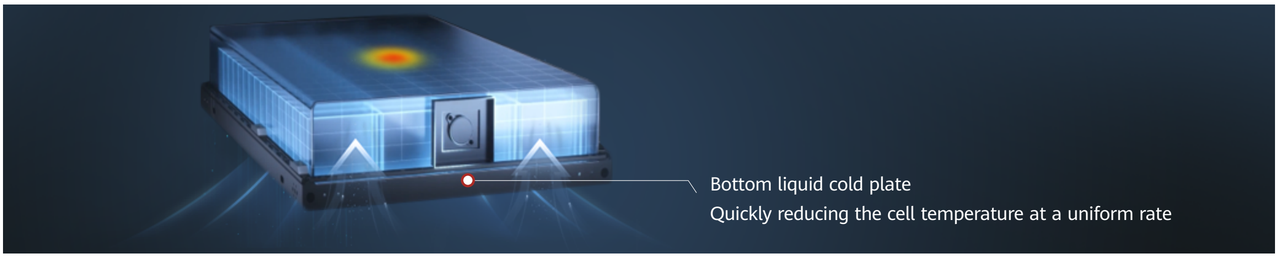


Figure 31 Rapid cooling of the liquid cold plate

02 Pack Level: Positive-Pressure Oxygen Blocking, Preventing Battery Pack Fire

The positive-pressure oxygen blocking design prevents external gases from entering the battery pack due to a pressure difference, effectively preventing oxygen from entering the battery pack and reducing the possibility of fire in the battery pack. Additionally, the battery pack is protected to IP65, which is resistant to high temperatures and ensures that the sealing does not fail at high temperatures. In this way, the battery pack does not catch fire.

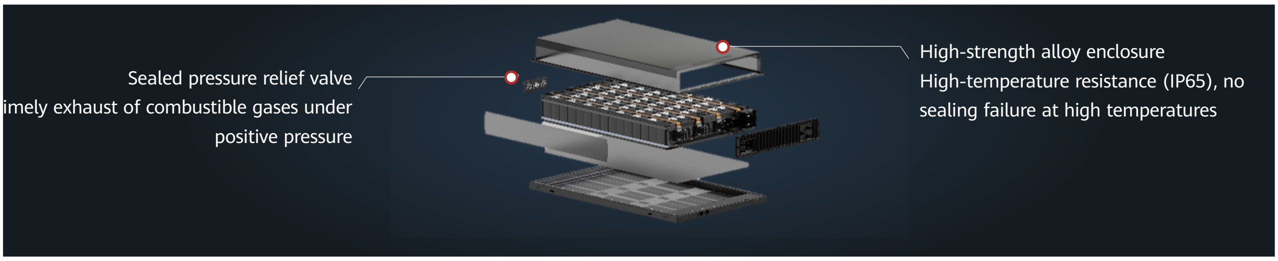


Figure 32 Positive-pressure oxygen blocking design for the battery pack

A sealed pressure relief valve is mounted on the rear of the battery pack. Under normal operating conditions, the pressure relief valve is closed to prevent external moisture from entering the battery pack, reducing the risk of short circuits. In the case of thermal runaway, combustible gases are quickly generated in the battery pack, resulting in increasing pressure. Positive pressure is maintained within the battery pack, preventing external oxygen from entering the battery pack, reducing the risk of fire. When the pressure exceeds a certain threshold, the pressure relief valve automatically opens to discharge the combustible gases in time, preventing structural damage caused by high pressure.

In addition, the metal enclosure is made of a high-strength alloy material, which provides excellent high-temperature resistance and high-strength performance. Results of rigorous tests show that the battery pack enclosure can stay intact in a high-temperature environment above 350°C for a long time. The enclosure can cope with the high-temperature impact of thermal runaway and high-pressure impact of gases produced by cells without structural damage such as deformation, seams, and cracks. Even at high temperatures, the enclosure provides IP65 protection and high sealing performance, ensuring positive-pressure oxygen blocking.

Normal state: The pressure relief valve is closed.
Thermal runaway: The pressure relief valve is opened if the pressure is 4±1 kPa.

The metal enclosure top cover is made of high-strength alloy and is resistant to high temperature. The enclosure top cover material can withstand a temperature of 350°C or higher for a long time. In addition, the enclosure does not seam or crack under the direct impact of gases released by cells (melting point of aluminum alloy: 600°C to 650°C).

According to the actual test result, positive pressure is still maintained inside the battery pack after thermal runaway. As a result, oxygen cannot enter the battery pack, and the enclosure does not crack.

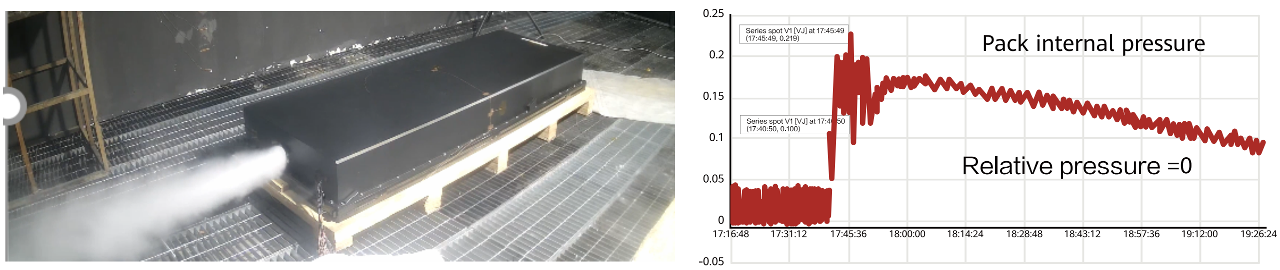


Figure 33 Internal pressure change of the battery pack during a thermal runaway test

03 System Level: Directional Gas Exhaust, Prevent Explosion Inside the Cabinet

In conventional solutions, if thermal runaway occurs in a battery pack, combustible gases are directly discharged inside the cabinet. After the gases accumulate, fire and explosion may occur. The unique directional exhaust technology is used to connect the pressure relief valve at the rear of the battery pack to the duct at the rear to form an L-shaped directional duct. If thermal runaway occurs in the battery pack, combustible gases (such as H2 and CO) are exhausted from the pressure relief valve and then to the outside of the cabinet through the duct. No gas overflows into the cabinet, ensuring that the concentration of combustible gases in the cabinet is far below the explosive limit.

The directional duct shall meet the safety requirements of high temperature resistance, high sealing performance, and high reliability. The cross-sectional area of the directional duct is designed based on the volume of gases produced during the battery pack thermal runaway, ensuring timely exhaust of combustible gases. In addition, a high IP rating level is maintained inside the duct. Sealing mechanical parts of the duct can withstand a temperature of at least 200°C and high-temperature smoke corrosion, ensuring reliable sealing of the duct.

L-shaped directional duct: preventing explosion

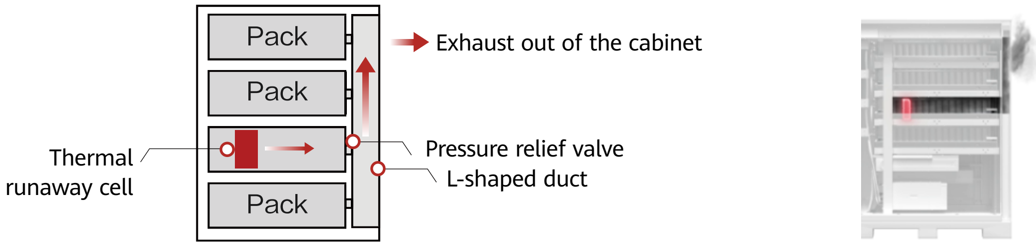


Figure 34 Directional duct design

In the actual test, gas concentration detection sensors are installed at different positions in the cabinet. When thermal runaway occurs in the battery pack, combustible gases are discharged through the directional duct. The test result shows that the concentration of combustible gases in the cabinet is lower than the explosive limit.

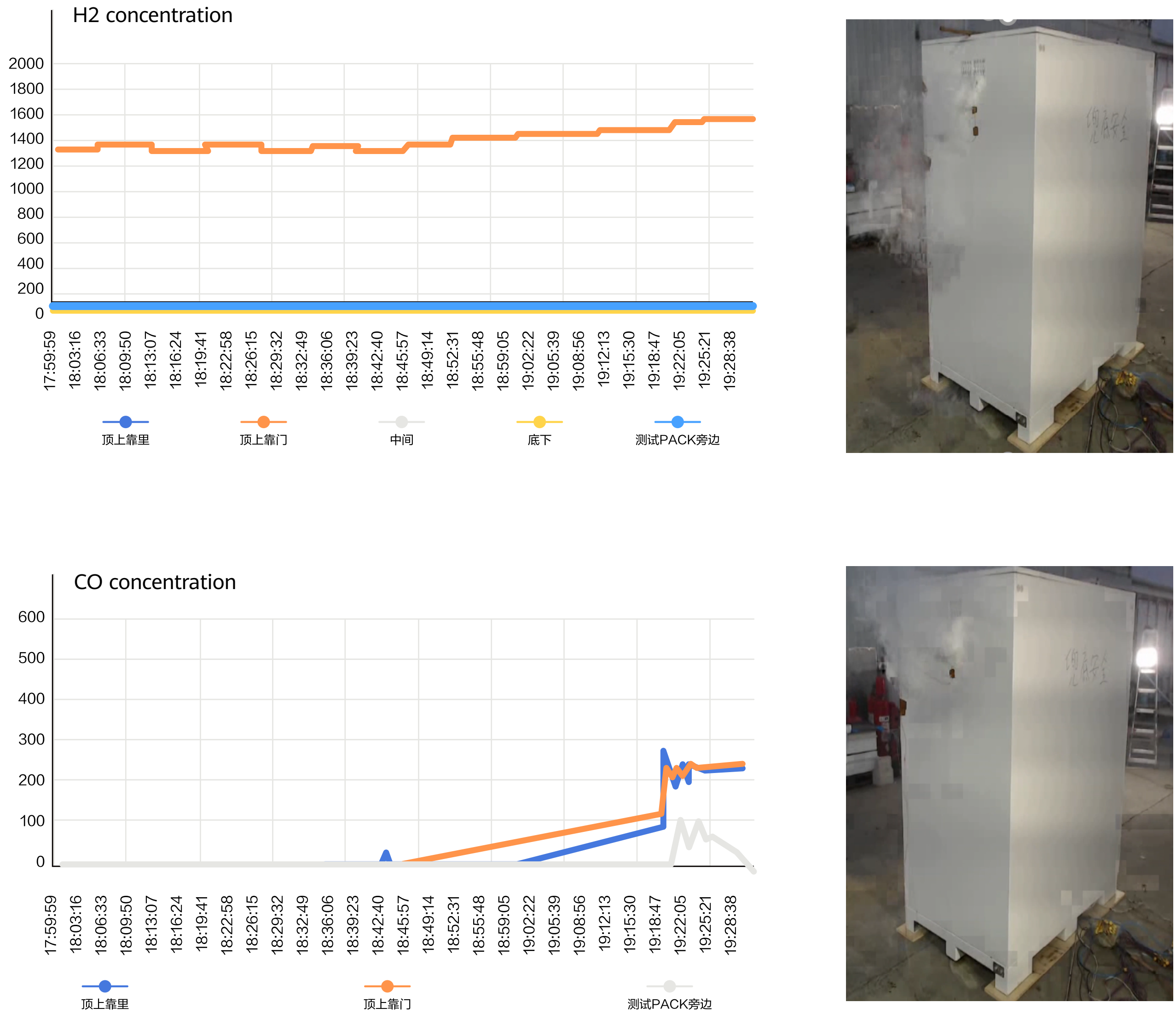


Figure 35 Gas concentration detection inside the cabinet

04 Consumption Level: Top Explosion Vent Preventing Personal Injury

Conventional ESS cabinets do not provide dedicated explosion relief design or adopt front/rear-mounted explosion relief, which may cause fire and explosion in the cabinet or even disintegrate the cabinet. High-temperature gases, debris, and burning chip debris can be ejected in all directions, posing a threat to the safety of nearby individuals.

The ESS of Huawei Digital Power adopts the top-mounted explosion relief design. Once thermal runaway occurs inside the ESS, the hot air can be discharged vertically in a very short time. Professional explosion relief simulation is used to determine the proper explosion relief area and pressure to ensure the explosion relief effect. The top cover and the explosion relief panel are integrated to ensure the airtightness during normal ESS operation. In addition, there are hinges around the explosion relief panel. During the explosion relief process, the hinges effectively control the movement track of the explosion relief cover, preventing the cover from falling out of the cabinet under great impact. This prevents personal injury.

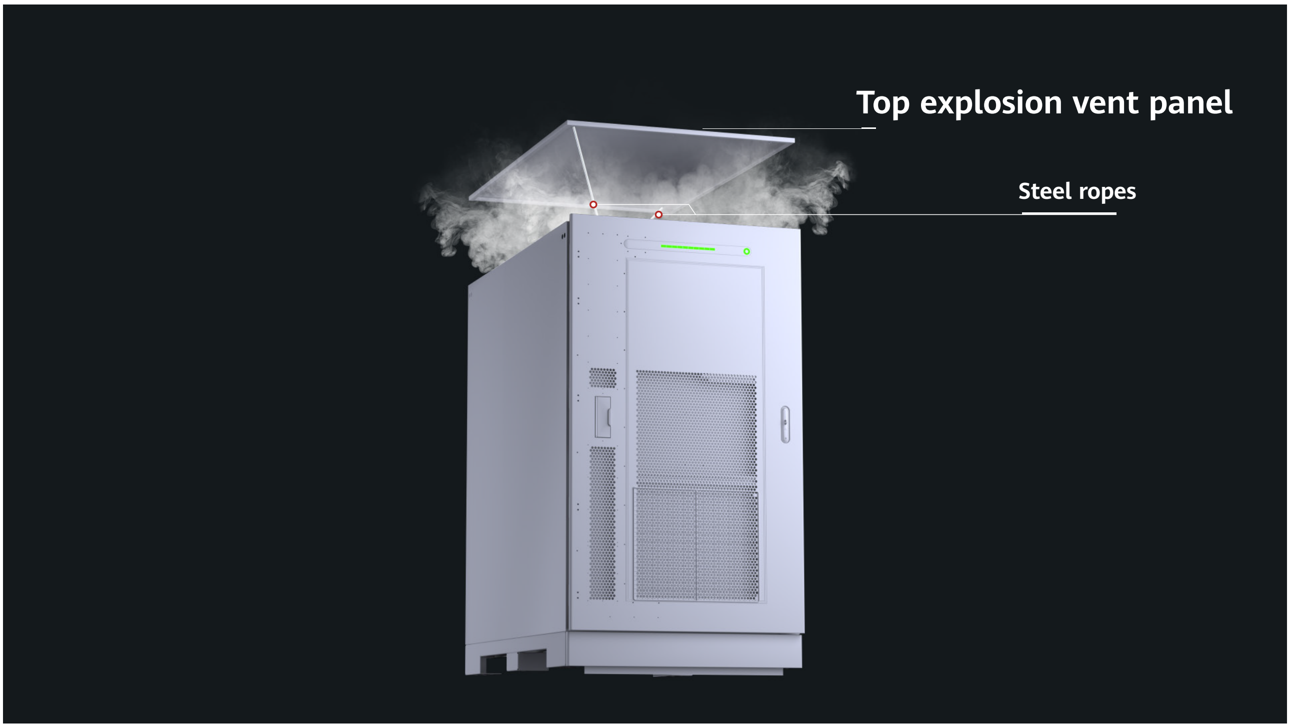


Figure 36 Top explosion vent design

3.4 Building a Safety-Centered Quality System

With the continuous iteration of energy storage technologies, the energy storage industry will develop towards low costs, high energy storage density, high cycle stability, and long-period storage. As an important cornerstone of energy storage industry development, energy storage safety is still a severe challenge for the industry and may become the biggest competitiveness for companies in the industry in the future. Once a major safety issue occurs, its negative impact can last for several years and even influence the trajectory of the entire industry.

High power	Energy-intensive	Personal safety	Strict operation procedure
High voltage, high current, and high power	Energy-intensive ESSs	Personal safety involved	Strict electrical operation regulations
·Arcing and carbonization due to poor contact ·Explosion due to capacitor and power module failures ·Renewables integration requiring synergy with the power grid	·Built-in energy ·High requirements on charging and discharging ·Easy to catch fire, explode, and challenging extinguishing effort upon failures	·Increasing power and energy ·Close distance ·Accidents endangering personal safety	·High requirements on operation procedures ·High requirements on personnel qualifications ·High requirements on operation protection

Figure 37 Electrical safety: the core of the energy storage industry

Building on the industry's past experiences and lessons, Huawei has established a comprehensive E2E electrical safety system. This system spans all critical stages, including product design, manufacturing, supply chain, safety evaluation, storage and logistics, O&M, and emergency response. In this way, Huawei ensures comprehensive safety of its products and solutions.

Figure 38 E2E management process of enhanced electrical safety system

Traditionally, electrical safety has been treated by manufacturers in the industry as a basic quality metric, often measured using failure rates. However, the current pace of industry development calls for a concept shift. Huawei has focused on strengthening core foundational quality across all aspects of electrical safety, establishing a robust energy storage safety management system, and positioning safety as a key competitive advantage. By implementing explicit management and clear red-line policies, Huawei presents safety standards, operating procedures, potential risks, and hazards transparently. This approach ensures that professionals involved in every stage, design, production, processing, manufacturing, and sales, can easily adhere to and monitor these guidelines.

Figure 39 The principle of enhanced electrical safety system

Additionally, Huawei integrates safety elements into E2E organizational structure, business processes, personnel capability development, operational mechanisms, and safety operation tool chain. By doing so, it has established a comprehensive and rigorous electrical safety and quality management system. This system ensures the electrical quality and safety of ESSs, driving the industry's stable and sustainable progress.

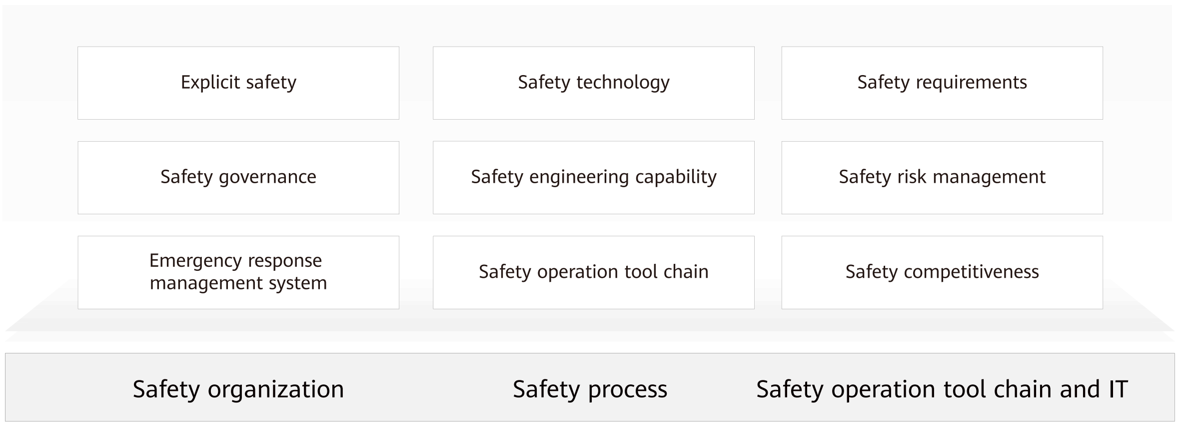


Figure 40 Enhanced electrical safety system architecture

Adhering to a quality-first principle, Huawei uses a standardized, modular, and platform-based architecture to achieve hardware and component standardization and interchangeability. It employs a rigorous E2E quality control system to ensure product reliability. Furthermore, Huawei has established a third-party safety attack-defense lab to perform independent safety acceptance test to ensure reliable implementation of safety design. Multi-level design and verification ensure high quality, safety, and reliability of energy storage products.

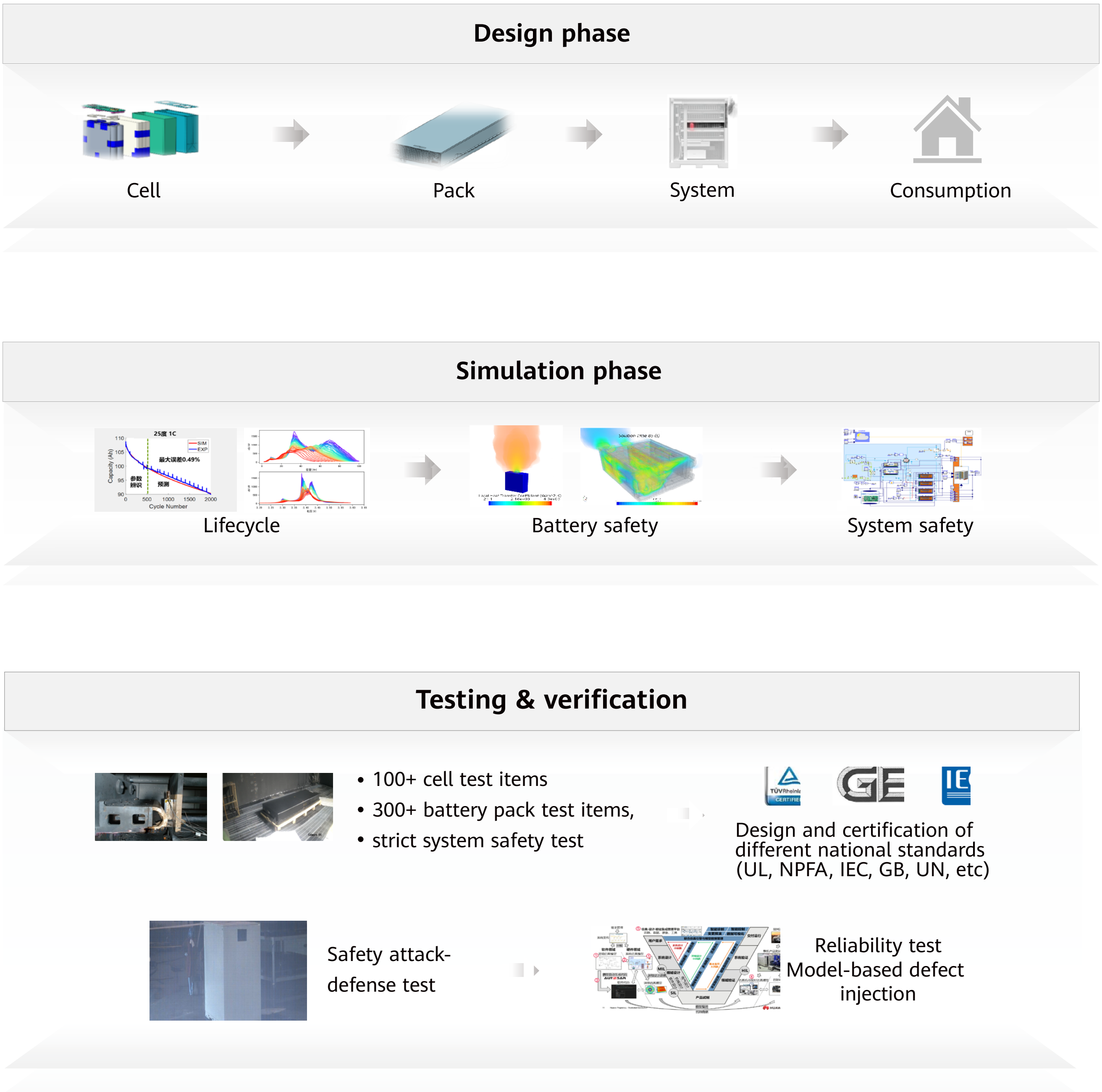


Figure 41 Design and verification of enhanced electrical safety system

Safety Classification: Key to Sustainable Industry Development

04

4.1 Existing Safety Standards in the Industry

Currently, safety standards for C&I ESSs vary across countries. In China, GB standards are predominantly used, while Europe adheres to EN standards, the Americas to UL, and there are also internationally recognized IEC standards. Additionally, components within ESSs, such as cells, battery packs, and PCSs, may be governed by multiple safety standards. Although there are many safety standards in the industry, according to the data of ESS accidents in recent years, exiting standard levels cannot completely eliminate safety risks. In addition, the formulation of some standards often lags behind reality, and the standard level is usually raised after an accident occurs.

Table 3 Global ESS standard statistics

Category	Standard	Description
Battery cell and pack	·IEC 62619 (international) ·UL 1973 (US standard) ·GB/T 36276 (Chinese standard)	Mechanical, electrical, and environmental safety of cells and packs. Functional safety complies with IEC 60730-1 Annex H.
ESS	·IEC 62477-1 (international) ·UL 9540 (US standard) ·EN 62933-5-1 (European standard) ·GB/T 36929 (Chinese standard)	Electrical, thermal, mechanical, structural, and environmental safety of the ESS

In the current C&I scenario, the preceding standards are only basic specifications. Strict compliance with these basic standards can reduce risks to some extent, but it does not mean that ESSs can run safely and stably for a long time in various application environments. Proactive risk prevention, timely loss mitigation, and effective fault diagnosis are not yet implemented.

4.2 Necessity of Safety Classification for ESSs

Currently, the ESS industry lacks unified safety classification standards. Companies do not have clear standards to adhere to during the design, construction, and operation of ESSs, leading to inconsistent quality in energy storage products and services in the market. This inconsistency hinders the progress of industry technologies and the healthy development of the market, and weakens the industry's competitiveness and sustainable development potential in the energy sector.

Furthermore, regulatory authorities struggle to provide targeted supervision for energy storage projects of varying risk levels. Inadequate regulation of high-risk projects can lead to safety accidents, while excessive regulation of low-risk projects increases compliance costs for companies.

Refined ESS safety standards and graded standards for different application scenarios not only implement precise protection, but also help establish an emergency response mechanism, making rescue

Table 4 Importance of ESS safety classification

Precise Protection	Emergency Response
Through safety classification, precise protection measures can be tailored to different system levels. For example, in high-risk level-1 ESSs, stricter personnel access controls can be implemented, along with more advanced personal protective equipment (PPE). These measures aim at minimizing the exposure of individuals to hazardous environments.	Clear safety classification plays a crucial role in developing corresponding emergency response mechanisms. In the event of an accident, rescue personnel can swiftly assess the level of danger and the potential scope of harm based on the ESS's safety classification. This enables the development of more scientifically sound and effective rescue plans, enhancing response efficiency and ensuring the safety of rescue personnel and nearby individuals.
Differentiated Maintenance	**Risk Assessment and Insurance**
Safety classification allows for more targeted maintenance strategies. For ESSs with higher safety levels, where failures could result in substantial property losses, more frequent and meticulous device inspection and maintenance shall be implemented. This proactive approach helps identify and address potential issues in a timely manner, reducing the likelihood of device failures and safeguarding valuable assets for enterprises.	Insurance companies can leverage the safety classification of ESSs to assess risks more accurately and set reasonable premium rates. Companies, in turn, can select insurance plans that align with the safety classification of their ESSs. This approach not only helps reduce insurance costs but also ensures adequate financial compensation in the event of an accident, minimizing property losses.

4.3 Grades and Standards

TÜV Rheinland has developed a safety classification system for evaluating ESS safety. Building on existing standards, this system addresses pain points in the safety of current C&I ESS products as well as the concerns of end users by refining safety definitions and tailoring the classification to various scenarios.

The standard is divided into three grades: basic safety, plus safety, and prime safety.

Basic safety

- Meeting basic regulations and standards to achieve market entry is the baseline for ESSs.

Plus safety

- Beyond this, plus safety in areas such as mechanical, electrical, thermal, and environmental protection.

Prime safety

- In extreme scenarios, when an ESS is passively ignited, thermal runaway at the battery pack level shall not propagate or result in personal injury.

Basic safety serves as the fundamental baseline, while plus safety represents a step forward through improved protective measures to control disasters and minimize losses. However, only prime safety can establish a comprehensive and seamless defense, ensuring the long-term stable operation of ESS.

Safety Classification

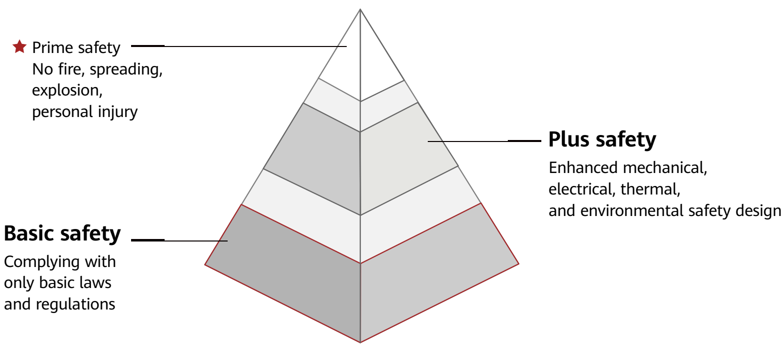


Table 5 Safety grades

Item	Basic Safety Requirements	Plus Safety Requirements	Prime Safety Requirements
Electrical safety	EN/IEC 62477 or UL 9540 or UL 1973	★ DC side insulation monitoring function or enhanced insulation between cells and output ports	☆ Electrolyte leakage simulation test
Transportation and structure safety	UN 38.3	☆ Pack soaked in water, 50% height ☆ Device enclosure meeting the IP55 ☆ Internal modules meeting IP66/67 ☆ Warehousing design	☆Fire resistance test of the protective enclosure (C&I: 1 hour)
EMC	IEC 61000-6-X		
Functional safety	IEC 60730-1 Annex H or ISO 13849 or IEC 61508	☆ ISO 13849−1 PLc or equivalent ☆ Current sensing redundancy ☆ Temperature detection ratio 50%	☆ ISO 13849 PLd or equivalent
Fire safety	UL 9540A	★ Using fire suppression devices	☆ Number of cells under thermal runway diffusion: ⩽ 1; Number of cells under thermal runaway: ⩽ 3
	NFPA 855	★ After thermal runaway, the electrolyte shall not flow to any PCB or electrified conductor.	☆ Thermal runway diffusion + ignition test
	NFPA 68 or 69	★ Number of cells under thermal runway diffusion: ⩽ 2; Number of cells under thermal runaway: ⩽ 5	☆ Explosion test
Battery safety	IEC 62619, IEC 63056 or UL 1973		☆ All module over charging
Chemical substance safety	INew battery regulations, RoHS + REACH (when applicable)	☆ REACH SVHC 240	
Cell safety	IEEE 1625, used to confirm the basic requirements for checking the internal structure of a cell, including the electrode plate, electrode lug, separator, internal insulation/isolation, thermal performance, and safety measures	☆ Crushing and nail penetration tests for cells: no fire	
Function requirements		★ Audible and visual alarm	

Notes:

- The plus safety requirements at least 5 optional test items.
- The prime safety requirements at least 3 optional test items.

Rigorous Safety Tests: Highest Safety Level in the Industry

05

5.1 Comprehensive Safety Tests with Requirements Stricter Than Industry Standards

To verify the reliability of C2C electrical and thermal safety of Huawei ESSs, Huawei Digital Power has commissioned TÜV Rheinland to perform a series of strict verification tests on electrical and thermal safety. The products have passed the tests. The following figures and data are obtained from TÜV Rheinland's authoritative reports and certificates.

5.2 Extreme Thermal Runaway Tests: No Diffusion, No Explosion, and No Injury

01 Thermal Propagation and Ignition Tests

In terms of cell-level thermal runaway suppression, Huawei Digital Power uses the cell heat insulation design and rapid liquid cooling technology to effectively control the cell temperature and

• Test purpose

To verify that Huawei C&I ESSs can effectively suppress thermal runaway propagation after thermal runaway occurs and exhaust combustible and toxic gases in the cabinet in a timely manner.

• Test method

1) Before the test, charge the ESS with a constant current of 56 A until the voltage reaches 216 V. Then, charge the ESS with a constant voltage until the current reaches 5.6 A (end-of-charge current).

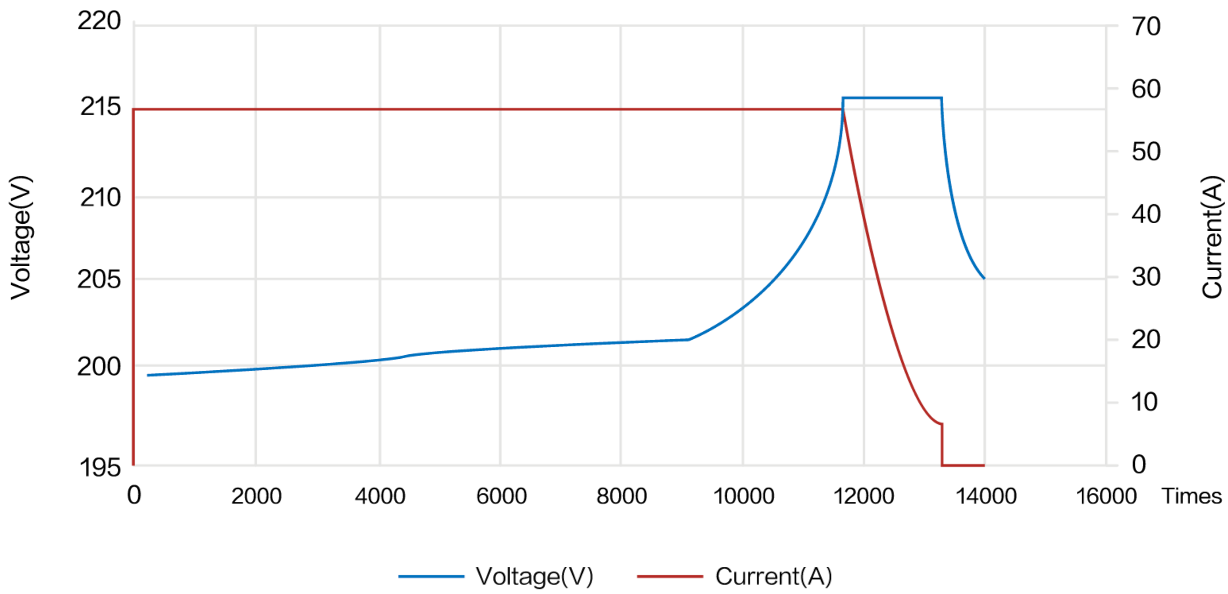


Figure 42 ESS overcharge test process

2)Cell 23 is the initiating cell. Cell 23 is heated by the heater at a rate of 4–7°C/minute until thermal runaway occurs in it.

3)After thermal runaway occurs in the cell, the igniter installed in the cabinet is activated.

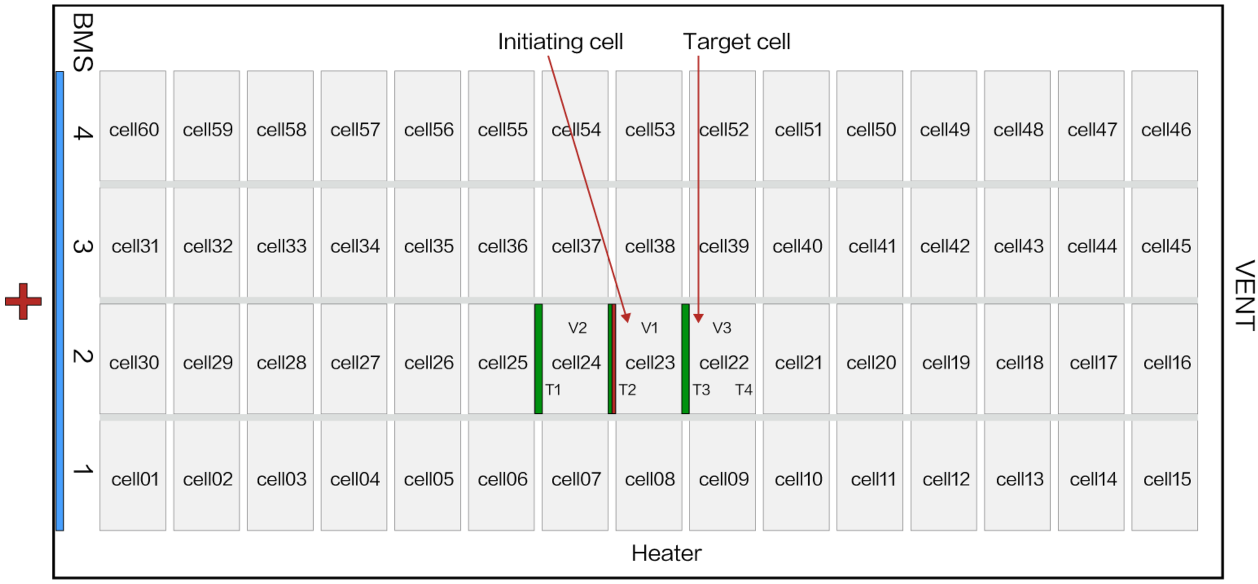


Figure 43 Positions of the thermocouple and heater

• During the test:

V1 is the voltage of cell 23, V2 is the voltage of cell 22, and V3 is the voltage of cell 24. Due to thermal runaway, the voltages of cell 23 and cell 22 decreased to 0 V in sequence during the test.

During the test, the H2 and CO concentrations inside the cabinet were always 0.

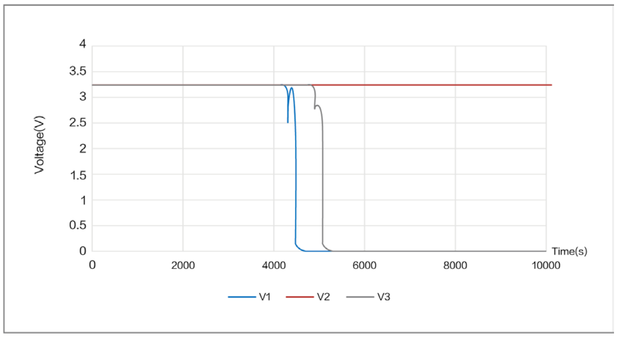


Figure 44 Voltage changes of cells

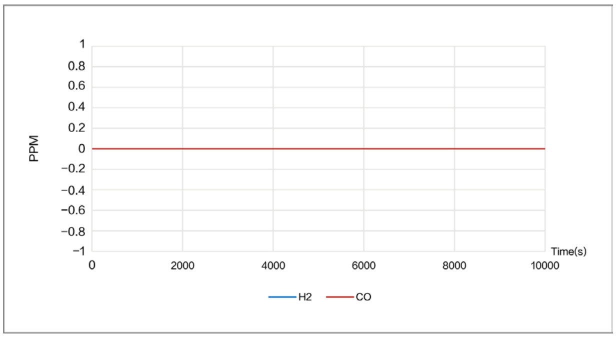


Figure 45 Changes in concentrations of H2 and CO

Huawei ESSs passed the thermal runaway propagation and ignition tests and obtained the compliance certificate issued by TÜV Rheinland, which fully proves the advantages of Huawei C&I ESSs in thermal runaway propagation suppression and internal gas exhaust system.

Because thermal runaway occurred in the two cells, the temperature and pack voltage fluctuated sharply. The temperature increased from 0°C to 500°C within about 5000 seconds and then gradually decreased. The pack voltage decreased from 200 V to 193.5 V.

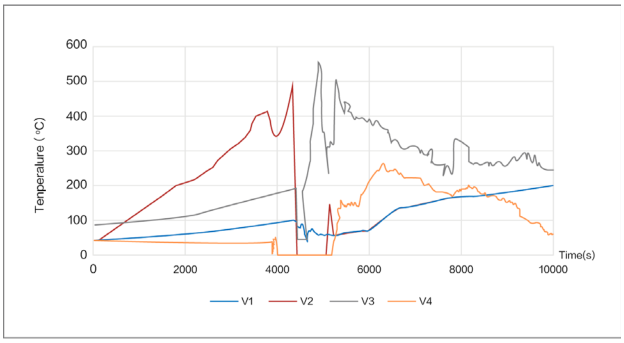


Figure 46 Temperature changes in cells 23, 22, and 24

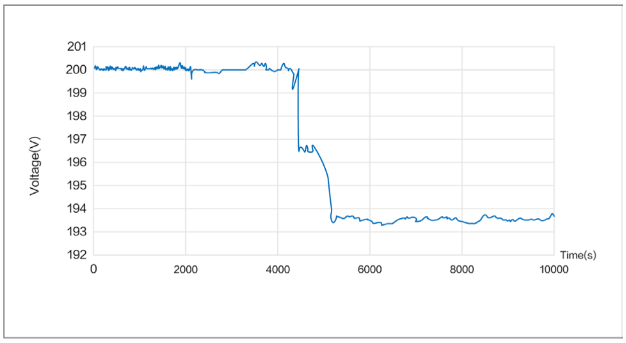


Figure 47 Voltage changes of the initiating pack

The results show that thermal runaway occurs at the heated cell 23 and the target of thermal runaway propagation (cell 22), and further thermal runaway propagation is effectively suppressed. In addition, combustible gases generated by cell thermal runaway propagation are exhausted through the duct, and the concentration of combustible gases in the cabinet is insufficient for ignition. After the test, the appearance of the cabinet is intact and no destructive damage occurs.

Figure 48 Product before the test

Figure 49 Product after the test

Huawei ESSs passed the thermal runaway propagation and ignition tests and obtained the compliance certificate issued by TÜV Rheinland, which fully proves the advantages of Huawei C&I ESSs in thermal runaway propagation suppression and internal gas exhaust system.

02 Explosion Relief Test

• Test purpose

To verify that the explosive pressure can be normally released through the explosion relief panel and that there is no dangerous shock wave around the product. The cabinet shall provide a directional duct to prevent the accumulation of combustible gases.

• Test method

The test simulates battery thermal runaway in the ESS cabinet. An igniter is used to ignite combustible gases in the cabinet. The test personnel check whether the pressure relief panel of the cabinet can be opened properly and whether the ambient environment is damaged.

1) Before the test, set the position where a dummy stands.

Figure 50 Position of the dummy before the test

2) Perform the ignition test.

Figure 51 Explosion relief test in progress

During the test, after thermal runaway occurs in the cell, the gas sensor in the cabinet detects that the gas concentration increases rapidly and quickly reaches the measurement range limit of the gas sensor. After the gas is ignited, the gas concentration in the cabinet decreases.

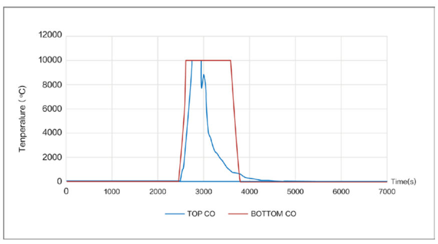


Figure 52 Changes in CO concentration inside the cabinet

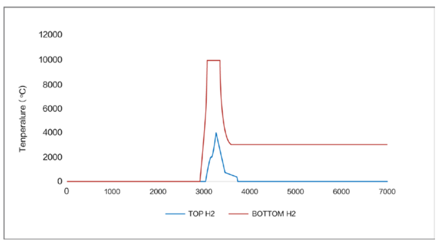


Figure 53 Changes in H2 concentration inside the cabinet

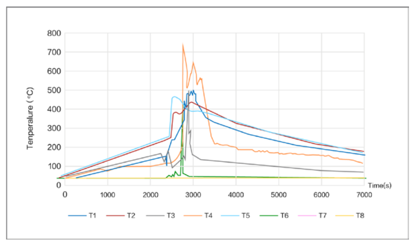


Figure 54 Cell temperature changes

- **Test result**

The explosion pressure is normally released through the explosion relief panel. No dangerous shock wave exists around the product. No debris exists 3 m away from the cabinet. The dummy 1 m away from the product is not damaged. The dummy is not injured by the explosion shock wave, demonstrating that the safety of surrounding personnel and environment is guaranteed.

Figure 55 Product before the test

Figure 56 Product after the test

Huawei ESSs passed the explosion relief test and obtained the compliance certificate issued by TÜV Rheinland. This proves that Huawei C&I ESSs are capable of effectively suppressing fire and explosion risks and minimizing hazards and risks after fire and explosion.

03 Enclosure Burning Test

• Test purpose

To verify the fire resistance of Huawei C&I ESS enclosure. The test focus is the heat insulation of enclosure materials and the integrity of the enclosure after the test. Ensure that the enclosure can isolate most heat at high temperatures, withstand the extreme heat without cracking, and prevent excessive release of harmful substances from inside the enclosure.

• Test method

Test the fire resistance of the cabinet wall.

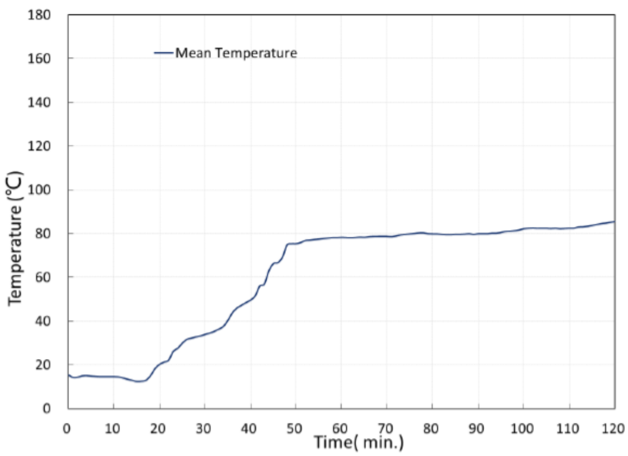


Figure 57 Mean temperature changes of the non-exposed surface

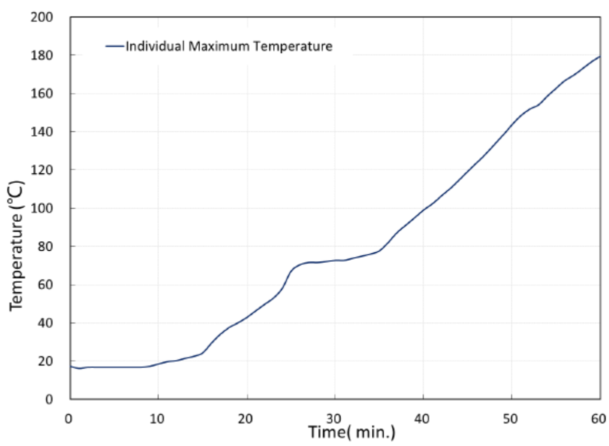


Figure 58 Individual maximum temperature changes of the non-exposed surface

• Test result

After the ESS is exposed to fire for 60 minutes in the furnace, the unexposed surface is intact without any damage or crack. Apart from partial deformation of the exposed surface, the entire structure remains intact. During the exposure, there is no flame propagate outside the cabinet.

According to the standard requirements, the difference between the average temperature and the initial temperature of the unexposed surface shall be lower than 140°C, and the difference between the maximum temperature and the initial temperature shall be lower than 180°C. The data shows that the temperature differences are much lower than standard limits, proving that Huawei ESSs provide excellent heat insulation performance.

Exposed surface before the tes	Non-exposed surface before the test	Exposed surface after 60 minutes of burning	Non-exposed surface after 60 minutes of burning

Figure 59 Samples before and after the test

Huawei C&I ESSs are recognized by TÜV Rheinland for their excellent performance in the enclosure burning test and obtained the compliance certificate issued by TÜV Rheinland, which proves that Huawei C&I ESSs can protect surrounding personnel and the environment in the case of an inevitable fire.

Thermal runaway diffusion and ignition tests | Explosion relief test | Fire resistance test

Figure 60 Certificates issued by TÜV Rheinland

5.3 Prime Safety: The Industry's First Highest Safety

Seite *Page* 1 / 2

Zertifikat *Certificate*

Zertifikatsnummer *Certificate No.:* R 50659837 0001	**Berichtsnummer** *Report No.:* CN24PDF5 001
Genehmigungsinhaber *License Holder:* Huawei Digital Power Technologies Co., Ltd. Office 01, 39th Floor, Block A, Antuoshan Headquarters Towers, 33 Antuoshan 6th Road, Futian District, Shenzhen, 518043 Guangdong P.R. China	**Fertigungsstätte** *Manufacturing Site:* SHENZHEN HUAHAO MECHANICAL & ELECTRICAL CO.,LTD. Dongguan Branch company Second Floor No.738 Meijing Middle Road, Changtang Community, Da Lang Town, Dongguan City, 523779 Guangdong P.R. China
Prüfzeichen *Test Mark:* TÜVRheinland CERTIFIED	**Geprüft nach** *Tested according to:* 2 PfG 2988/08.24

Geräteidentifikation
Product Identification

Produkt: *Product:*	Energy Storage System (Energy Storage System)
Modell: *Type:*	Modelle sind auf nächste(r) Seite(n) gelistet *Type designation(s) are listed on the next page(s)*
Technische Daten: *Technical Data:*	LUNA2000-215-2S10, LUNA2000-215-2S11, LUNA2000-215-2S12, LUNA2000-161-2S11, LUNA2000-107-1S11 Level 3: Safety Prime Level Technical data(s) are listed on the next page(s) ANLAGE (Appendix): 1
Gültig ab: *Valid from:*	2025-03-07
Ausstellungsdatum: *Date of issue:*	2025-03-07

Zertifizierungsstelle:
Certification body:

A. Chen

TÜV Rheinland LGA Products GmbH, Tillystraße 2, 90431 Nürnberg

www.tuv.com

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Figure 58: Huawei's C&I ESS obtained the highest safety level certification

Energy storage safety is the cornerstone of the sustainable and high-quality development of the industry. With the rapid development of energy storage technologies, Huawei Digital Power has invested in the quality and safety field and continuously promoted the safety and reliability of ESS through continuous technological innovation and strict safety standards.

The Huawei Digital Power upgrades the traditional cabinet-level thermal runaway non-diffusion to the battery pack-level thermal runaway non-diffusion, helping the energy storage industry upgrade safety and achieving higher-level safety protection. Huawei Digital Power adheres to the concept of ultimate safety, leads the healthy and sustainable development of the energy storage industry, contributes to the construction of a clean, low-carbon, safe, and efficient new power system, and provides important reference for the standardization and development of the global energy storage industry.

Summary and Prospect

06

Safety Classification: A Growing Trend

Continuous deployment of C&I ESSs is a key to achieve green and low-carbon transformation. In this process, safety is the most important prerequisite and a basic requirement. Currently, C&I ESSs are experiencing rapid development, and the industry's basic safety design standards are no longer adequate to ensure the safety of people and property around ESS facilities. Higher-level safety standards are needed to provide stronger protection. The classification of safety standards within the industry is set to become a key trend in the future.

Comprehensive Safety: The Guarantee

For devices deployed in densely populated areas, ensuring comprehensive safety is crucial for protecting nearby people and property. C&I ESS facilities shall meet not only the most basic safety standards but also plus safety requirements, and ideally, prime safety standards. This is essential to ensure the long-term, stable operation of ESSs.

ESS Safety: Huawei's Pursuit

Huawei is committed to systematic safety design for C&I ESSs in three dimensions: equipment, assets, and personnel. Huawei ESS solution enables flexible application across all scenarios. With just one management platform, it delivers intelligent management throughout the entire lifecycle. By adhering to the industry's prime safety standards, the solution ensures comprehensive protection for your personnel, assets, and devices.

Dual-link Safety: for Every Business

Huawei's C2C dual-link safety architecture covers safety from cell to consumption, setting a new benchmark for C&I ESS safety. On the path of pursuing safety, Huawei will continue to collaborate with industry peers to advance the refinement of safety standards for ESSs. Together, the goal is to create ESS facilities that are safe and reliable, make green electricity available to every business.

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