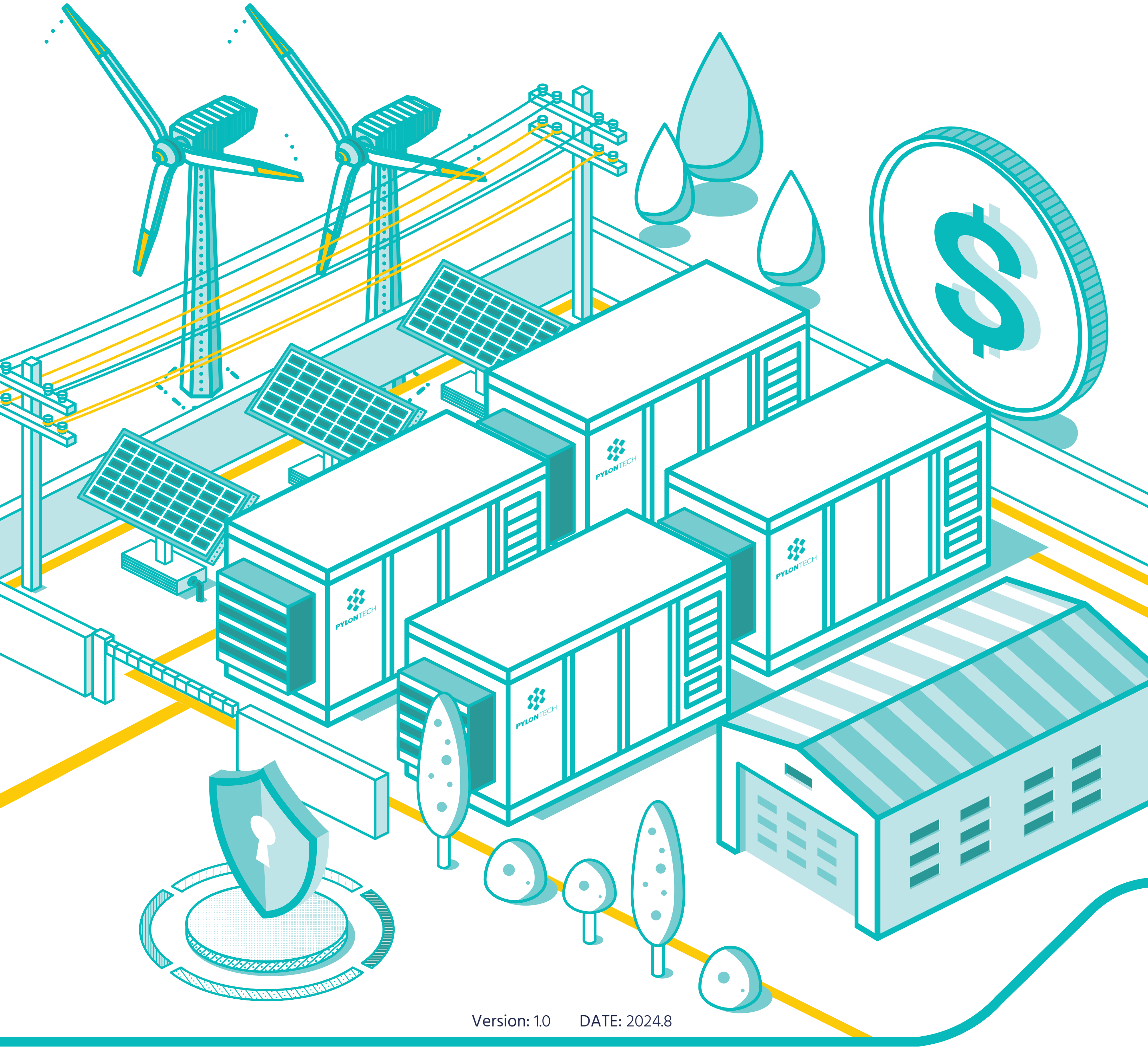
Commercial & Industrial Energy Storage System Safety

White Paper



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CONTENTS

INTRODUCTION

As the global transition to renewable energy accelerates, energy storage systems play an increasingly crucial role in achieving a zero-carbon society and reducing dependence on fossil fuels. These systems are integral across various sectors, enhancing energy self-sufficiency, improving grid stability, and lowering operational costs and risks in commercial and industrial settings. Pylontech, committed to driving the future of smarter power, actively advances the adoption of energy storage systems by offering comprehensive solutions. These solutions enhance electricity availability, reduce energy costs, and provide ancillary support to the grid, making energy storage systems a crucial part of the future electricity industry.

Recent advancements in battery technology, along with decreasing costs and increased production volumes, are driving the development of a more energy-independent economy. However, the conveniences brought by these technological advancements also come with significant safety challenges. Recent reports have highlighted a significant number of energy storage incidents. Since 2023, there have been over 70 energy storage incidents globally, most of which involved electrochemical storage projects. These incidents pose severe threats to both personal and asset safety. In response to these challenges, Pylontech adheres to the principles of responsibility and accountability, continuously optimizing products and technologies to ensure safety and reliability.

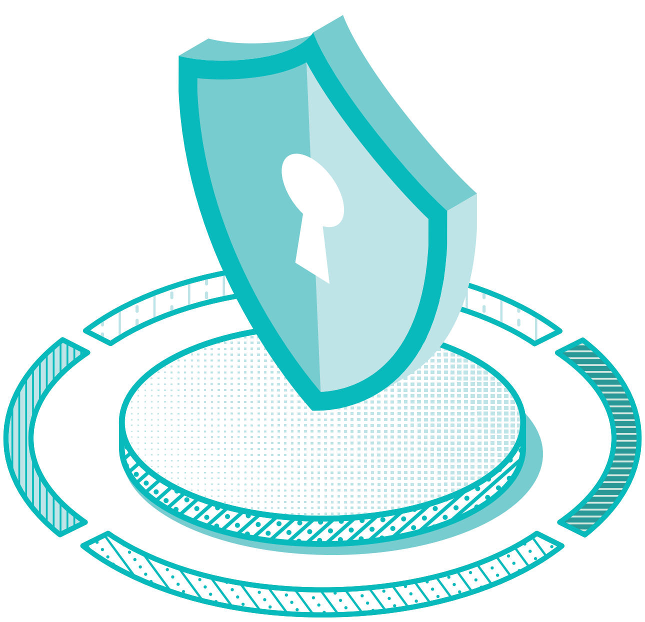
At Pylontech, we are dedicated to liberating your energy sustainably. This commitment drives our focus on ensuring the highest safety and security standards for our clients' assets. We prioritize comprehensive safety principles in our products and address concern for safety. This safety white paper is a testament to our dedication to protecting our customers' and delivering dependable solutions.

In this white paper, we offer an in-depth analysis of safety design in energy storage systems and practical solutions for managing safety risks. This aligns with our commitment to protecting customer value and contributing to a sustainable future.

01

SAFETY IS A TOP PRIORITY

The core of a battery energy storage system is rechargeable batteries, primarily represented by lithium-ion batteries, which have superior characteristics such as high energy density, high power density, high efficiency, and long service life[1-2]. However, these advantages also bring some potential safety risks related to thermal stability and internal short circuits. For instance, the electrolyte used in lithium-ion batteries is flammable, and excessive heat generated by high internal currents, most commonly from short circuits, can ignite the electrolyte, leading to rapid thermal runaway, fire, or even explosion, posing serious threats to personal and property safety. In recent years, incidents of battery energy storage have been occurring frequently worldwide, drawing significant attention to the necessity of safety design in energy storage systems.



CASE

On 19 April 2019, an incident at an energy storage system owned and operated by Arizona Public Service (APS) prompted a major shift in hazard mitigation in the industry. The facility, which featured a modular building design resembling a large containerization system, had experienced a thermal runaway event.

Accident scene images

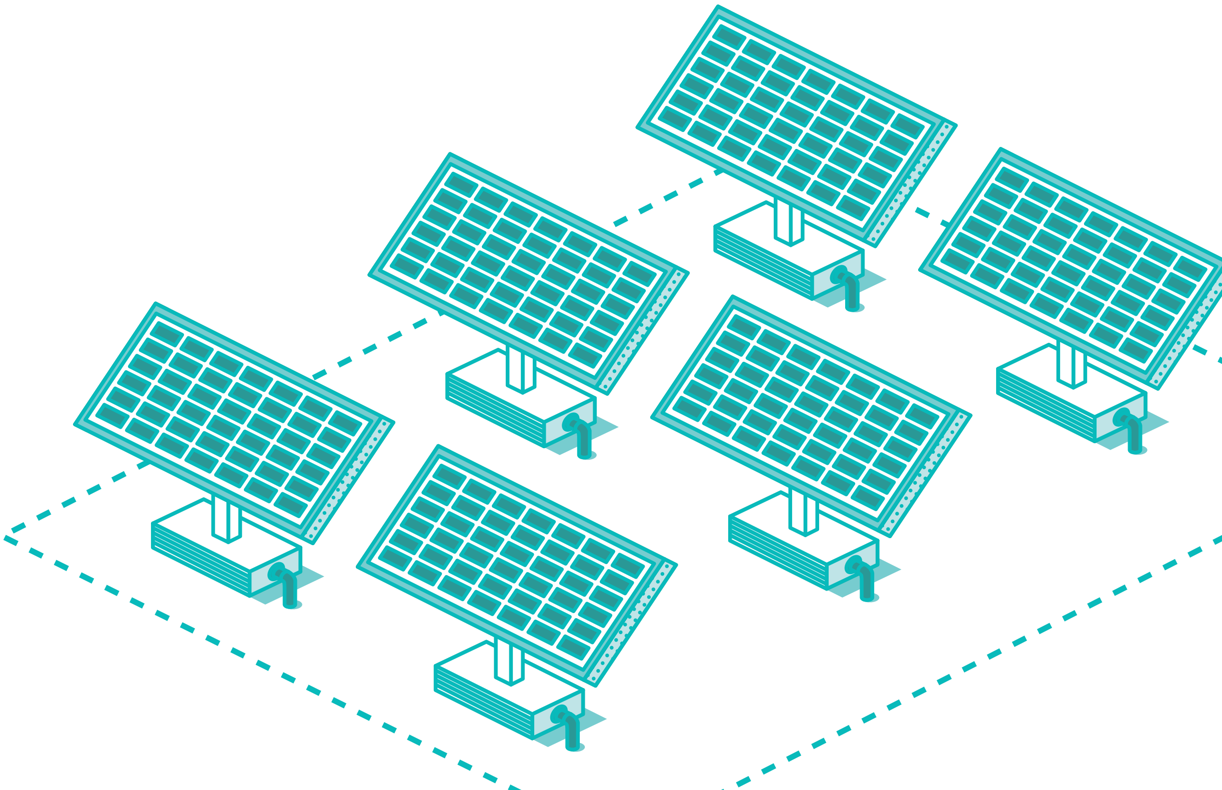
Although the energy storage system was equipped with a clean agent fire suppression system, it lacked deflagration ventilation or explosion protection (i.e. it did not meet explosion control requirements). The fire department failed to take appropriate and immediate action due to the absence of system and incident information. When the Hazardous Materials Treatment (HAZMAT) team attempted to enter the energy storage system to assess the magnitude of the incident, an explosion occurred, severely injuring several firefighters. According to the McMicken Incident Technical Analysis and Recommendations Report (Arizona Public Service, 2020), the five factors that led to the incident are as follows [3]:

1. An internal failure of the battery cell triggered a thermal runaway.
2. The clean agent fire suppression systems were unable to stop the thermal runaway.
3. The facility lacked a thermal barrier between battery cells, allowing the thermal runaway event to spread to neighboring battery cells.
4. The lack of ventilation increased the concentration of combustible gases released from the batteries.
5. The emergency response plans did not include fire suppression, ventilation, or entry procedures.

02

ENERGY STORAGE SAFETY RISKS

The safety of energy storage systems includes several aspects. This chapter identifies and analyzes the safety risks in the entire life cycle of energy storage systems from three aspects: battery, electrical, and system integration.

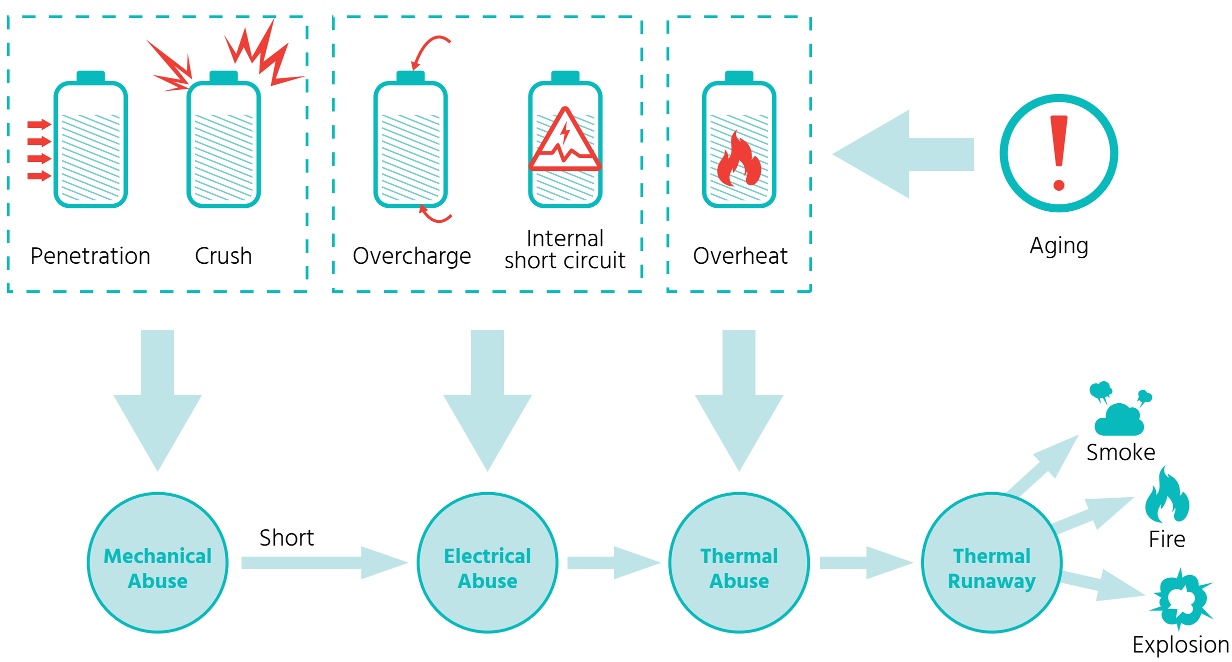


2.1 | Battery Risk

The individual battery cells are the core safety risk of the energy storage system, which consists of many single cells connected in series and parallel. Each cell is charged and discharged through the redox reaction of the positive and negative electrodes, to achieve the mutual conversion between electrical and chemical energy[4]. The safety characteristics of each battery cell directly affect the overall safety of the energy storage station. The structural and material characteristics of high energy density batteries are the primary source of the danger, and the thermal runaway inside individual battery cells is the root cause of safety hazards of the energy storage power station[5].

Variations in battery design, quality of materials, and manufacturing processes can all contribute to potential safety risks. Defects in battery design, the use of low-quality materials, or improper assembly of battery components can individually or collectively increase the likelihood of battery overheating or failure. In the process of storage, transportation, and use, batteries are exposed to many hidden safety risks, including a series of safety accidents caused by battery leakage of liquid and gas, water exposure, physical deformation, and so on.

Lithium-ion batteries have a higher energy density compared to other types of batteries. Therefore, they are more prone to thermal runaway due to both internal causes (internal short circuit) and external causes (including mechanical, electrical, and thermal abuse), which can result in the generating large amounts of flammable gases, leading to a significant risk of fire and explosion.



Thermal runaway occurrence and associated misuse[6]

Thermal runaway in lithium-ion batteries is characterized as follows:

1. Thermal runaway occurs rapidly and lasts for a long time.

2. The temperature during thermal runaway is high, releasing toxic and hazardous substances.

3. Once a fire occurs in a place where lithium-ion batteries are mass-produced and stored, the surrounding lithium-ion batteries are highly prone to a chain reaction, which develops rapidly and is difficult to control.

4. Thermal runaway battery extinguishing is difficult and technical.

5. Prolonged spontaneous combustion or even explosion.

2.2 | Electrical Risk

Electric Shock Risks

Since the AC and DC voltages of energy storage systems are typically higher than the safe voltage for the human body, there is an inherent electrical safety risk. If protection measures against electric shock fail, direct or indirect contact with live parts will pose a danger to human safety.

Electrical Operational Failures (Safety of the Device)

Risk is primarily manifested in overloads and short circuits. Overload refers to the electrical equipment, wire power or current exceeding its rated value, causing the temperature of the wires or equipment to surpass permissible limits, which accelerates the aging of surface insulation. A short-circuit current typically exceeds the normal operating current by dozens of times, causing high currents that can overheat electrical equipment, damage insulation, and even burn electrical lines and equipment, potentially leading to fires.

Electrical Fires

Electrical fires primarily arise from internal factors in the energy storage system, particularly failures related to overheating or electrical faults (arc flashes). According to the U.S. Occupational Safety and Health Administration (OSHA), arc flash accidents account for about 80% of all electrical accidents. Even if no workers are injured, arc flashes can damage electrical equipment, and lead to costly component replacements and power system downtime. Arc flashes typically occur when the electrical insulation between energized conductors is broken or unable to withstand the applied voltage.

2.3 | Systems Integration Risk

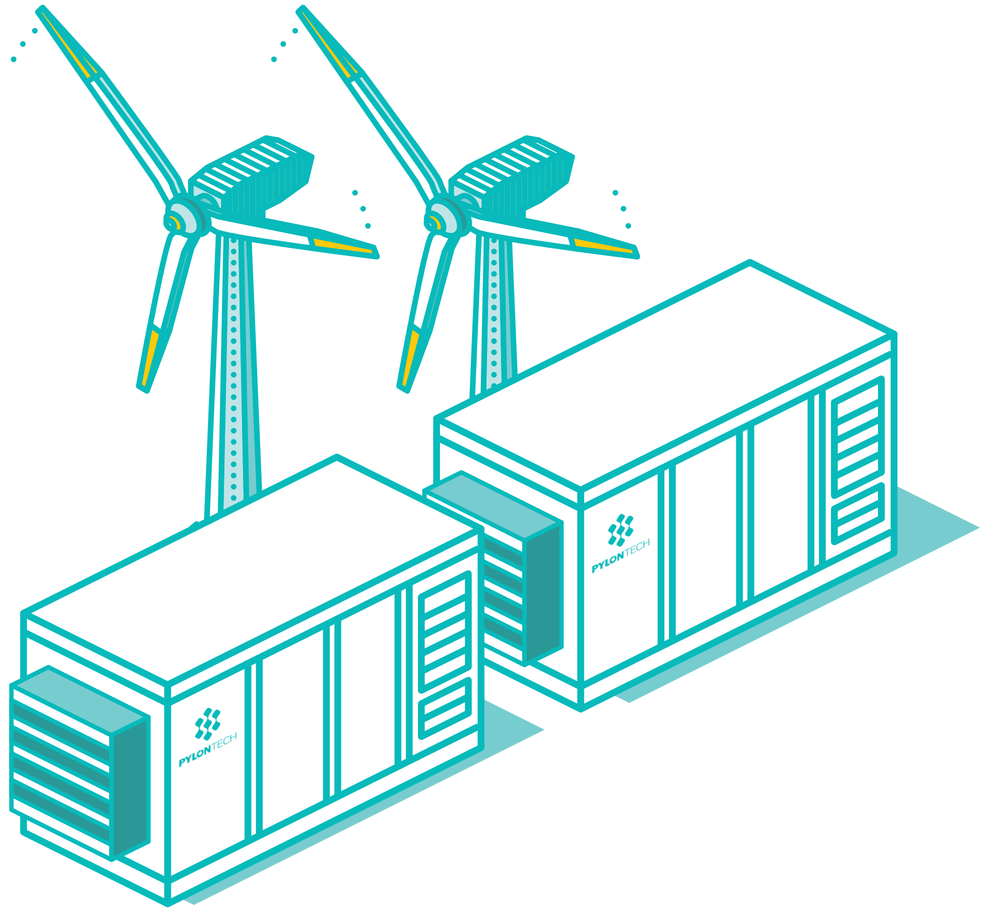
The failures of energy storage systems often stem from poor integration, incompatible components, incorrect installation, or improper commissioning procedures, which significantly contribute to the safety risk of energy storage systems.

Integration is the most common root cause of battery energy storage system failures, with the majority of such incidents involving the Balance of System (BOS) components. These components include safety elements such as DC and AC wiring, HVAC subsystems, and fire suppression systems. Lithium-ion battery storage systems contain components from multiple vendors that may not be designed to work together seamlessly. Therefore, integration is a critical part of the deployment and installation process to ensure compatibility and functionality of all interfaces.

03

ENERGY STORAGE SAFETY SOLUTIONS

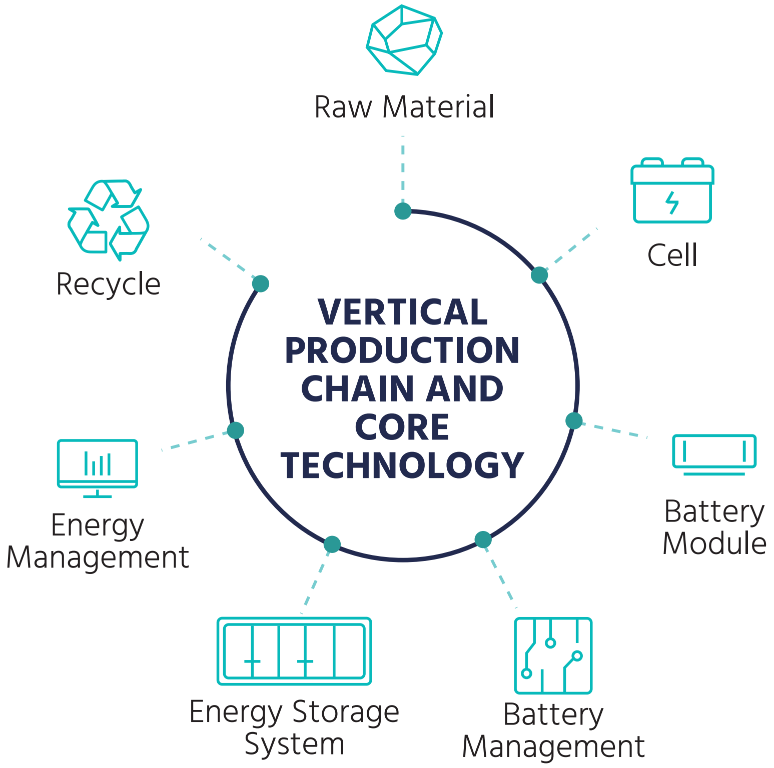
Based on the identification and analysis of safety risks associated with energy storage systems, Pylontech implemented a series of safety solutions to address each risk. These solutions were certified by relevant authorities after conducting a variety of safety tests. This chapter will be elaborated from three perspectives: battery design, electrical design, and system integration design.



3.1 | Battery Design

Pylontech is an industry-leading provider of lithium-ion battery energy storage systems. Through long-term independent research and development, the company has mastered core technologies across the industry chain, including lithium-ion cells, modules, battery management systems, and energy storage system integration.

Leveraging over 10 years of expertise in electrochemical technology, the company has developed advanced safety and reliability features, including intrinsic battery safety, passive safety measures, and thermal runaway warning algorithms. The company has mastered technologies for analyzing key exothermic reaction paths, electrolyte behavior, material properties, and diaphragm timing, as well as module heat-gas coupling and online safety early warning systems. Additionally, the company's products feature high-reliability structural designs and are equipped with precise, intelligent and high-reliable battery management systems to achieve reliable battery safety design.



3.1.1 Intrinsic Safety Design

The intrinsic safety of lithium-ion batteries mainly refers to the inherent safety features of the battery itself and should be considered during the design and manufacturing process. These safety characteristics are influenced by the battery's material selection, structural design, manufacturing process, and so on.

Material Selection

Our researchers strived to achieve a significant improvement in battery safety through material selection and optimization. With a variety of analytical testing methods, they performed time sequence analysis of the thermal runaway process in lithium-ion battery cells and developed a thermal runaway model. Then, they explored the influence factors of self-produced heat temperature (T1), thermal runaway trigger temperature (T2), thermal runaway maximum temperature (T3), and the gas production volume of the gas-producing components as well as other characteristic parameters. They comprehensively analyzedthe mechanism of thermal runaway, which guided the optimization and improvement of battery cell safety.

The theoretical model analysis indicates that improving battery cell safety involves slowing down the thermal runaway reaction rate, reducing heat production, and decreasing the content of combustible gases. The approach to enhancing battery safety includes the following measures:

- To improve the temperature of thermal runaway T1 and T2 as well as reduce the temperature of thermal runaway T3 and H2 can guide the optimization and improvement of the safety of battery cell (e.g. to improve T1 and T2 by 20%, and decrease T3 by 10%).
- The timing regulationg of thermal failure chemical reactions can be achieved through optimization of positive and negative electrode materials as well as diaphragmand electrolyte. Among them, modifying the electrode interface to block exothermic side reactions, reducing electrolyte flammability, and optimizing gas-producing components(aim to narrow the deflagration limit of thermal runaway gases and increase their flammability threshold) are important ways to improve the thermal stability of batteries.

Structural design

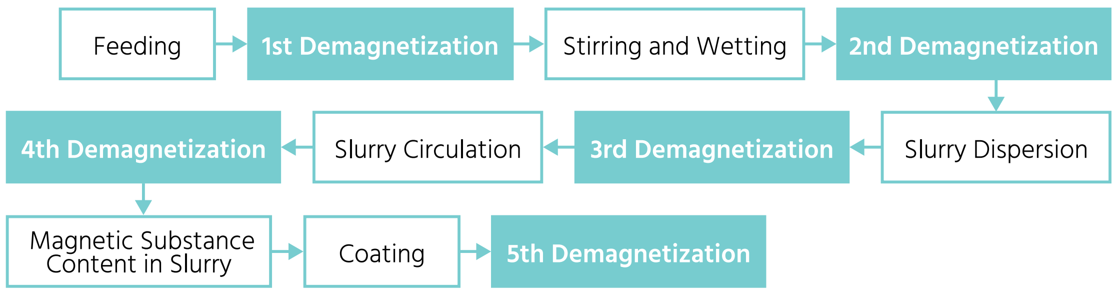
To enhance the mechanical stability and safety margin of the cell, it is recommended to adopt a cell structure that can effectively isolate the positive and negative electrodes and prevent internal short circuits. Square aluminum shell batteries offer better safety and longevity compared with soft-pack and cylindrical batteries due to the following features:

- The shell has sufficient strength to withstand external impacts.
- The sealing adopts laser welding, which has good sealing and high reliability and avoids liquid leakage.
- The shell and positive electrode are designed with weak conductivity to prevent electrochemical corrosion and avoid liquid leakage.
- Pressure relief valve design can achieve fixed pressure and directional bursting, allowing the battery's internal gas and heat to release and preventing battery explosions or fire. The system design also can achieve effective thermoelectric separation, significantly enhancing safety.
- Square aluminum shell batteries have extra space to accommodate more electrolytes, which contributes to a longer battery lifespan.

Manufacturing Process

Pylontech has always emphasized the great importance of energy storage product safety, and applied strict quality standards throughout the manufacturing process, from the battery cell to the whole battery system. Metal impurities, metal particles, and internal insulation control, which affect the safety of battery cell products, are strictly controlled at every stage to eliminate potential safety risks.

First of all, the magnetic metal impurity content of the raw materials of the battery cell is controlled to ≤ 1 ppm during initial inspection. Throughout the process from powder feeding to homogenization and coating, 5 permanent magnetic and electromagnetic impurity removal devices are set up to control the magnetic metal impurity content of the coated slurry remains ≤200ppb, to maximize the control of metal impurities entering the raw materials.

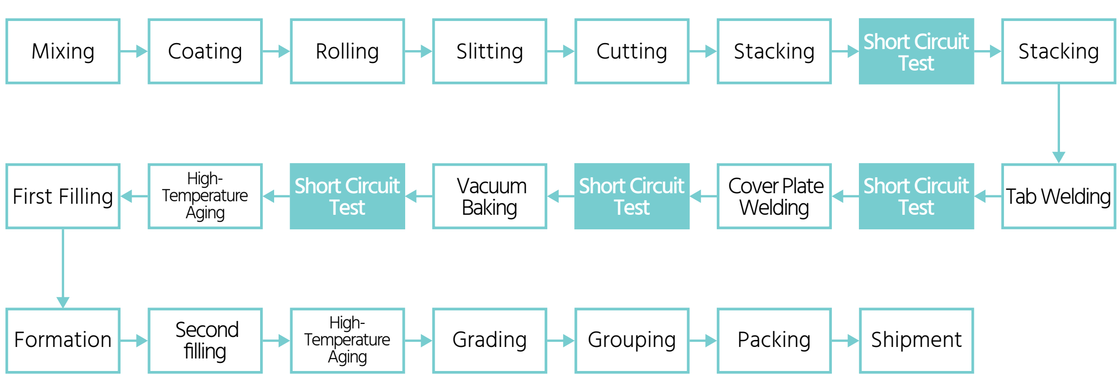


Schematic diagram of 5-channel demagnetization

Secondly, during the slitting process, in addition to strictly controlling the service life of the slitting tool, an ultrasonic dust removal device is set up on the slitting surface to remove dust and metal particles generated by the slitting, preventing them from entering the interior of the battery cell.

In addition, the stacking process adopts a CCD positioning device with an accuracy of ≤0.2mm to strictly control the wrapping dimensions of the stacked pieces. At the same time, a hot-pressing process of glue-coated diaphragm is employed to set the shape of the core after stacking, avoiding the insulating hazard caused by the displacement of the pole piece.

Furthermore, the manufacturing process includes four HIPOT tests in the assembly of the battery cell, which fundamentally eliminates the risk of internal micro-short circuits. We also maintain a comprehensive quality tracking system throughout the entire production process, from cell production to system integration, ensuring that quality is consistently monitored and controlled.



Aluminum casing battery cell manufacturing process

3.1.2 Passive Safety Design

Passive safety design of lithium-ion batteries refers to a series of design measures to protect the battery system as well as reduce the risk of accidents and losses in the event of system failure. This mainly involves preventing the spread of thermal runaways, implementing pressure release mechanisms, and incorporating isolation design.

First, thermal runaway heat spread is a major risk for lithium-ion batteries. Under abnormal conditions such as short circuits, high temperatures, or overpressure, thermal runaway may be triggered, causing the battery to heat up, smoke, catch fire, and even spread to neighboring cells. To prevent this situation, thermal runaway protection measures and thermal insulation materials are commonly used in lithium-ion battery design.

In extreme cases, if rapid heat spread is not contained in time, the loss of control of a single cell will spread to the entire energy storage system, resulting in substantial economic losses and potentially endangering personnel. By setting up nano insulation boards between the cells, high temperatures and flames can be efficiently blocked. In this way, the thermal runaway will not spread to neighboring cells. This helps maintain the safe operation of the whole energy storage system. The nano insulation boards we used offer the following advantages:

- **Outstanding Thermal Insulation Performance**

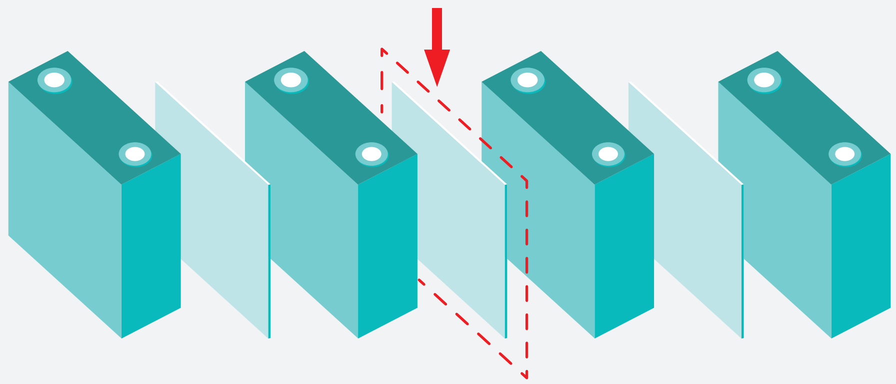
  Nano powder with a light-blocking component, produced via CVD (Chemical Vapor Deposition), effectively blocks heat transfer. The thermal conductivity of the nano insulation board remains below 0.036w/m-k at 800°C, which surpasses the performance of aerogel felt.

- **Extremely Low Density**

  Compared with traditional insulation materials, nano insulation boards have a lower density and are lighter in weight.

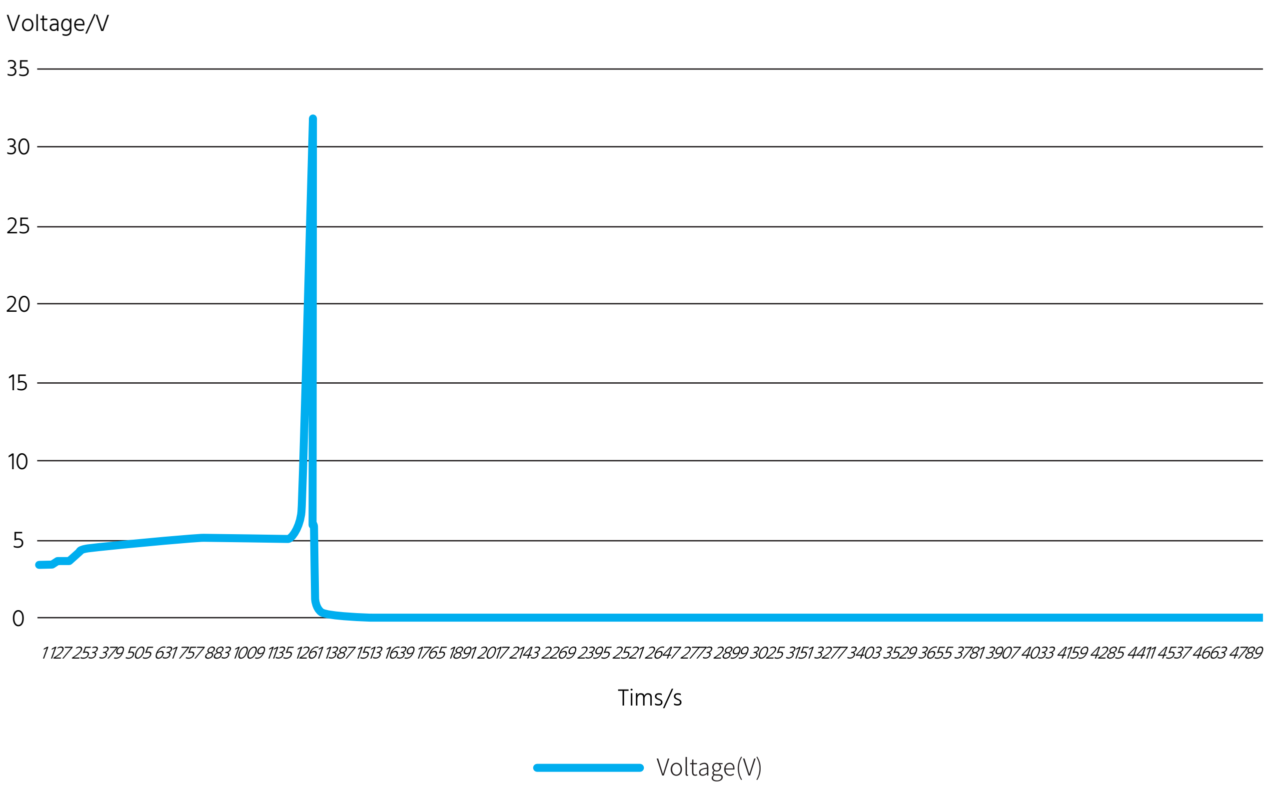
- **Stable Chemical Properties**

  Energy storage devices are required to adapt to various complex environments, such as high temperatures, extreme cold, as well as high salt and humidity conditions. Nano insulation mats have excellent temperature resistance and hydrophobicity. Their service life far exceeds the design life of energy storage products, providing long-term and stable protection for energy storage systems.

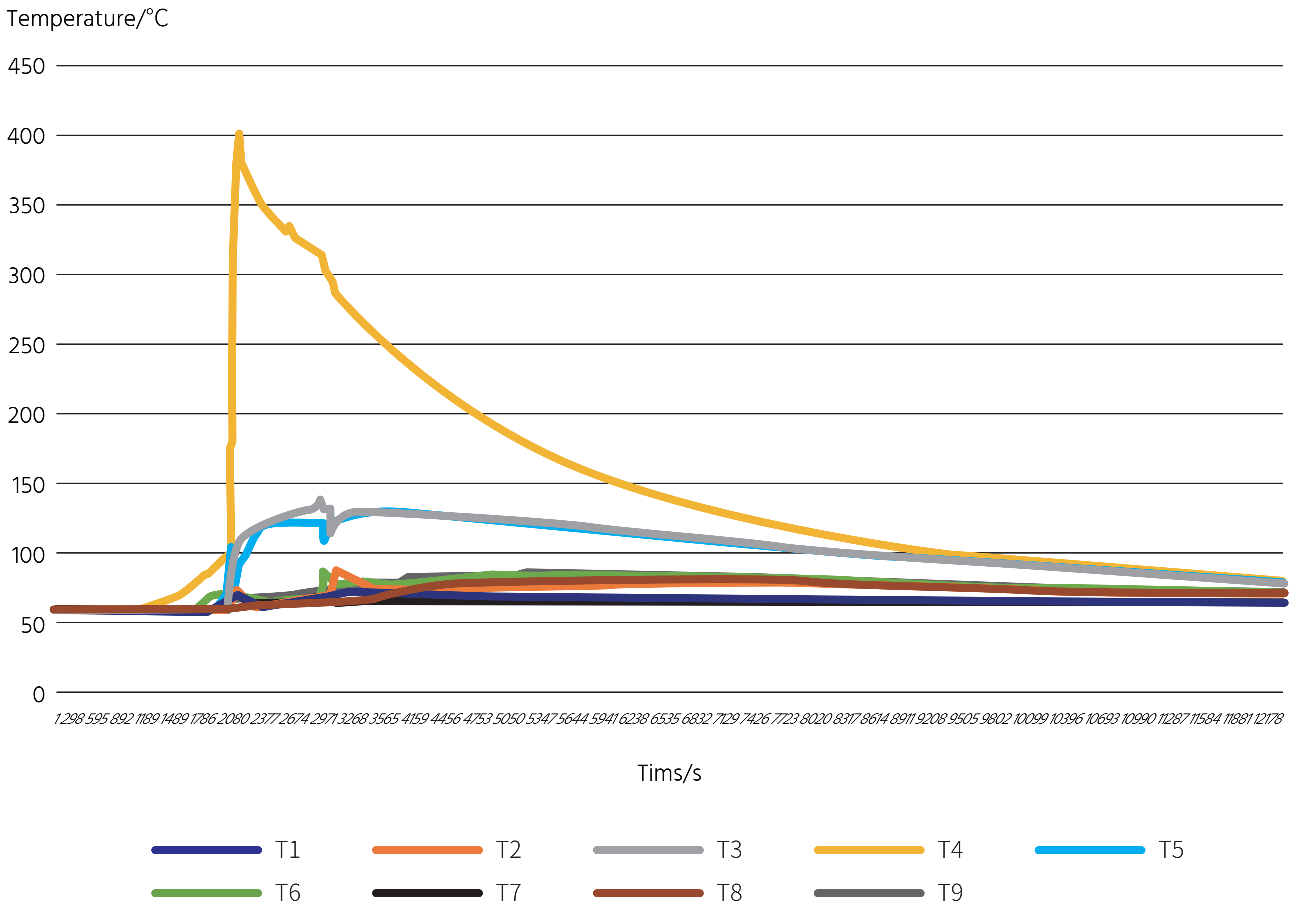


Nano insulation boards

In our thermal runaway heat spreading test, the test cell was charged with a nominal current of 157A until the thermal runaway condition was triggered. Data was continuously recorded until the thermal runaway cell released all its energy. Upon completion of the test, no thermal spreading was observed in the battery module, and the battery did not catch fire or explode.



Voltage profile



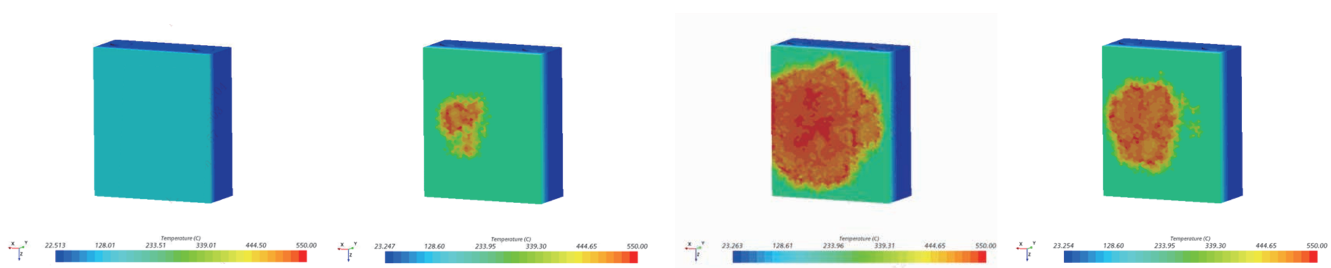
Temperature profile

As shown in the diagram, T1 to T9 represent the temperature schematic of different areas within the battery module when a single battery module undergoes thermal runaway. T4 corresponds to the temperature of the battery cell during thermal runaway. During thermal runaway, the temperature of the battery cell rises rapidly, and after the energy is released, the temperature of the battery cell decreases slowly.

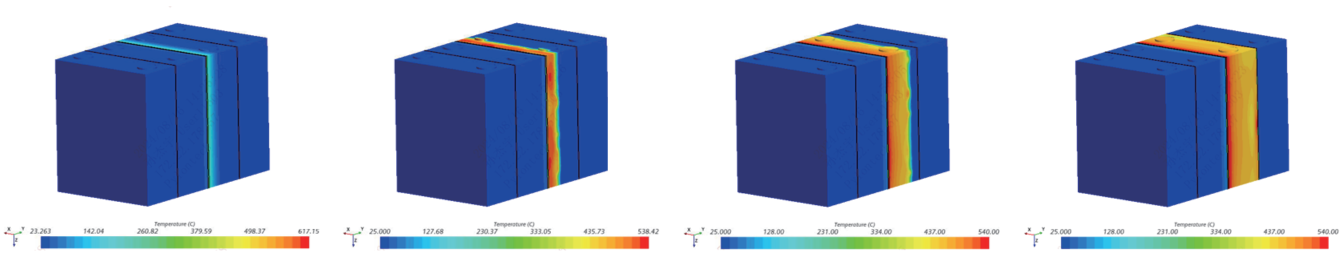
Secondly, to prevent the battery from a potential explosion after thermal runaway, lithium-ion battery designs also adopt pressure release technology. When the internal temperature rises abnormally and pressure increases, the holes on the battery shell will release the pressure automatically. This mechanism helps prevent damage to the battery system from explosion.

In addition, for lithium-ion battery systems, isolation design serves as an effective passive safety strategy. By dividing the system into multiple relatively independent units for cooperative use, any failure will affect only one or a few units, without compromising the stability of the whole system.

To further optimize passive safety technologies, models for heat spreading simulation, hot gas coupling, and heat spreading inhibition of Li-FePO4 batteries are established (as shown in the following figure). These models enable an in-depth analysis of the mechanisms behind thermal runaway heat spreading, the development of reliable inhibition measures, as well as the optimization of thermal isolation and fireproofing materials. The goal is to enhance heat spreading control and energy flow inhibition technologies within the module system, aiming for 100% heat spreading-free modules.



Schematic diagram of the evolution of thermal runaway spreading of the battery cell



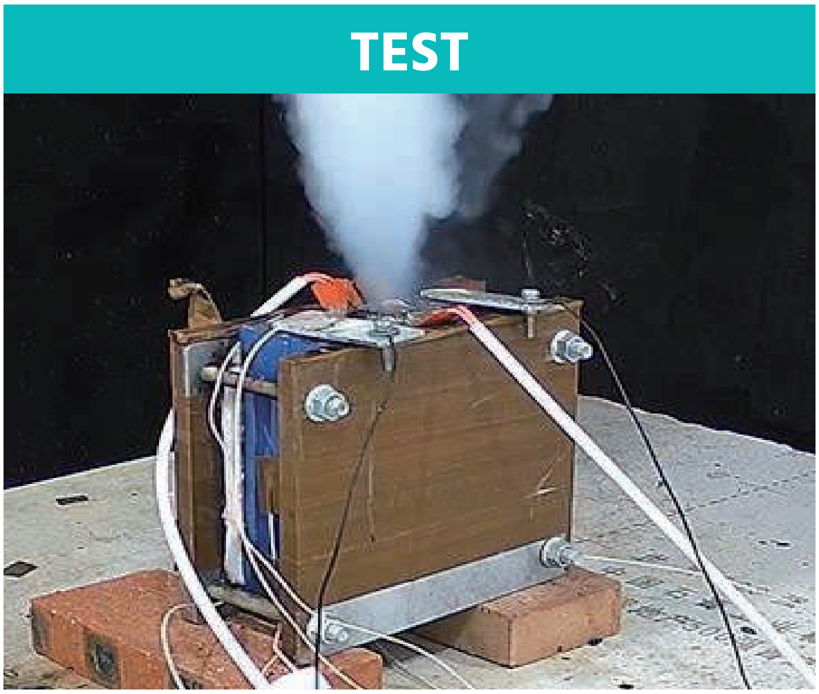
Schematic diagram of the evolution of thermal runaway spreading of the module

3.1.3 High Standard Safety Performance of Battery

In addition to strictly controlling the safety of lithium-ion batteries from cell production to system integration, Pylontech actively engages in rigorous international and domestic testing. It is one of the most qualified energy storage manufacturers with its core products certified by international standards such as IEC, UL, and JIS, as well as the national standards including China's GB/T 36276, GB/T 34131, etc. These certifications ensure the safety and reliability of our products.

Generally, lithium-ion cells undergo thermal runaway when heated to above 200 ° C. However, when tested at 175°C (10°C above the melting point of the diaphragm) and held for 4 hours, Pylontech's product did not experience thermal runaway. Until heated to 300 ° C (as shown in the following figure), thermal runaway occurred finally. This reflected the excellent quality and safety of Pylontech's lithium-ion leading position batteries and underscored its international leading position in battery safety performance.

To prevent the risk of cell fire, the battery system has passed the thermal runaway test in compliance with the UL9540A standard.



UL9540A: 2019 thermal runaway test

3.2 | Electrical Design

Although energy storage is generally considered safe, potential risks such as electric shock (electrocution), operational faults, and electrical fires can pose significant threats and compromise the reliability and safety of energy storage systems. Therefore, improving the safety of commercial and industrial storage products is an important goal in electrical design. The following sections will discuss in detail how to enhance the safety of electrical design.

3.2.1 Electric Shock Risk Prevention

Considering the safety risks posed by electric shock, it is essential to implement layers of protection to ensure personal safety. The main aspects of prevention include:

Basic Protection

Basic insulation is usually achieved by insulating materials, baffles and enclosures.

Fault Protection

Ensuring safety through reliable earthing.

Operating and Use Conditions

Providing protection through instruction and training for general and authorized personnel and requiring the use of safety equipment during maintenance.

Reinforcement Measures

Strengthening precautionary measures, focusing on detailed prevention actions.

1 Automatic Disconnection of Power Supply

RCD (Residual Current Device) or zero sequence transformer is implemented in the incoming circuit for protection. If the residual current exceeds the limit or the transformer current is non-zero, the system will promptly send abnormal information, alerting the customer to carry out maintenance.

2 Insulation Resistance Monitoring

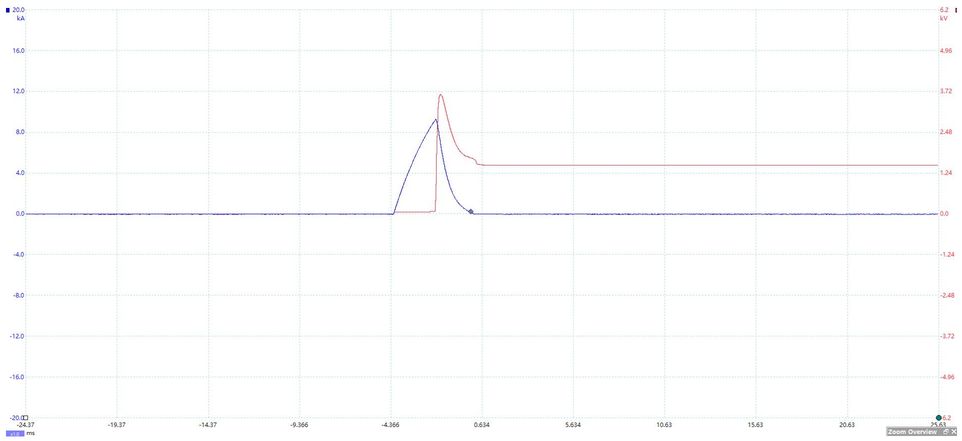
In the whole life cycle, insulation resistance is monitored by an on-line inspection system. The system will alert the customer and shut down if insulation anomalies are detected.

3 Arc Flash Protection

According to OSHA federal regulations, NFPA 70E, IEEE 1584, and AS 5139, arc flash hazards are calculated for each charged working position in the whole power system, determining the injury/risk category, confirming the protection level, and making the arc flash protection boundaries. Arc flash energy is reduced by incorporating overcurrent protection devices within the battery module, control module, and inverter.

Arc-flash Energy and Protection Level of Individual Battery Pack

The fusing characteristics captured by the oscilloscope are shown below:



U=1508VDC

1=15.09KA

T=3.15ms

I_p=9.255KA

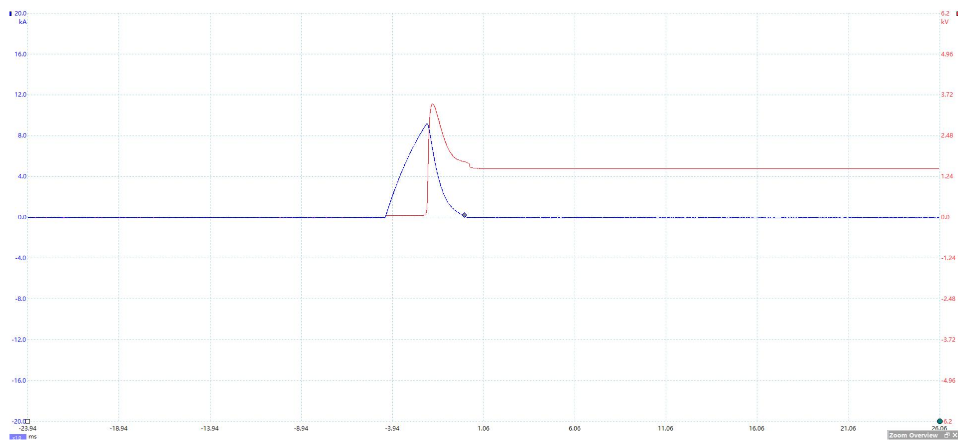
U_p=3.626KV

$I^2t_{pre\text{-}arcing}$=76.01KA²S

$I^22t_{operation}$=111.4KA²S

$T_{pre\text{-}arcing}$=2.263ms

$T_{operation}$=4.378ms



U=1508VDC

1=15.09KA

T=3.15ms

I_p=9.158KA

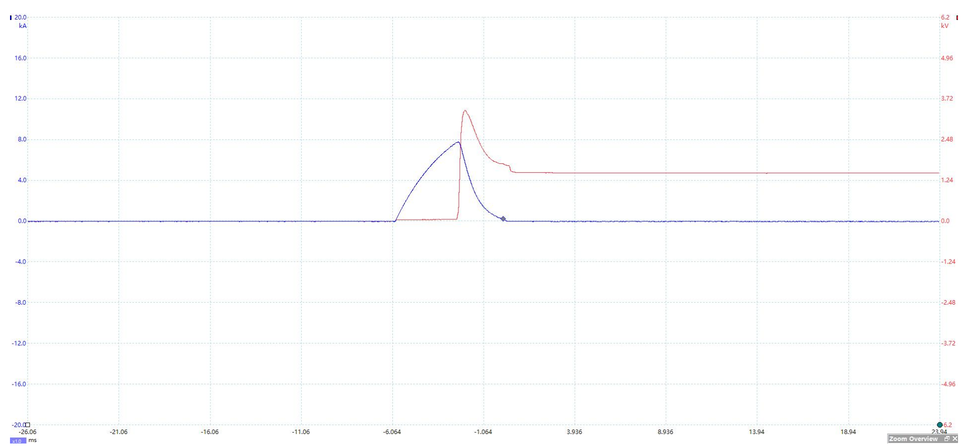
U_p=3.444KV

$I^2t_{pre\text{-}arcing}$=71.73KA²S

$I^22t_{operation}$=112.0KA²S

$T_{pre\text{-}arcing}$=2.210ms

$T_{operation}$=4.487ms



U=1508VDC

1=15.09KA

T=3.10ms

I_p=7.790KA

U_p=3.369KV

$I^2t_{pre\text{-}arcing}$=87.0KA²S

$I^22t_{operation}$=122.4KA²S

$T_{pre\text{-}arcing}$=3.366ms

$T_{operation}$=6.103ms

Fuse upper and lower matching test

The PACK of M7 has an internal fuse, so the arc flash energy without fuse is not considered, and the arc flash energy of a single PACK is calculated directly, according to the arc flash energy calculation formula:

$$I_{Em}=0.01 \times V_{sys} \times I_{arc} \times (T_{arc}/D^2) \times MF$$

The arc flash energy is Em=0.079 cal/cm^2. At this energy level, the PPE (Personal Protective Equipment) level is 1. Since the energy value is less than the acceptable expected value of 1.2 cal/cm^2, the arc flash risk assessment classifies the energy consequence level as Insignificant.

Arc flash energy of a battery string

The arc flash energy is Em = 0.13 cal/cm^2. This value is also below the expected acceptable energy level of 1.2 cal/cm^2, resulting in an arc flash risk assessment energy consequence level of Insignificant.

Level	Level Arc Flash Energy	PPE Level	Consequence Level
Single battery	0.079cal/cm^2	1	Insignificant
Single string	0.13cal/cm^2	1	Insignificant

Step 1

Collection of electrical information: short-circuit calculation data of the equipment to be evaluated under various working conditions; Relay protection characteristics and single-line diagrams of the system required for arc-flash analysis

Step 2

Short-circuit calculations: short-circuit calculations for each operating condition of the system to obtain the short-circuit current Ibf (A)

Step 3

Determine the arc flash current: according to NFPA 70E 2021, DC system arc flash current Iarc=0.5 Ibf (A)

Step 4

Determine the arc time Tarc (s)

Step 5

Determine the incident energy IEm (cal/cm2)

Step 6

Determine the injury / risk category, determine the level of protection (PPE level)

Step 7

Determine the arc flash protection boundary AFB (cm)

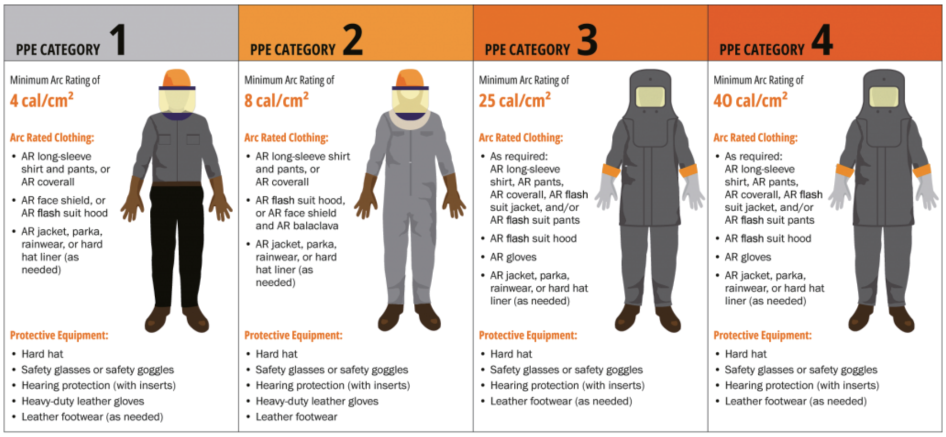
Step 8

Arc flash injury assessment filed

Arc flash assessment procedure

According to the requirements of the IEEE 1584-2018 standard, if an arc flash occurs when the human body is at a certain distance from a device and the heat applied to the surface of the skin is 1.2 cal/cm^2 (second-degree burn criterion, 1cal = 4.2J), then this distance is considered to be the arc flash protection distance.

To operate electrical equipment within this distance, suitable personal protective equipment must be fitted. According to NFPA 70E on the classification of arc flash protection level, before the arc flash protection, field operators need to be equipped with a complete set of safety tools and clothing. Arc flash protection can be designed to achieve level 1 or lower (as shown below), allowing field operators to wear basic protective equipment.

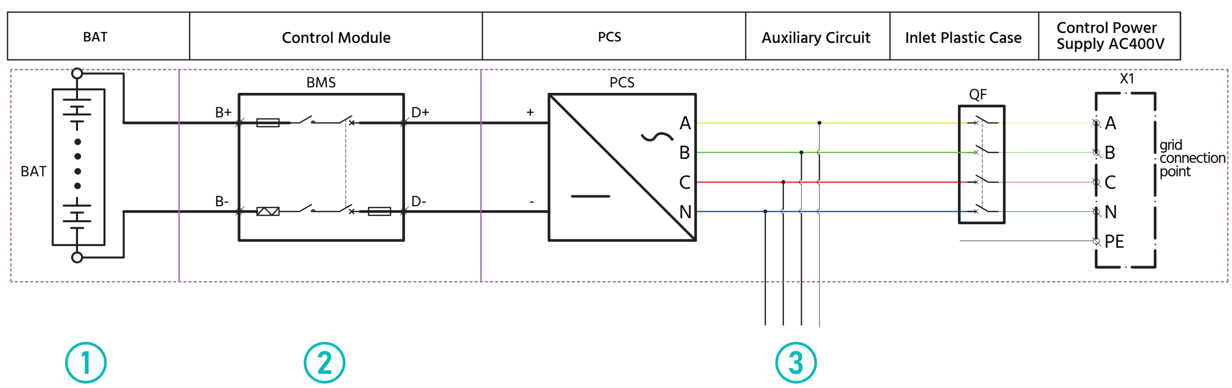


Arc flash protection level (National Fire Protection Association, NFPA)

3.2.2 Electrical Operation Fault Prevention

To cope with various faults in electrical operation, we usually adopt multiple protection measures, including a combination of hardware and software, active shutdown, rapid isolation, and other measures to achieve comprehensive protection.

- At the battery module level, dual isolation is formed by primary BMS and fuse.
- At the battery string level, active protection is achieved by the secondary BMS and contactors, and passive protection is ensured by fuses, circuit breakers, and disconnect switches. This approach achieves comprehensive protection from small to large currents.
- At the system level, passive isolation is achieved by circuit breakers, disconnect switches and fuses, combined with inverters and tertiary/quaternary BMS for comprehensive hardware and software protection. In addition, using fuses at different levels and locations provides graded protection against short-circuit faults, enabling rapid response and preventing fault propagation.



Primary side schematic diagram

Notes: Phase 1: Battery   Phase 2: Control module   Phase 3: AC side

When an overload or short circuit occurs in Phase 1, the protection element-fuse is activated, and Phase 2 and Phase 3 are protected from damage.

When an overload or short-circuit occurs in Phase 2, the protective elements circuit breakers and fuses are activated. This prevents damage to Phase 1 and Phase 3.

When an overload or short circuit occurs in Phase 3, the protective elements, including circuit breakers, isolating switches, and fuses, are activated. This ensures that Phase 2 and Phase 1 are protected from damage.

Short Circuit Protection Design

When a short circuit occurs in the battery system, it can be cut off in time to avoid the spread of the fault.

- ### Single String Battery System Short

  Circuit current: Imax = 113.61kA

  The maximum short-circuit current of 12 strings of DC convergence: Imax =163.32kA

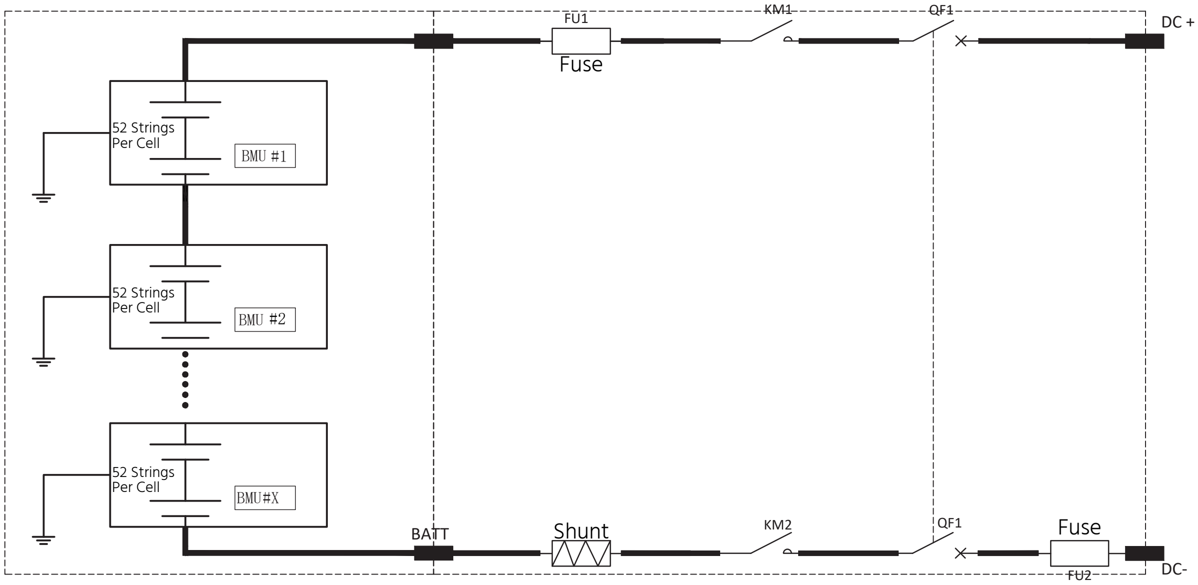
- ### Short-circuit Protection Design

  Based on the above calculation results, the adoption of the fast fuse can achieve ms-level short-circuit fault protection.

  The battery module adopts a fuse, near the total negative, as shown in the figure below.

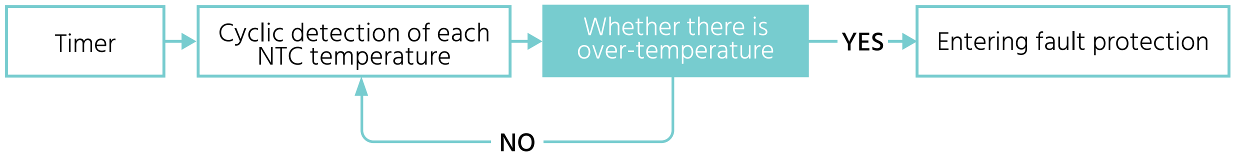
  The control module adopts 2 fuses, respectively near B+ and D-, as shown in the following figure.

  The confluence side optionally adopts 1 fuse at the positive pole.



Short-circuit prdduction design

At the same time, the temperature sensing probes are installed in the key connection parts of the energy storage system, which can effectively detect the overload situation. These probes can also quickly identify temperature anomalies caused by poor contact at each connection point and abnormal connection terminals. By comparing the feedback temperature values with set thresholds, faults can be accurately and swiftly detected. This allows for timely disconnection of the internal circuit to prevent heat spread.



Electrical terminal over-temperature protection mechanism

3.2.3 Electrical Fire Risk Prevention

In response to electrical fire risks, protection focuses on preventing fires before starting and managing them when they occur.

- Effective measures are taken to prevent fires before starting and reduce the spread of fire when they occur, such as spatial isolation of electrical components, positioning electrical parts away from combustible materials, good ventilation, and proper contact of connection points, as well as the rational selection of electrical components and wires, etc.
- In case of a fire, the spatial isolation of electrical components effectively prevents the spread of internal fire and reduces the influence of external fire on electrical components. The installation of electrical components far away from combustible materials reduces the risk of ignition. Electrical components made of plastic must meet the fire-retardant rating of UL94 V0. The flame-retardant rating of plastics is divided into HB, V2, V1, and V0. V0 is the most stringent. Even if a fire occurs, it can be extinguished quickly by relying on the performance of the plastic material itself.

The following points describe the flame-retardant ratings (from HB, V-2, V-1 to V-0 in ascending order):

HB

The lowest flame-retardant rating in the UL94 standard. It requires a burning rate of less than 40 mm per minute for samples that are 3 to 13 mm thick, less than 70 mm per minute for samples less than 3 mm thick, or extinguishing before reaching 100 mm.

V-2

The Flame must extinguish within 30 seconds after two 10-second burn tests. The flame could ignite medicated cotton 30cm below.

V-1

The Flame must extinguish within 30 seconds after two 10-second burn tests. The flame could not ignite medicated cotton 30cm below.

V-0

The Flame must extinguish within 10 seconds after two 10-second burn tests. No burning material should fall off.

3.3 | System Integration Design

Pylontech commercial and industrial storage products, in addition to the intrinsic safety of the battery cell, and electrical safety, will also consider all other aspects of the product's safety performance, such as structural safety, fire safety, explosion proof and relief, fire-resistant safety, as well as software strategy control.

3.3.1 Installation Design

Compliant power connection cables will be included with the battery, and the battery's external bracket assembly will keep the battery stable once installed. Components such as the wiring cables and racks are designed to be easy to install, avoiding dangerous accidents caused by mishandling.

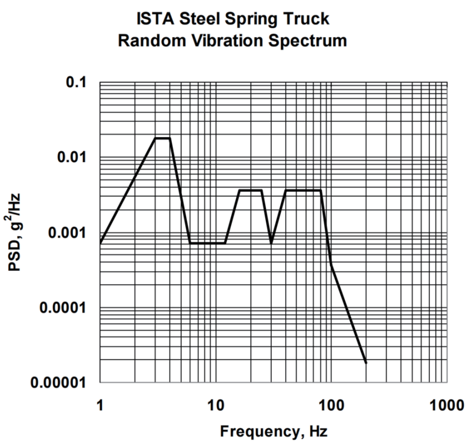
The whole battery has passed drop tests such as IEC62619, UL1973, etc. This ensures that the shell will not be broken, the cells will not be damaged, the BMS will function normally, and the battery will still be able to be used normally after a drop or a collision.

For outdoor cabinets or containerized products, the structural strength of the cabinet or box will be simulated or tested according to ISTA-3E transport vibration standards. The test standards are as follows:

> **The following breakpoints shall be programmed into the vibration controller to produce the acceleration versus frequency profile(spectrum) below with an overall Grms level of 0.54. The theoretical stroke required to run this vibration profle is 1.777 in (45.13mm) peak to peak.**

Frequency (Hz)	PSD Level, g^2/Hz
1.0	0.00072
3.0	0.018
4.0	0.018
6.0	0.00072
12.0	0.00072
16.0	0.0036
25.0	0.0036
30.0	0.00072
40.0	0.0036
80.0	0.0036
100.0	0.00036
200.0	0.000018

ISTA-3E transport vibration standard (National Fire Protection Association, NFPA)



Calculating Test Time

Estimate the anticipated total distance of the ground shipment the packaged-product may encounter during distribution to determine a test time from the following formulas:

ISTA-3E transport vibration standard
(National Fire Protection Association, NFPA)

Test Time duration in minutes = (Transport Miles) ÷5. Maximum test time 240 minutes

or

Test Time duration in minutes = (Transport Kilometers) ÷8. Maximum test time 240 minutes

A single battery module will not form a circuit. It must be used with BMS. The positive and negative power interfaces are distinguished to avoid positive and negative reversed. The circuit will not be formed when the relay is not switched on to ensure the safety of users.

3.3.2 Firefighting Strategy

Standards

The fire protection design of Pylontech products adheres to NFPA standards in North America, EN standards in Europe, and AS standards in Australia. The products meet the most stringent requirements of NFPA855 and have obtained UL9540A certification.

No.	NFPA Standards
1	NFPA 13, Standard for the Installation of Sprinkler Systems
2	NFPA 15, Standard for Water Spray Fixed Systems for Fire Protection
3	NFPA 68, Standard on Explosion Protection by Deflagration Venting
4	NFPA 69, Standard on Explosion Prevention Systems
5	NFPA 70, National Electrical Code
6	NFPA 72, National Fire Alarm and Signaling Code
7	NFPA 855, Standard for the Installation of Stationary Energy Storage Systems
8	NFPA 2001, Standard on Clean Agent Fire Extinguishing Systems
9	NFPA 2010, Standard for Fixed Aerosol Fire-Extinguishing Systems

No.	European Design Standards
1	EN 12845:2015+A1: 2019, Fixed firefighting systems - Automatic sprinkler systems - Design, installation and maintenance
2	EN 15004-1:2019, Fixed firefighting systems - Gas extinguishing systems - Part 1: Design, installation, and maintenance (ISO 14520-1:2015, modified)
3	EN 15276-2:2019, Fixed firefighting systems - Condensed aerosol extinguishing systems - Part 2: Design, installation and maintenance
4	CEN/TS 54-14:2018, Fire detection and fire alarm systems - Part 14: Guidelines for planning, design, installation, commissioning, use and maintenance
5	BS 5839-1:2017, Fire detection and fire alarm systems for buildings Part 1: Code of practice for design, installation, commissioning, and maintenance of systems in non-domestic premises
6	BS 5839-6: 2019+A1: 2020, Fire detection and fire alarm systems for buildings – Part 6: Code of practice for the design, installation, commissioning, and maintenance of fire detection and fire alarm systems in domestic premises
7	EN15276-2 2019 Fixed firefighting systems-Condensed aerosol extinguishing systems 2: Design, installation, and maintenance

No.	Australian Design Standards
1	AS 2118.1:2017, Automatic fire sprinkler systems, Part 1: General systems
2	AS 4214:2018 Amd 1:2019, Gaseous fire extinguishing systems
3	ISO 7240-14:2013, Fire detection and alarm systems — Part 14: Design, installation, commissioning and service of fire detection and fire alarm systems in and around buildings
4	AS 1670.1:2018, Fire detection, warning, control and intercom systems — System design, installation and commissioning, Part 1: Fire
5	AS 1670.5:2016, Fire detection, warning, control and intercom systems — System design, installation and commissioning, Part 5: Special hazards systems
6	AS/NZS 60079.29.2:2016, Explosive atmospheres, Part 29.2: Gas detectors - Selection, installation, use and maintenance of detectors for flammable gases and oxygen
7	AS/NZS 3000:2018 Electrical installation (Australian/New Zealand Wiring Rules)
8	AS 4487-2013 Condensed aerosol fire extinguishing systems — Requirements for system design, installation and commissioning and test methods for components
9	AS 1345-1995 Identification of the contents of pipes, conduits and ducts

Fire Protection System

The fire protection system mainly includes smoke detectors, temperature-sensing detectors, and sound-light alarms. If any detector is activated, the H2 combustible gas detectors will alarm. The sound-light alarm will emit alarm signals which will be output to the central control cabinet.

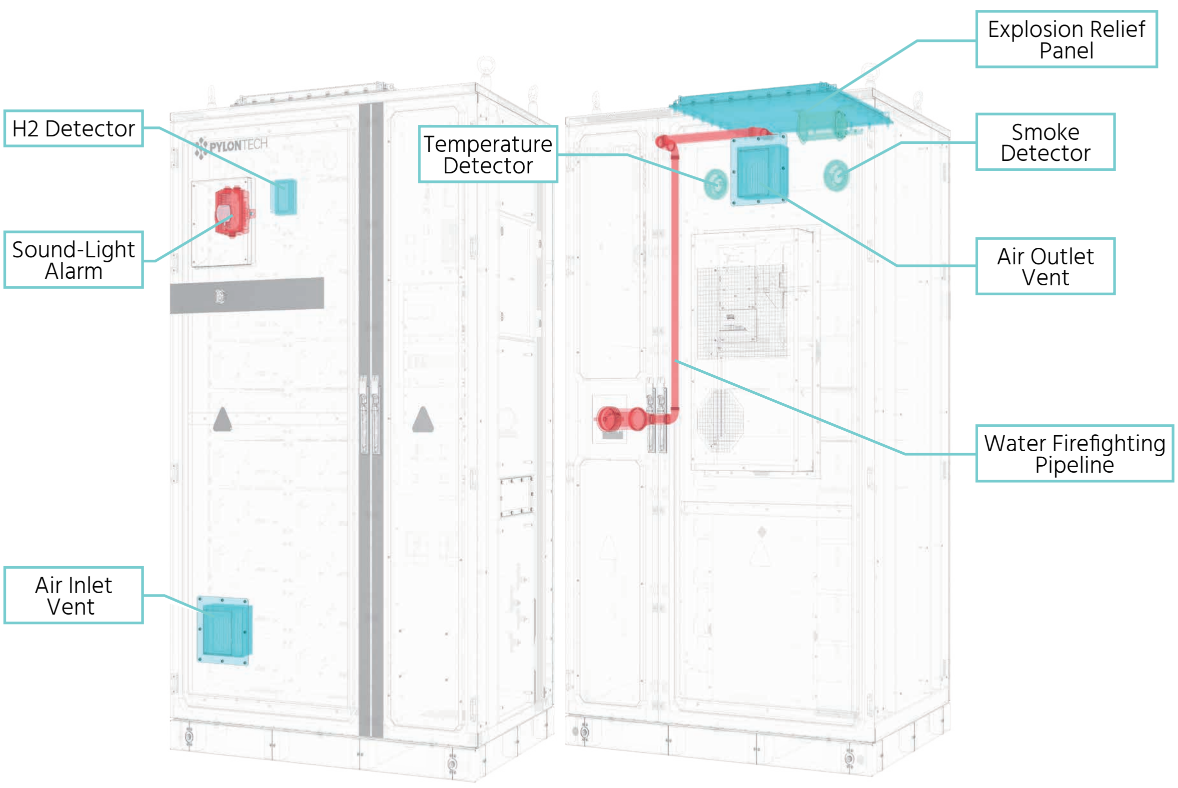
Working mechanism of the fire protection system

Aerosol Fire Extinguishing System

The aerosol fire extinguishing device is installed in the cabinet. When the battery thermal runaway or battery fire occurs and the temperature inside the cabinet reaches 93°C, the aerosol be activated will activate to extinguish the fire by total flooding. At the same time, a dry contact signal is sent to remind the relevant personnel that the gas extinguishing agent has been released.

Water Extinguishing

Pylontech adheres to NFPA13 requirements, installing a water firefighting pipeline, reserving temporary firefighting connections and joints in line with the local form of firefighting connections as well as selecting the pipe wall thickness and correct installation method of the nozzle, to ensure the safety of our customers.



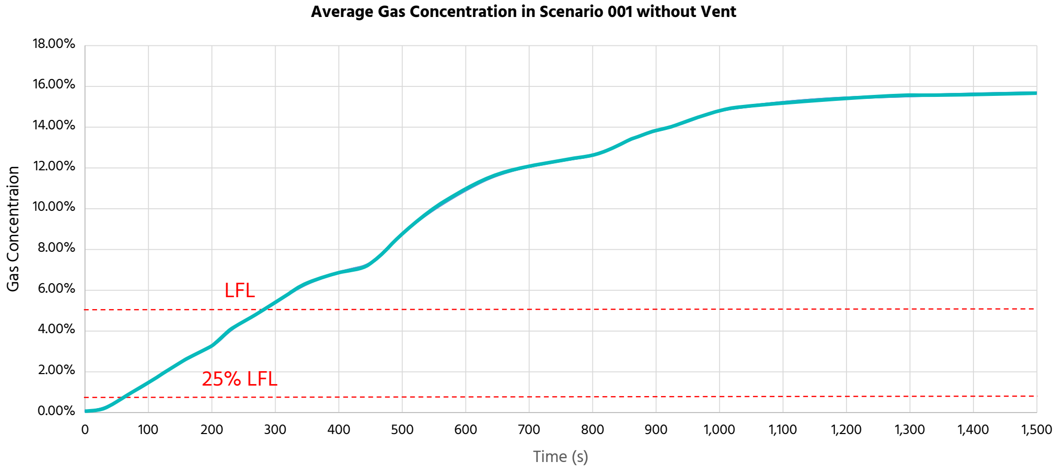
Firefighting system schematic diagram

Explosion Proof and Relief

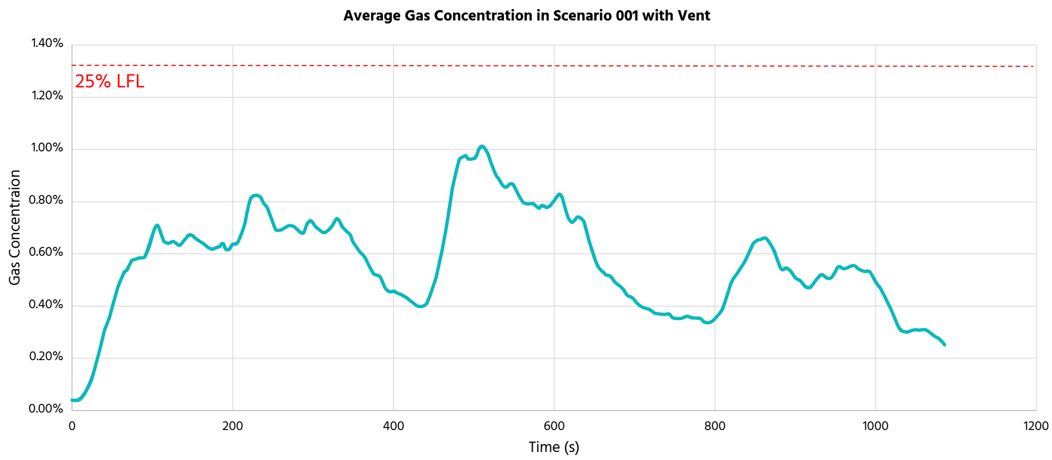
Combustible Gas Detection System

It mainly includes an H2 combustible gas detector, an air inlet device, and an air exhaust device. When the concentration of H2 combustible gas reaches 10% LEL, the air exhaust fan will be activated to ventilate the battery cabinet and prevent explosion-proof. At the same time, a dry contact signal is sent to the control cabinet.

When thermal runaway occurs, combustible gases are released, of which hydrogen content accounts for more than 50%. When Hydrogen concentration in the air exceeds a certain limit, an explosion will occur. This limit is called the lower explosive limit of explosion (LFL). According to NFPA855, the explosion-proof exhaust system should be able to control the concentration of combustible gases to less than 25% of LFL. The following is our design simulation:



Combustible gas concentration without an explosion-proof ventilation system



Combustible gas concentration with an explosion-proof ventilation system

The configuration of an explosion-proof ventilation system reduces the volume of combustible gases inside the cabinet.

Failure to switch on the fan will result in the accumulation of combustible gases in the cabinet exceeding 25% of the LEL, or even reaching the LEL.

With the fan on, the average concentration of combustible gases in the cabinet can be kept below 25% of the LFL.

Explosion Relief Device

The explosion relief is installed on the top of the cabinet. It is designed according to NFPA68 and does not affect the protection rating of the cabinet.

When thermal runaway occurs, the lithium-ion battery will be decomposed to produce a large amount of combustible gas, increasing air pressure inside the cabinet. When the air pressure increases to a certain value, the explosion relief panel will be passively released to relieve the air pressure and the combustible gas.

> **The above two explosion-proof and explosion-relief solutions are applied to prevent the risk of explosion of the cabinet due to excessive accumulation of combustible gases inside the cabinet. The selection of explosion-proof fans and explosion relief panels is calculated through simulation.**

3.3.3 Battery BMS Control and Protection Solutions

Pylontech's commercial and industrial storage battery products use Pylontech's self-developed cells, which are connected in series to form a battery module. With its own designed BMS, it can maximize the performance of the battery cells and avoid the abnormal state. Battery system design including the electrical design, BMS strategy design as well as the management of battery voltage, temperature, and current can effectively ensure the safety and reliability of battery systems in different operating conditions.

BMS Embedding

By combining active and passive fuses and other electrical components, the BMS of the battery sets protection values for voltage, current, and temperature. When the temperature of the battery cell exceeds 60°C, the battery will not be allowed to be charged and discharged. This strategy not only can cut off the circuit in time to reduce safety accidents from high temperatures but also ensure that the cell does not work under high temperatures, thereby preserving the decay of the performance of the battery cell and reducing the safety risk.

Cloud Monitoring

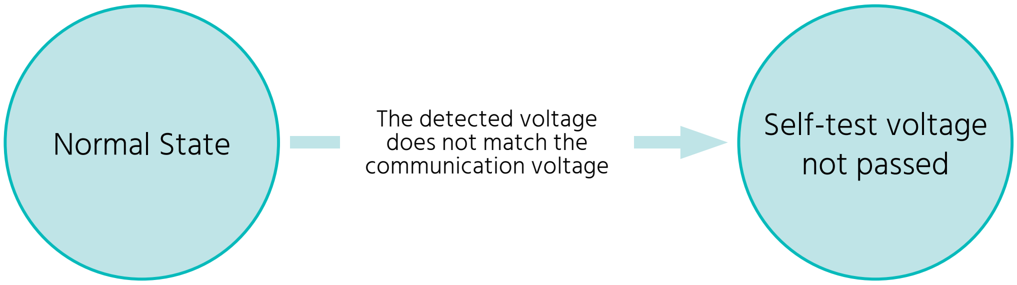
Users can view both current and historical information of the battery in real-time on the cloud platform. The information includes precise voltage, current, and temperature data down to the single-cell level. Based on the above data, the SOC and SOH of the battery cells can be calculated through Pylontech's self-developed algorithms. The platform displays the abnormal conditions and protection status, making it easy to identify battery problems. It effectively helps users monitor the battery's operating and safety status, thus reducing risks associated with battery deterioration.

Integration Compatibility

Pylontech’s products are compatible with several inverters, which adhere to Pylontech's protocols and BMS strategy. The system charges and discharges according to the current limit set by the battery, preventing dangerous accidents caused by over-voltage and under-voltage conditions.

Power-on Self-test Function

The system performs a self-test upon power on by comparing various parameters, such as system capacity, number of modules and system voltage, etc. For example, it compares the battery voltage (obtained by cascade communication) with the BAT terminal voltage (obtained by the detection). If they match, the self-test passes. Otherwise, it will report a fault and will not close the relay. This function can address the risks associated with disconnecting the cascade communication cable before powering on, incorrect insertion of the cascade communication cable, or improper connection of the battery power cable.



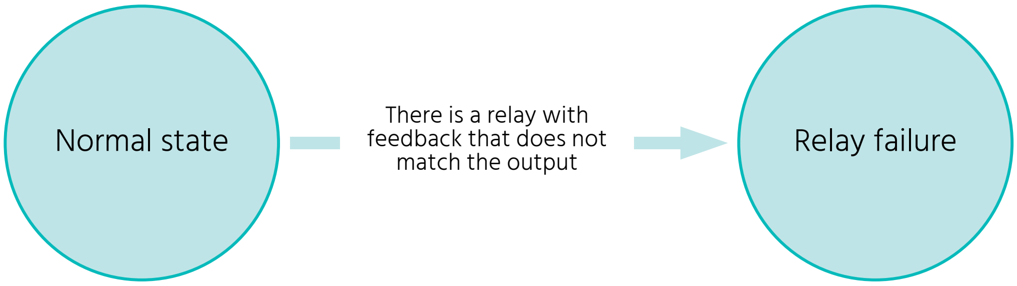
Power-on self-test function flowchart

System Protection Mode

When the battery system encounters conditions such as over-temperature, under-temperature, over-voltage, under-voltage, over-current, or communication interruption, it will activate the relay within the battery master control to disconnect the DC input and output terminals and report the fault. The relay is equipped with a dual protection mechanism, ensuring that a fault is reported even if the relay feedback signal fails.

- ### Relay Detection and Protection Function

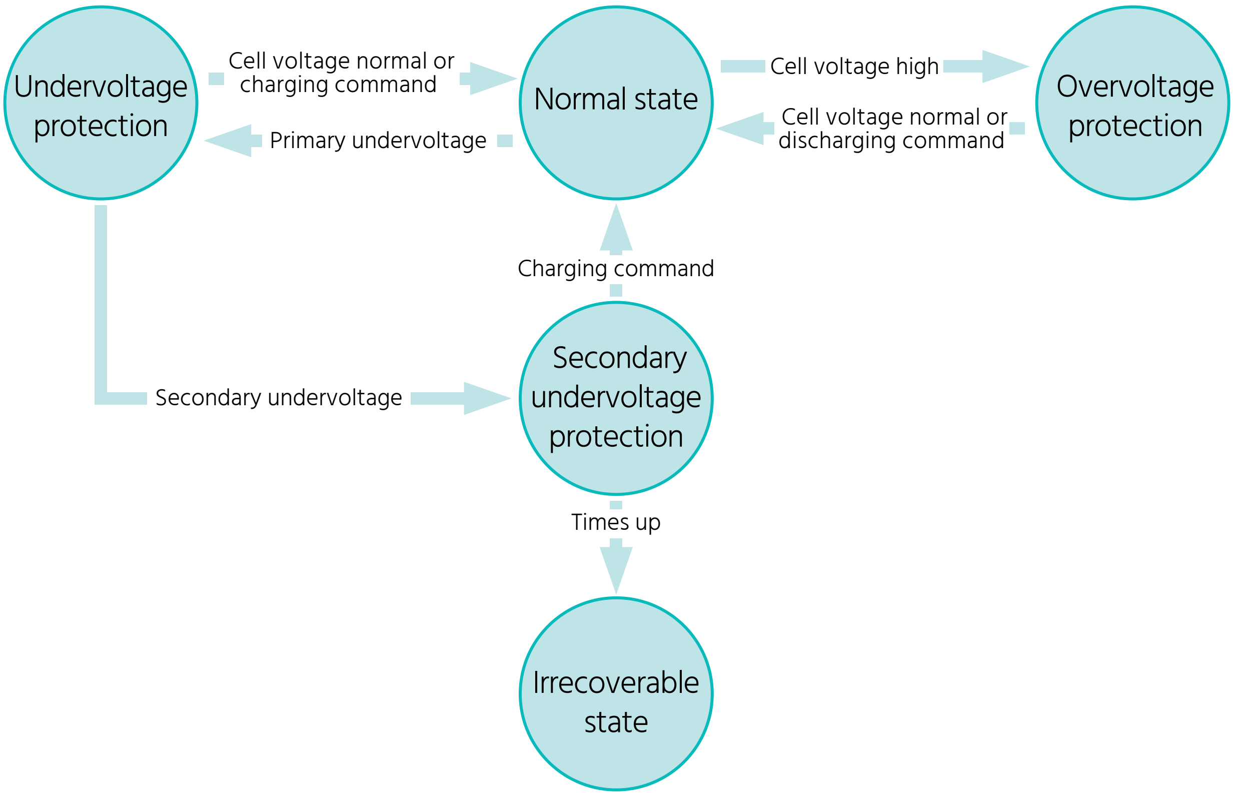
The system compares the enable and feedback state of the dual backup relays in real-time. If there is a fault, all relays will be disconnected, and the fault will be reported. This function can solve the risks of relay sticking, relay detecting wire failure, or loosening.



Relay detection and protection function flow chart

Voltage Protection Function

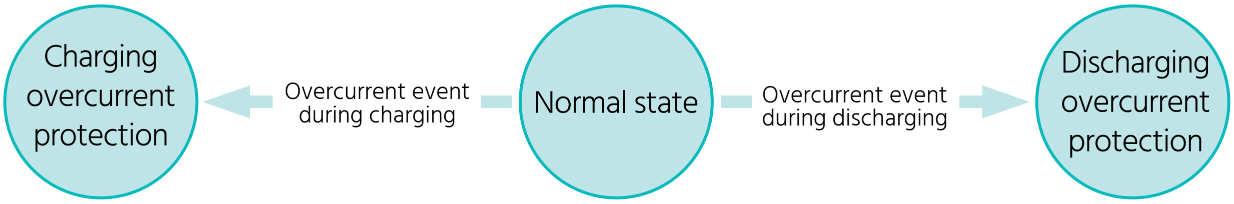
The system detects the voltage of the battery cells. If the over-voltage or under-voltage condition occurs, it will disconnect the relay to enter the protection state.



Voltage protection function flowchart

Current Protection Function

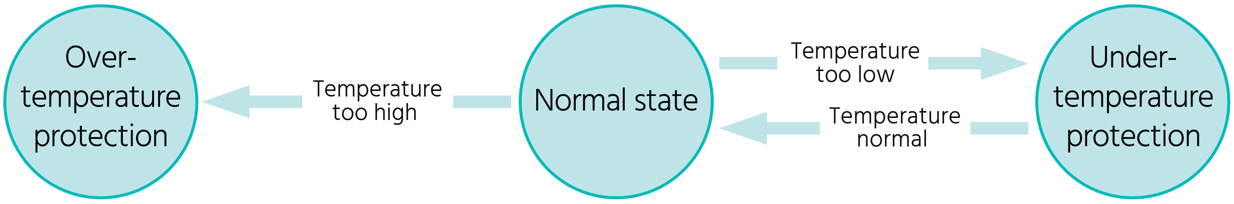
The system implements to detect the current. If there is an overcurrent or short circuit, it will disconnect the relay to enter the protection state. At the same time, the hardware is equipped with protection devices such as fuses or air openers.



Current protection function flowchart

Temperature Protection Function

The system detects the temperature of the electric cells. If there is charging or discharging under low or high-temperature conditions, it will disconnect the relay to enter the protection state.



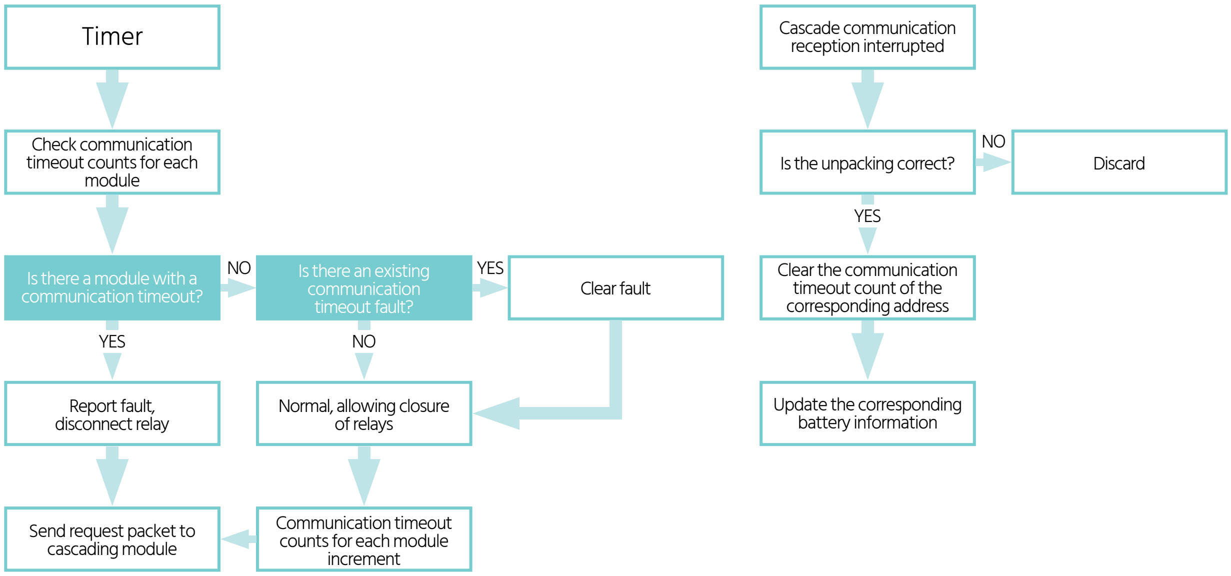
Temperature protection function flowchart

Current Limit Mode

In the case of high temperature, low temperature, high pressure, low pressure, etc., the system will provide an external current limit value, suggesting the external power supply to charge or discharge with a more reasonable current value, thereby enhancing the system's stability.

Cascade Communication Status Detection and Protection Function

The system can detect the communication status between the BMU and control module in real-time during operation. When the communication is unnormal, the system will disconnect the relay and report a fault. This function can solve the risk of disconnecting the cascade communication line during operation.



Cascade communication status detection function flowchart

3.3.4 Outdoor Cabinet and Container Safety Design

For commercial and industrial applications, Pylontech's outdoor cabinet and container products incorporate the following safety-oriented designs:

Structural Strength of Outdoor Cabinets and Containers

Structural strength simulations will be conducted for the outdoor cabinet. Environmental adaptability includes resistance to wind, snow loads, and earthquakes. In terms of transportation, the simulations include compliance with UN38.3 certification and support for battery transport. Transport vibration simulations, lifting simulations, and drop simulations are conducted according to ISTA-3E standards to ensure that no hazards occur during transportation and use. Pylontech performs these simulations based on stringent standards.

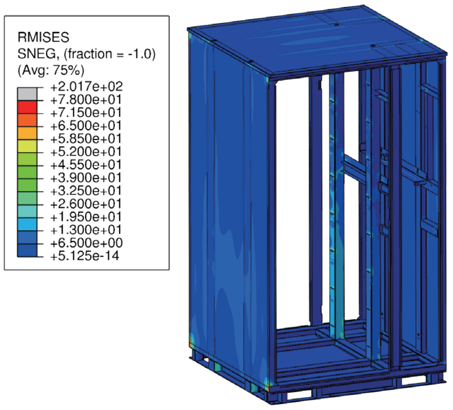
- **Introduction of selected steel:**

  The cabinet is made of high-quality SGCC (hot dipped galvanized steel sheet) material with a yield strength exceeding 300 MPa.

Simulation content	Reference standard
Wind Resistance	70m/s (Typhoon force 17 or above)
Snow load	150pounds/ft^2
Seismic	ASCE 7-16 (American Standard 2016 Load Specification)
Transport	ISTA-3E (International Standard for Transport Packaging)

Outdoor Cabinet and Container Fire Resistance Level

Outdoor cabinets and containers are designed for fire resistance accordingly, with the fire resistance capacity of containers above 1h and outdoor cabinets above 30 minutes.



Thermal Management of the Outdoor Cabinet and Container

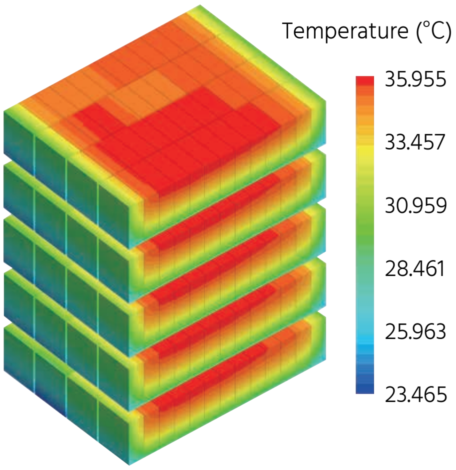
Thermal design for the outdoor cabinet and container involves thermal simulation and flow field simulation, along with prototype testing related to environmental reliability.

Outdoor cabinet thermal simulation

Through the design and selection of liquid cooling plate, pipeline and liquid cooler, it can be ensured that the temperature difference at the “center of the upper surface” of the cell in thermal management system is controlled at about 3℃.
The following figure shows the temperature of the battery cell under 0.5P continuous cycling condition in 25℃ environment, where

The maximum temperature at the ”center of the upper surface” of the cell in the system is 36.0°C.

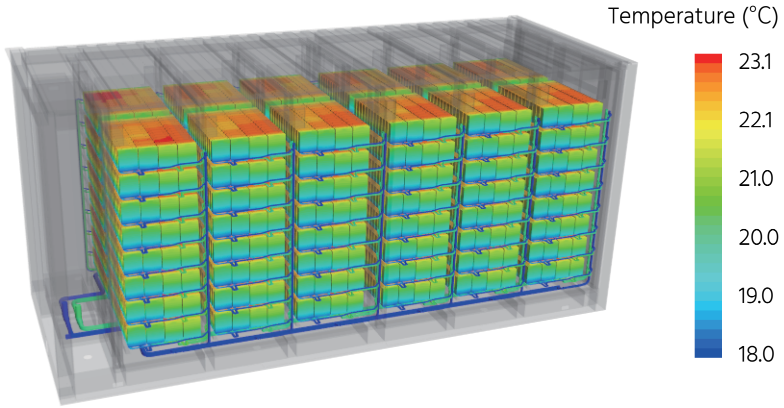
The maximum temperature difference at the “upper surface center” of the core in the system is 3.3°C.



Outdoor cabinet thermal management simulation

Container thermal simulation

In container applications, the maximum temperature difference at the "center of the upper surface" of the cells in the system can also be guaranteed to be: 3~5°C.



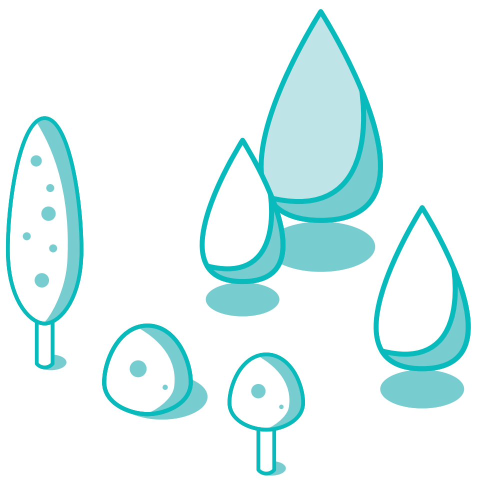
Container thermal management simulation

04

SUMMARY AND OUTLOOK

As renewable energy adoption accelerates, energy storage is essential for maximizing efficiency, guaranteeing availability and creating substantial value. Safety remains a critical focus in the development of these Therefore, Pylontech has implemented cutting-edge safety designs in battery cells, electrical components, and system integration to effectively manage and mitigate associated risks.

Guided by our vision to energize billions with smarter power, we are committed to advancing new standards in safety and collaborating with the most rigorous compliance partners. We aim toto drive the transformative benefits of green power across all sectors, paving the way for a secure, sustainable, and resilient energy future.



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