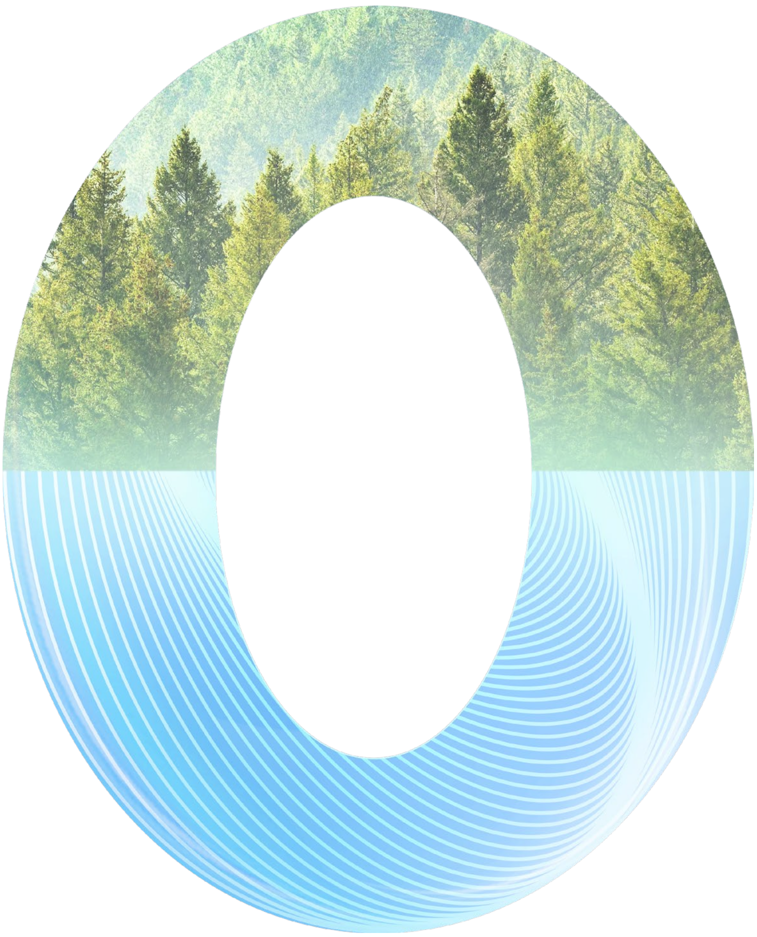
Data Center Lithium-ion Battery Safety Application

White Paper



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1. Executive Summary

Lithium-ion batteries (Li-ion) have emerged as a cornerstone of modern data centers due to their high energy density, long service life, compact footprint, and environmental advantages. As the demand for reliable and sustainable energy solutions grows, Li-ion technology is rapidly replacing traditional Lead-Acid batteries. The market for Li-ion batteries in data centers is forecasted to grow significantly, driven by trends such as renewable energy integration, energy storage, and cost optimization.

Despite their benefits, Li-ion batteries present unique safety challenges, particularly related to thermal runaway and fire risks. Industry incidents, such as the 2022 South Korea data center fire, highlight the critical need for comprehensive safety measures. Effective implementation requires careful consideration of battery selection, robust management systems, optimized environmental design, and full compliance with safety standards.

This white paper provides a technical analysis of Li-ion battery applications in data centers, emphasizing:

- **Comparative Advantages:** Longer lifecycle higher energy efficiency compared to Lead-Acid batteries.
- **Safety Considerations:** Key risks, such as thermal runaway, and mitigation strategies through advanced battery management systems (BMS).
- **Implementation Guidelines:** Best practices for Li-ion battery deployment, including room design, transportation, and maintenance.
- **Future Trends:** Emerging innovations, including solid-state batteries and predictive monitoring solutions, which aim to enhance safety and efficiency.

2. Introduction

2.1. The Role of Batteries in Data Centers

Batteries play an important role in data center operations, serving as both a backup power source and a means of energy storage. They ensure uninterrupted operation during power outages and facilitate energy efficiency by leveraging renewable sources and demand-side management strategies.

2.1.1. Backup Power Supply

The primary function of batteries in data centers is to ensure uninterrupted operation of critical infrastructure during power outages. In the event of mains supply failure, data centers rely on diesel generators and uninterruptible power supply (UPS) batteries to maintain continuous power delivery, thereby preventing disruptions to IT services.

Industry standards, such as the TIA-942-B-2017, specify backup time requirements for data centers based on their tier levels: Tier 1- Tier 4: 10 minutes @ end of battery life.

In practical scenarios, a backup duration of 15 minutes is commonly implemented to provide additional reliability.

2.1.2. Energy Storage for Operational Efficiency

The second critical application of batteries in data centers is energy storage, which has gained significant attention in recent years. Beginning in the second half of 2021, the Chinese government introduced policies aimed at promoting energy storage solutions in data centers. For example, on July 14, 2021, China's Ministry of Industry and Information Technology released the Three-Year Action Plan for New Data Center Development (2021-2023). This initiative supports the adoption of Li-ion batteries, hydrogen storage, and flywheel energy storage as diversified solutions for backup power and energy optimization.

These energy storage strategies aim to:

- Facilitate the efficient utilization of clean and renewable energy in modern data centers.
- Enhance the energy consumption structure to align with goals of carbon peaking and neutrality in the information and communications industry.

Moreover, energy storage systems contribute to economic efficiency by leveraging mechanisms such as peak shaving and capacity allocation, which help reduce operational costs and improve environmental sustainability through reduced carbon emissions.

2.2. Overview of Battery Technologies

2.2.1. Lead-Acid Battery

Lead-acid batteries are rechargeable energy storage systems with lead-based electrodes and acidic electrolytes. They operate by converting chemical energy to DC electrical energy and vice versa, enabling repeated charge and discharge cycles. These batteries have a specific energy of 33–42 Wh/kg [1][2], an energy density of 60–110 Wh/L [2], a power-to-weight ratio of 180 W/kg [3], and a charge/discharge efficiency of 50–95% [4]. Their low internal resistance supports high-current discharge, while deep-cycle designs are ideal for applications requiring regular discharges, such as photovoltaic systems, electric vehicles, and uninterruptible power supplies [5].

2.2.1. Li-Ion Battery

Li-ion batteries, first commercialized by SONY in 1991, are rechargeable systems that operate by shuttling lithium ions (Li^+) between positive and negative electrodes during charge and discharge cycles. Positive electrodes typically use lithium compounds such as $LiXCoO_2$, $LiXNiO_2$, or $LiXMnO_2$, while graphite serves as the common negative electrode. The electrolyte contains dissolved lithium salts like $LiPF_6$. These batteries are often referred to as "rocking chair batteries" due to the intercalation and de-intercalation of Li^+ between electrodes.

Lithium-ion batteries exhibit a specific energy of 100–265 Wh/kg [6][7], an energy density of 250–730 Wh/L [7], a power-to-weight ratio of 250–340 W/kg [6], and a charge/discharge efficiency of 80–90% [8]. Common cathode materials include lithium cobalt oxide, lithium manganese oxide, lithium nickel oxide, and lithium iron phosphate (LFP).

Among these, LFP batteries stand out for their cost-effectiveness, resource abundance, and balanced performance. They feature moderate working voltage, high discharge power, fast charging, long cycle life, and excellent thermal stability. Additionally, they align with environmental and safety requirements, making them a preferred choice for high-performance applications [9].

2.3. Growing Adoption Trends and Market Outlook

Currently, Lead-Acid batteries exhibit several disadvantages in large-scale energy storage applications, including limited capacity, substantial weight, significant space requirements, shorter lifespan, and higher maintenance demands. These factors result in a cycle cost disadvantage when compared to more advanced technologies.

In contrast, Li-ion batteries offer superior characteristics such as higher energy density, smaller footprint, and an extended life cycle, making them an optimal replacement for Lead-Acid batteries. Specifically, LFP batteries, which are based on mature technologies, present key advantages in terms of cost, safety, and cycle durability. As a result, LFP batteries are set to play a crucial role in energy storage applications within data centers.

According to recent market reports, the shipment of electrochemical cells from the top 10 manufacturers is projected to grow consistently from 2018 to 2025. Over this period, the market share of Li-ion batteries in data centers is expected to increase from 15% to 38.5%. Based on these growth trends, it is anticipated that within the next three to five years, Li-ion batteries will not only approach but may exceed the market share of Lead-Acid batteries. As such, the dominance of Li-ion batteries in the data center and energy storage markets is becoming a widely accepted consensus across the industry.

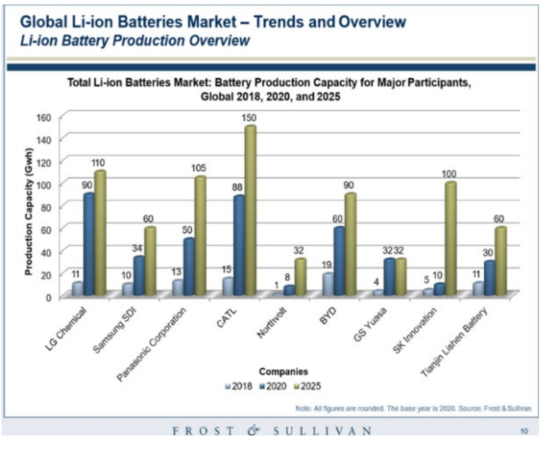


Figure 1 2018 - 2025 Cell Manufacturer Shipments

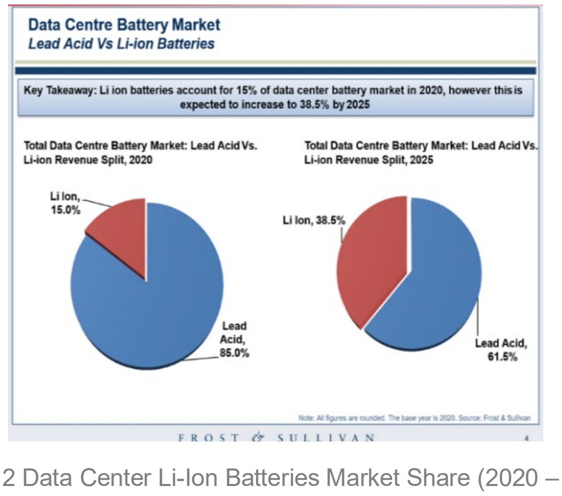


Figure 2 Data Center Li-Ion Batteries Market Share (2020 – 2025)

2.4. Importance of Safety and Sustainability

While Li-ion batteries provide significant advantages, they also pose unique safety challenges, particularly related to thermal runaway and fire risks. Addressing these challenges requires integrating advanced BMS, designing optimized environments, and adhering to strict safety standards. The drive toward sustainability further reinforces the adoption of Li-ion batteries, which contribute to carbon reduction and reduced environmental impact.

This paper explores the technical, safety, and operational considerations of Li-ion battery applications in data centers. It provides insights and best practices for deploying these advanced energy solutions safely and effectively.

3. Comparison of Li-ion and Lead-Acid Batteries

Traditional Lead-Acid batteries have served as the backbone of energy storage in data centers for decades. However, their limitations, such as a shorter lifecycle, larger footprint, and maintenance demands have prompted the shift to Li-ion alternatives. This section provides a comprehensive technical comparison between Li-ion and Lead Acid batteries.

3.1. Life Cycle

Li-ion batteries are known for their extended cycle life, which is a significant advantage in applications requiring long-term reliability.

Li-Ion Batteries:

- At 100% Depth of Discharge (DOD), Li-ion batteries can achieve up to 3,000 cycles.
- At 50% DOD, the cycle count can reach 6,000 cycles.

Lead-Acid Batteries:

- At 100% DOD, Lead-Acid batteries typically offer only 150 cycles.
- At 50% DOD, the cycle life increases to approximately 600 cycles, but these batteries often need frequent replacements, particularly in low-power grid scenarios.

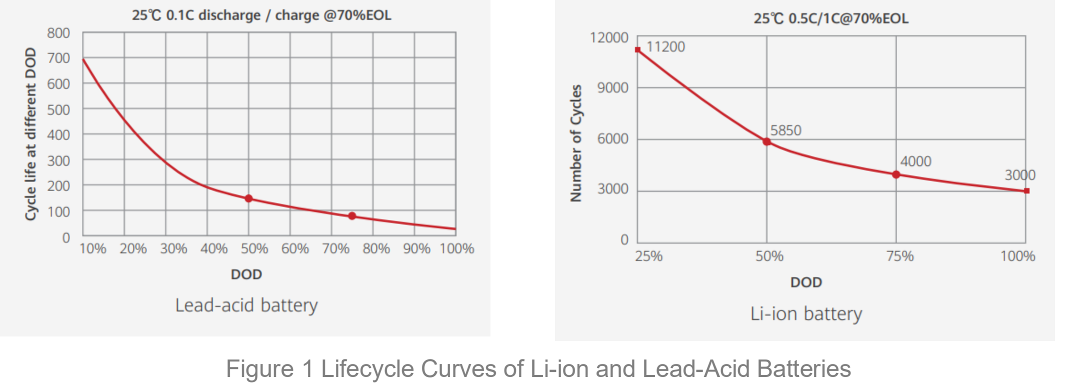


Figure 1 Lifecycle Curves of Li-ion and Lead-Acid Batteries

3.2. Discharge Rate and Capacity Loss

Li-ion batteries excel in applications requiring high-rate short-term discharges, which is crucial for data centers during peak power demand.

Li-Ion Batteries:

- They can maintain over 90% discharge efficiency even at high discharge rates. The capacity decreases gradually with increasing discharge rate.

Lead-Acid Batteries:

- While capable of high-rate discharge, the capacity drops rapidly as the discharge rate increases. This requires over-sizing of battery banks, adding to the capital investment.

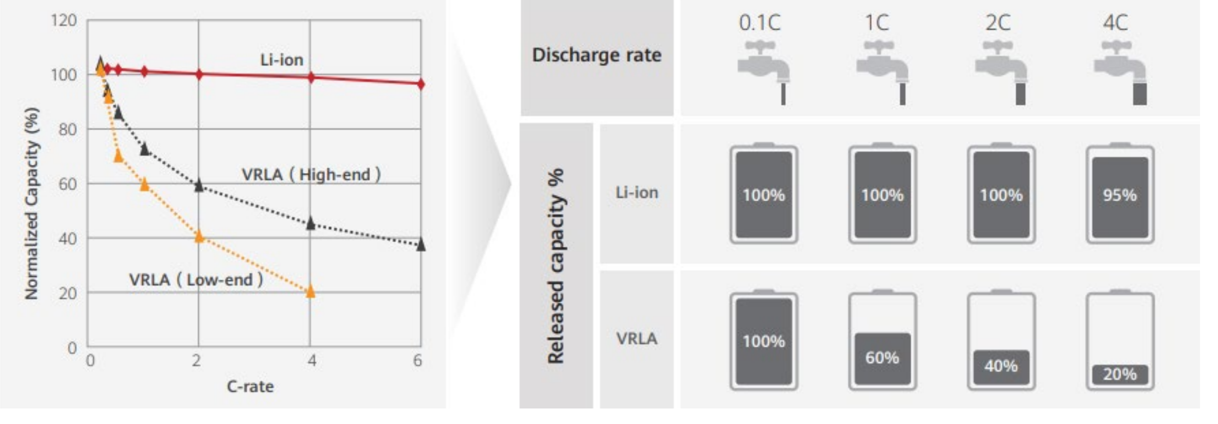


Figure 2 Discharge Curves of Li-ion Batteries and Lead-Acid Batteries at Different Rates

3.3. Footprint

Li-ion batteries significantly reduce the weight and size by approximately 70% compared to Lead-Acid batteries, making them more suitable for space-constrained environments.

Li-Ion Batteries:

- Weight-to-Energy Density Ratio: 100–150 Wh/kg
- Bulk Energy Density: 200–300 Wh/L

Lead-Acid Batteries:

- Weight-to-Energy Density Ratio: 30–50 Wh/kg
- Bulk Energy Density: 60–90 Wh/L

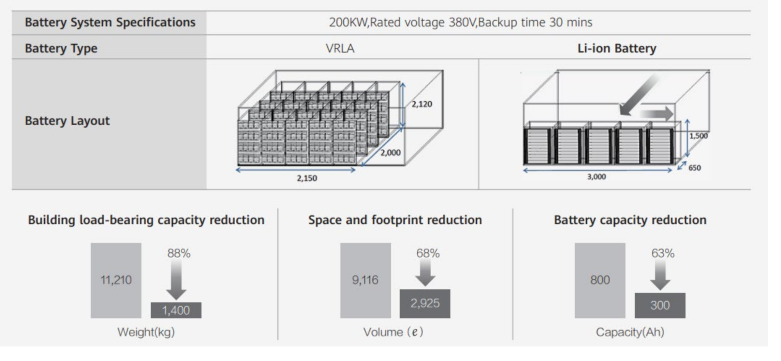


Figure 3 Comparison of the Footprint and Load-Bearing Capacity of Li-ion Batteries and Lead-Acid batteries with the same Backup Time

3.4. Environmental Benefits

Li-ion batteries are more environmentally friendly compared to Lead-Acid batteries, which contain hazardous materials.

- **Li-Ion Batteries:** Use lithium metal or lithium alloys for electrodes and organic electrolyte solutions, which do not contain heavy metals. Additionally, Li-ion batteries can undergo over 5,000 charge cycles, reducing waste generation and improving sustainability. Waste Li-ion batteries are also easier to dispose of, further minimizing environmental impact.
- **Lead-Acid Batteries:** Contain toxic heavy metals such as lead, cadmium, and mercury, along with acidic electrolytes, which pose risks to human health and the environment.

The following table summarizes key differences between Li-ion and Lead-Acid Batteries:

Table 1 Li-ion & Lead Acid Batteries Comparison Summary

Criteria	Li-ion Batteries	Lead-Acid Batteries
Lifecycle	- Up to 3,000 cycles at 100% DOD	- Only 150 cycles at 100% DOD
	- Up to 6,000 cycles at 50% DOD	- About 600 cycles at 50% DOD
Floating Charge Life	- Float charging at 25°C: service life > 10 years	- 3 to 7 years at 25°C under similar conditions
Discharge Rate	- Maintains over 90% efficiency at high discharge rates	- Capacity drops significantly at high discharge rates, requiring oversizing
Footprint	- Weight-to-Energy Density: 100–150 Wh/kg - Bulk Energy Density: 200–300 Wh/L	- Weight-to-Energy Density: 30–50 Wh/kg - Bulk Energy Density: 60–90 Wh/L
Environmental Impact	- Contains no toxic heavy metals - Easier disposal - Over 5,000 charge cycles reduce waste generation	- Contains toxic heavy metals (lead, cadmium, mercury) - Difficult to dispose of safely
Maintenance	- Low maintenance requirements	- Requires frequent replacements and higher maintenance costs
Space and Weight	- 70% smaller and lighter than Lead-Acid batteries, suitable for space-constrained environments	- Larger and heavier, leading to higher space and structural demands

4. Safety Challenges Associated with Li-Ion Batteries

4.1. Overview of Common Safety Risks

The primary cause of safety incidents in Li-ion batteries is the uncontrolled internal heat generation, where the rate of heat production exceeds the rate of heat dissipation. This results in a build-up of heat within the battery, which, if not adequately managed, can lead to thermal runaway, fires, and explosions.

Thermal runaway in Li-ion batteries is an infrequent but unpredictable event, with multiple contributing factors. The primary causes of thermal runaway are as follows:

4.1.1. Cell Selection, Design, and Production Control

Safety in Li-ion batteries is heavily influenced by the design and manufacturing processes of the cells. The safety protocols for cells, such as LFP and ternary lithium cells, are similar. However, ensuring stringent safety standards in design and manufacturing helps prevent thermal runaway under normal operating conditions. While the physical properties of LFP cathode materials offer higher inherent safety compared to ternary cells, neither cell type is immune to fire. Both LFP and ternary lithium cells are susceptible to ignition under certain conditions.

4.1.2. External Mechanical Shock

Although Li-ion batteries are generally static in their operation and less prone to mechanical shocks, thermal runaway can be triggered by failures in charging/discharging processes, operational management, or system integration, particularly during high-stress conditions such as during transportation or mishandling.

4.1.3. Charge and Discharge Management

BMS are integral to ensuring the safe charging and discharging of Li-ion batteries. While BMS are designed to prevent thermal runaway by controlling charge and discharge parameters, they are only effective in preventing such events before they occur. Once thermal runaway is triggered, the BMS cannot control or mitigate the event, making it critical to employ additional safety measures.

5. Key Factors for Lithium-Ion Battery Secure Applications

5.1. Li-ion Battery Model Selection

Li-ion batteries are categorized into several types based on their chemistry, including Lithium Cobalt Oxide (LCO), Lithium Manganese Oxide (LMO), Lithium Iron Phosphate (LFP), and Nickel Cobalt Manganese (NCM) batteries. Each type is optimized for different applications:

- **LCO:** Primarily used in mobile phone batteries.
- **LMO:** Common in electric bicycle applications.
- **LFP:** Widely employed in electric buses, energy storage systems, and power stations due to its stability and safety profile.
- **NCM:** Typically used in electric vehicles and energy storage applications, offering high energy density.

Among these, LFP and NCM batteries are most commonly used in data center applications, with LFP offering higher reliability and energy density compared to other chemistries.

5.1.1. Thermal Stability of LFP vs. NCM

LFP batteries exhibit superior thermal stability compared to NCM and LMO cells, producing minimal heat under high temperature conditions:

- **LFP:** Generates only about 1 W of heat under peak conditions, maintaining stability even in high-temperature environments.
- **NCM:** Prone to oxygen evolution under high pressure or temperature, significantly increasing the risk of fire. Peak heat generation can reach approximately 80 W/min, potentially triggering explosive combustion within seconds.

The total heat generated by LFP batteries is substantially lower than that of NCM and LMO batteries, as represented by the area under the heat generation curve in thermal tests.

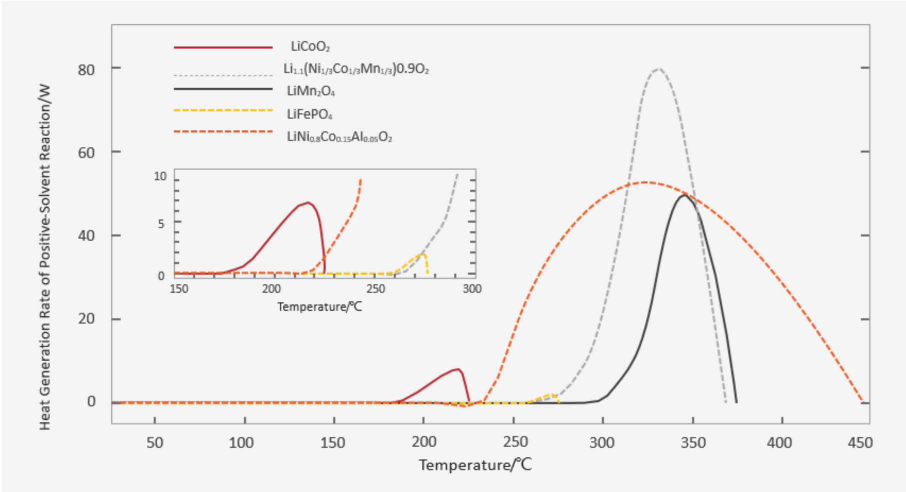


Figure 8 Comparison Curves of Heat Generated by Li-ion Batteries at Different High Temperatures

5.1.2. Oxygen Release During Over Charge/Over Discharge Conditions

The structural stability of the cathode material significantly influences the safety of Li-ion batteries during thermal runaway events:

- **LFP:** Features a stable, three-dimensional olivine structure that does not release oxygen when subjected to thermal runaway, reducing the risk of combustion.
- **NCM:** Contains a layered, two-dimensional structure that is prone to deformation under stress, leading to oxygen release during thermal runaway, which accelerates the risk of fire.

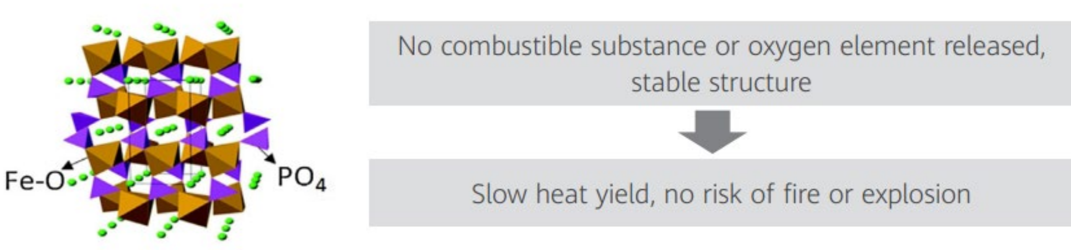


Figure 9 Molecular Structure of LFP

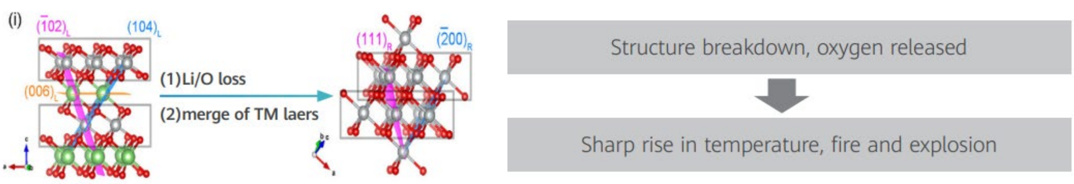


Figure 10 Molecular Structure of NCM [10]

5.1.3. Stability of LFP Compared to NCM

LFP batteries have been shown to outperform NCM batteries in stability under mechanical stress, such as internal short circuits. Standard tests, such as the needle puncture test, assess battery resilience under high-stress conditions:

- **LFP:** After a needle puncture, LFP batteries exhibit minimal heat generation, with a maximum surface temperature of 80°C. No fire or leakage is observed, and the battery shell remains intact.
- **NCM:** In contrast, NCM batteries undergo violent reactions when punctured, with rapid heat generation and oxygen release. The surface temperature can rise to 458°C within seconds, resulting in combustion and shell melting.

Figure 11 Nail Test of NCM and LFP

Table 6 Safety Test Comparison Between LFP and NCM Batteries (Puncture Test)

Material	Composition	Highest Temperature	Test Result
NCM	$Li(NiCoMn)_{1/3}O_2$	458°C	Fire within 1 second, thermal runaway within 4 seconds, shell melting
LFP	$LiFePO_4$	80°C	No fire, no leakage, intact shell

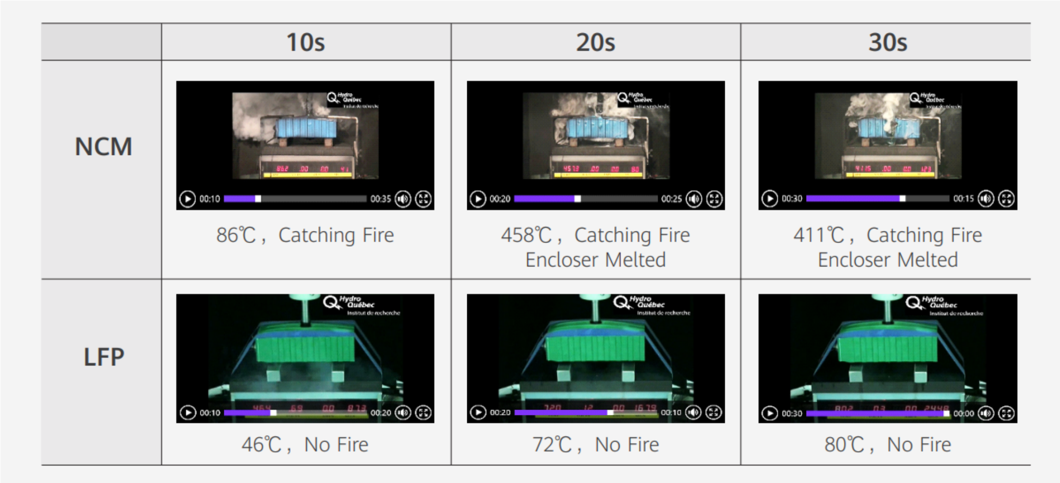


Figure 4 Safety Test Comparison Between LFP and NCM (Puncture Test) [11]

5.1.4. Data Center Li-ion Battery Application Summary

In data canter environments, selecting the right battery chemistry is crucial to ensuring reliability and safety.

Although NCM batteries offer higher energy density, their reliability is lower than that of LFP batteries. Therefore, and based on a comparative analysis, LFP batteries are the preferred choice for data center backup power systems, balancing safety, stability, energy density, and durability.

However, the application of Li-ion batteries in data centers also requires addressing operational challenges beyond material choice.

Table 1 LFP, NCM & Lead-Acid Batteries Comparison Summary

Feature	Lead-Acid Battery	NCM Battery	LFP Battery	Recommended Solution
Footprint	Large	Smallest	Small	Li-ion battery - Space Saving
Cycle Life	Short	Long	Long	Suitable for poor power grid scenarios
Float Charging Life	Short	Long	Long	No replacement needed during lifecycle
Discharge Rate	Low	High	High	Ideal for short-time high-current discharge
Discharge Efficiency	Low	High	High	Large energy for short-term discharge
Chemical Stability	Poor	High	Highest	LFP offers the highest reliability due to its olivine structure
Puncture Test	NA	Fire Risk	No Fire	LFP provides enhanced safety

5.2. Battery Management System (BMS)

Unlike Lead-Acid batteries, Li-ion batteries require a BMS for safe and efficient operation. The BMS acts as the central control unit, overseeing the performance and safety of the battery pack. Its functions vary depending on the application, but core responsibilities include battery status monitoring, security protection, energy management, thermal regulation, information management, and fault diagnosis. A schematic of the BMS functions is illustrated in Figure 13.

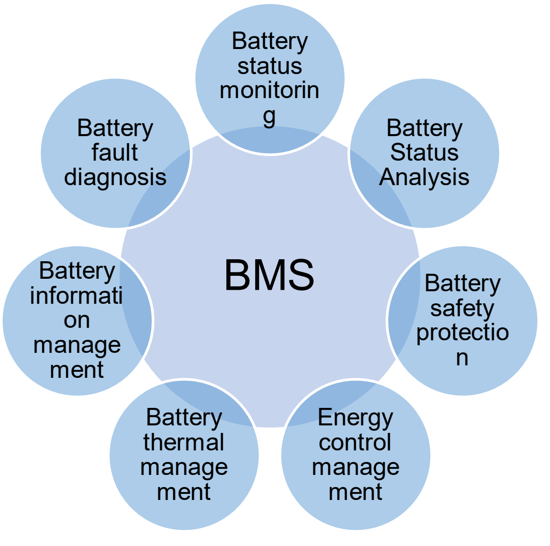


Figure 13 Main Functions of BMS

5.2.1. Battery Status Monitoring

Battery status monitoring is a fundamental BMS function, providing critical data for the operation and safety of the battery. The BMS continuously monitors key parameters such as battery voltage, current, temperature, insulation resistance, and the status of switching components within the battery system.

In data center applications, the BMS must be capable of accurately measuring these parameters under both normal and extreme conditions. Measurement precision, high sampling frequency, and built-in protection mechanisms (to prevent high-voltage faults) are essential for reliable performance.

5.2.2. Voltage Monitoring

The BMS monitors the total voltage of the battery pack as well as individual battery voltages. Voltage measurement typically operates within the range of 0–5V, with a measurement error not exceeding 0.3%, and a sampling period of no more than 200 ms. Common voltage detection methods include:

- **Common-mode and Differential-mode Measurement:** Common-mode involves calculating voltages relative to a single reference point using precision resistors, though it may lack accuracy. Differential-mode provides direct measurements from individual cells, offering greater precision.

- **Relay-based Collection:** This method uses relays controlled by a microcontroller to convert battery voltage into digital signals, although it requires a significant number of optical isolation components, increasing system complexity and cost.
- **Chip-based Voltage Detection:** Semiconductor chips designed for battery management can detect the voltage of multiple series-connected batteries. This approach allows for high-voltage detection and is commonly employed in centralized Li-ion battery systems, such as those found in data centers.

5.2.3. Current Monitoring

Since all batteries in a series-connected cluster share the same current, only the total current needs to be measured. The accuracy requirement is typically within ±1%, with a sampling period of 50 ms or less. Common current detection methods include:

- **Shunt-based Detection:** A low-resistance shunt is placed in series with the battery pack to measure the voltage drop, from which the total current is calculated. While cost-effective, this method generates heat loss, requiring adequate heat dissipation measures.
- **Hall Sensor-based Detection:** Hall sensors use the Hall effect to detect current and provide isolation from the circuit, enhancing anti-interference capability and offering lossless detection. This method is commonly used in data center applications.

5.2.4. Temperature Monitoring

Li-ion batteries perform optimally within specific temperature ranges. Thus, the BMS monitors both individual cell temperatures and the overall environment within the battery pack. Temperature monitoring typically spans from -40°C to 125°C, with an accuracy of ±2°C and a sampling period no longer than 5 seconds. Common temperature detection methods include:

- **Thermistor-based Detection:** Thermistors, whose resistance changes in proportion to temperature, are commonly used due to their low cost and adequate precision. This method is widely used in data centers.
- **Chip-based Temperature Sensing:** Integrated circuits (ICs) in battery management systems may include temperature detection capabilities, simplifying system design but increasing development and application costs.

5.2.5. Battery Status Analysis

Battery status analysis is the core function of the BMS, enabling performance evaluation and system optimization based on key battery parameters. This analysis ensures that the battery operates efficiently and safely by monitoring critical metrics such as State of Charge (SOC), State of Health (SOH), and additional parameters such as minimum/maximum voltage, temperature variations, remaining discharge time, and maximum continuous discharge power.

➢ SOC Estimation

SOC estimation, which determines the remaining capacity of the battery, is crucial for managing battery usage and longevity. The complexity of SOC estimation lies in the need for highly accurate data collection, including synchronous measurement of voltage, current, and temperature. Several SOC estimation methods are employed:

- **Open-Circuit Voltage (OCV) Method:** Simple and accurate, though susceptible to current influence, making it most effective when the battery is at rest.
- **Ampere-Hour Integration:** This method integrates current over time to estimate the SOC, but it accumulates errors over time, especially in long-term usage.
- **Internal Resistance Method:** Useful near the end of discharge, though its applicability is limited by the complex relationship between internal resistance and SOC.
- **Neural Network and Kalman Filter Methods:** These advanced algorithms offer high precision but require extensive training data and computational resources.

Given the prolonged high SOC levels in data center batteries, a combination of OCV, ampere-hour integration, and temperature-based corrections is commonly used to refine SOC estimates.

➢ SOH Estimation

SOH refers to the health of the battery, defined as the ratio of its current dischargeable capacity to its original capacity. It reflects the extent to which a battery's performance has deviated from its design specifications. Accurate SOH estimation is challenging, particularly in long-life applications such as data centers, where the battery may remain fully charged for extended periods.

Two primary SOH estimation approaches are used:

- **Experimental Measurement:** Methods such as full charge-discharge cycles and internal resistance estimation provide valuable data but are typically time-consuming and not always practical.
- **Algorithmic Estimation:** Algorithms such as particle filters, genetic algorithms, and extended Kalman filters offer adaptive models for SOH estimation, with varying levels of accuracy. Particle filtering and calendar life prediction methods are particularly useful in data center environments, where batteries are often in a high SOC state.

5.2.6. Battery Safety Protection

The BMS is critical for ensuring the safety of Li-ion batteries, providing both active and passive protection mechanisms.

- **Active Protection**

This involves monitoring and responding to abnormal conditions, such as over-charging, over-discharging, temperature extremes, or short circuits. Under these conditions, the BMS either halts charging or discharging and triggers alarms. For instance, the BMS will prohibit all operations during over-temperature scenarios and generate a critical warning. The protection thresholds for discharge rates are designed to the upper limit of the battery's safe operating range, ensuring reliability and optimal performance, even in high-discharge environments.

- **Alarm and Protection Mechanisms include:**

  - Over-temperature
  - Low temperature
  - Over-voltage
  - Under-voltage
  - Over-current (charging and discharging)
  - Short-circuit
  - Reverse connection
  - Insulation failure

- **Passive Protection:**

This refers to the backup protection provided by circuit breakers, fuses, and similar components in case active protection fails. This serves as an additional safety layer, minimizing risks when the primary active protection mechanisms cannot mitigate an issue.

5.2.7. Energy Control Management

Energy control management is integral to the BMS, comprising several key functions that optimize battery operation and performance.

- **Balance Management**

Ensures the uniform voltage distribution across batteries connected in series. Even after initial sorting, batteries experience voltage inconsistencies due to variations in internal resistance over time. The BMS employs passive or active balancing techniques to ensure the overall health of the battery cluster.

- **Passive Balancing:** This method uses resistive elements to dissipate excess energy from higher-voltage batteries, equalizing the voltage across the pack. While cost-effective and simple, passive balancing introduces energy losses and potential thermal issues.

- **Active Balancing:** Utilizes energy transfer methods, such as capacitive or inductive energy storage, to redistribute energy from higher to lower voltage batteries, enhancing energy efficiency and extending battery lifespan. However, it is more complex and costly, with ongoing research aiming to improve its practicality.

➢ Current Sharing Management

In parallel battery systems, the BMS ensures that batteries share the load evenly, preventing the 'barrel effect' where one weak battery limits the performance of the entire system. This is achieved through DC/DC converters that balance the current draw between parallel-connected battery clusters, ensuring uniform energy discharge.

➢ Charging and Discharging Management

The BMS governs the start, stop, and regulation of charging and discharging processes. It ensures safe charging protocols, such as constant current followed by constant voltage, and prevents over-charging. Additionally, it ensures stable discharge rates, particularly in multi-cluster configurations, to avoid operational disruptions caused by individual cluster failures.

5.2.8. Battery Thermal Management

Thermal management is vital to maintaining the battery's operational efficiency and preventing over-heating or under-heating, both of which can degrade performance or cause safety hazards. The BMS ensures the battery operates within an optimal temperature range, typically between 10°C and 45°C for most use cases, although this range may extend from 30°C to 55°C in specific applications.

➢ Heat Dissipation

This can be achieved through natural cooling, air cooling, or liquid cooling. Natural cooling relies on passive design to facilitate airflow, while air and liquid cooling provide more active thermal regulation. Liquid cooling is more efficient but comes with higher costs and complexity.

➢ Heating

In colder environments, the BMS can initiate battery heating using PTC or heating films, ensuring the battery operates within a suitable temperature range, especially in data centers or indoor environments where temperatures rarely fall below 0°C.

The BMS will monitor temperatures and activate cooling or heating systems when necessary, generating alerts or halting operations if temperatures exceed safe thresholds.

5.2.9. Battery Information Management

The BMS is responsible for managing the battery data throughout its lifecycle, including storage, display, and real-time analysis of operational parameters.

- **Data Storage**

Battery data is categorized into temporary and permanent storage, with the BMS continuously updating parameters like battery voltage, current, and SOC. Historical data helps refine the system's performance and can be crucial for diagnostics.

- **Display and Alarming**

Critical system information, such as battery health and voltage levels, is displayed on monitoring interfaces. Alarms are generated for abnormal conditions, and data is uploaded to a higher-level monitoring platform for further analysis and storage.

- **Data Communication**

The BMS ensures robust, secure communication through protocols like Modbus TCP, CAN, OPC UA, and dry contacts, facilitating smooth data exchange within the system.

5.2.10. Battery Fault Diagnosis

The BMS includes diagnostic capabilities that predict potential battery failures by analysing operational data. This proactive fault diagnosis uses predictive modelling to anticipate issues before they occur, allowing for early intervention and reducing downtime.

- **Battery Model-Based Diagnosis**

This method involves creating a detailed battery model (electrochemical, equivalent circuit, or data-driven models) to compare predicted behaviour with actual measurements, generating warnings when discrepancies occur. However, these models are complex and infrequently used in practice.

- **Non-Model-Based Diagnosis**

More commonly, fault diagnosis relies on statistical, data-driven, or expert system approaches, where deviations from expected performance patterns trigger alarms. While effective, these methods are highly dependent on the quality and quantity of available data.

In data center applications, fault diagnosis remains under-developed due to the limited dataset. However, as BMS technology evolves and more data becomes available, fault prediction will become a critical tool for improving reliability and system uptime.

5.3. Fire Safety Requirements for Data Center Lithium-ion Batteries

5.3.1. Fire Characteristics

In recent years, lithium-ion batteries have been widely used in power backup systems of data centers due to significant advantages such as high energy density, long service life, and low self-discharge rate. In general, lithium-ion batteries have high safety, but the fire characteristics are relatively complex due to the high energy density and continuous reaction after thermal runaway.

Due to electrical and thermal abuse, lithium-ion batteries are prone to thermal runaway, which can cause a fire or even an explosion. As a result, the safety of lithium-ion batteries has become an industry concern. Therefore, it is of great practical significance to study an effective method for extinguishing a lithium-ion battery fire, which can not only reduce the property loss of a company, but also ensure the life safety of personnel and the stable operation of data centers.

Compared to traditional fires, lithium-ion battery fires due to thermal runaway have their own unique characteristics.

(1) High Temperature Rise Rate and Heat Release Rate

Lithium-ion batteries spontaneously become exothermic due to abuse. After thermal runaway occurs, the heat release reaction inside the batteries is severe, and a large amount of heat is generated in a short period of time. As a result, the battery temperature rises sharply. When thermal runaway occurs, a large amount of combustible gases, electrolyte, and material particles are ejected from the battery pressure relief valve, which, after igniting at a high temperature, creates a violent jet fire with an extremely high heat release rate. Rapid temperature rise and heat release complicate lithium-ion battery fire control and can quickly spread to the entire battery module or system.

(2) Fast Fire Spread

To increase the energy density of the system, battery cells in the module are closely arranged. When a battery cell in the battery module fails and thermal runaway occurs, heat is quickly transferred to adjacent battery cells due to close arrangement. As a result, heat spreads in the battery module, and the fire spreads rapidly.

(3) Complex Fire Extinguishing and Easy Reignition

During thermal runaway, most of the exothermic reactions occur inside the battery. However, due to the obstruction of the shell, the extinguishant cannot easily enter the battery to block the thermal runaway chain reaction. During fire extinguishing, if the battery temperature cannot be completely lowered, the heat source cannot be eliminated, and the internal chemical reaction cannot be suppressed, the temperature will continue to rise, which may lead to reignition.

(4) Generation of Combustible and Toxic Gases

During thermal runaway of LFP batteries, the electrolyte produces a large amount of gases, including hydrogen, carbon monoxide, methane, and electrolyte vapor. If the concentration of combustible gases in the confined space exceeds the explosion concentration, there is a risk of explosion. In addition, the gases generated by thermal runaway is highly toxic and threaten personal safety. Therefore, proper ventilation and air exhaust measures must be taken to reduce toxic gases during fire extinguishing.

5.3.2. General Requirements

Based on the fire safety principle of "giving priority to prevention and then combining prevention and fire control", this section draws on the experience of global major fire accidents in recent years and summarizes global design experience of lithium-ion battery rooms for building fire control and achievements of fire control technologies. By conducting a large number of technical researches, technical workshops, and necessary physical fire tests, it solicits opinions from institutes in the fields of design, production, construction, scientific research, teaching, and fire control supervision.

Provided that the preceding mandatory specifications are met, it is recommended that relevant group standards and company standards be properly selected to optimize project functions and performance. However, the recommended engineering construction standards, group standards, and enterprise standards must be consistent with the mandatory engineering construction specifications. The technical requirements cannot be lower than those specified in the mandatory engineering construction specifications.

Based on the failure modes of lithium-ion batteries, the safety risks of lithium-ion battery rooms can be classified into direct risks and indirect (secondary) risks.

A direct risk is that the heat, smoke, and combustible gas released by a lithium-ion battery failure cause fire and explosion, which further damage and burn all equipment in the lithium-ion battery room.

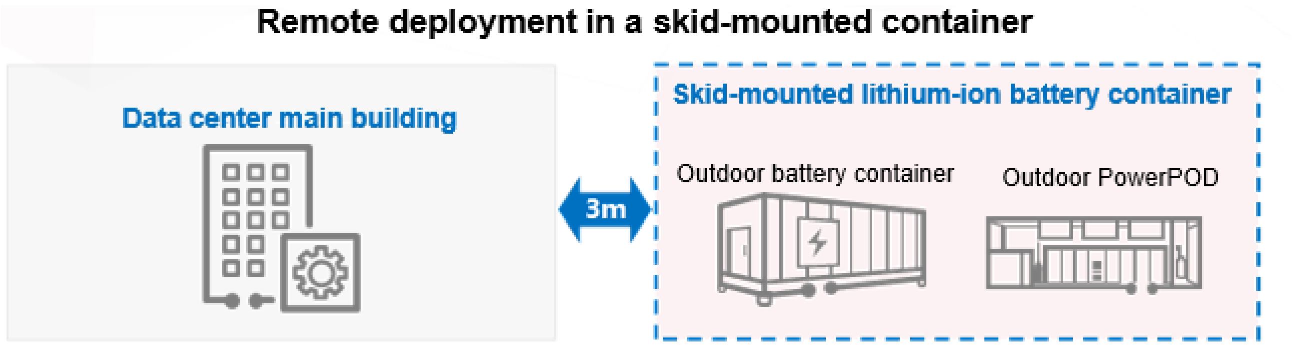
An indirect (secondary) risk refers to the impact on adjacent rooms and buildings of a fire or fire extinguishing resulting from a lithium-ion battery failure. For example, the fire may spread to adjacent rooms and buildings if it cannot be effectively controlled and smoke and combustible gases generated by lithium-ion batteries cannot be vented in a timely manner, which can spread to adjacent rooms, causing explosion hazards and damage to personnel, equipment, and buildings. Or the water that may be used to suppress the fire cannot be drained in time. As a result, the water spreads to surrounding rooms, causing unnecessary loss.

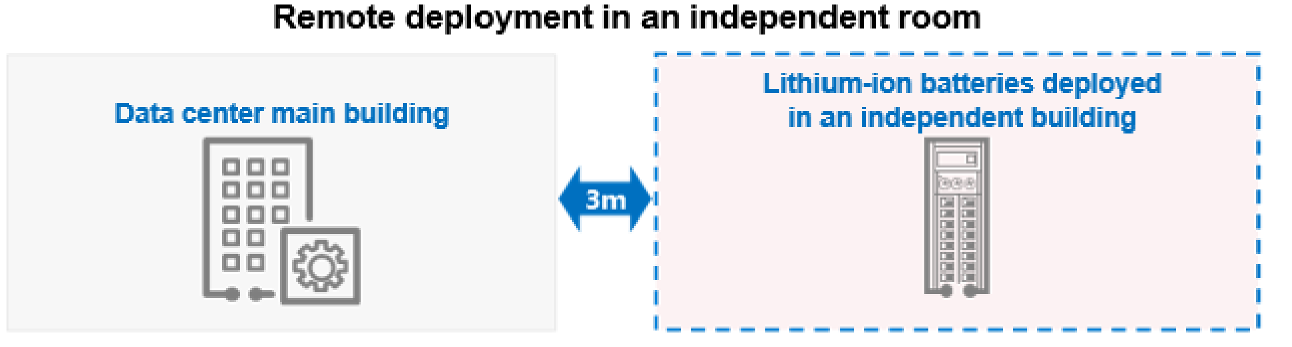
To minimize direct and indirect (secondary) risks, fire control facilities need to be designed in terms of the lithium-ion battery layout, automatic fire extinguishing system, ventilation and smoke control and exhaust, thermal runaway detection and alarm, drainage, emergency power-off, and explosion protection and pressure relief to avoid risks in advance.

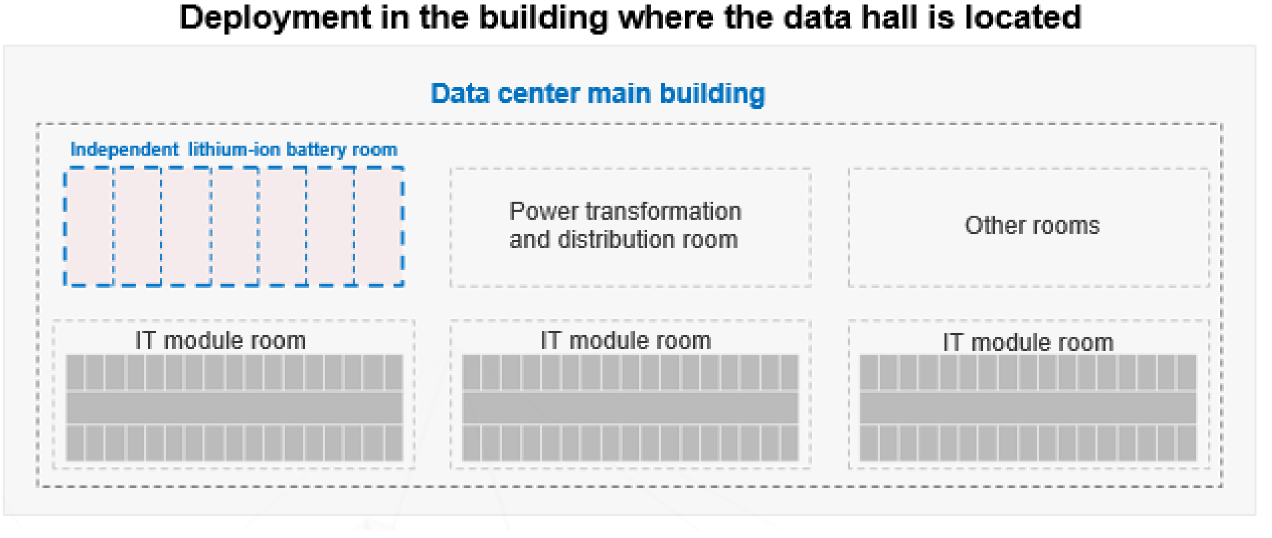
5.3.3. Plane Layout

5.3.3.1. Overview

Lithium-ion batteries for data centers shall be deployed based on comprehensive factors including cost-effectiveness and safety. Remote skid-mounted deployment with an independent container or cabinet is preferred. Remote deployment in an independent structure or building is an alternative. If the remote deployment conditions are not met, batteries can be deployed in an independent room against the exterior wall of the building where the main equipment room is located, as shown in the following figure.







If lithium-ion batteries are deployed in a data center building, they shall not be placed directly under a toilet or other places where water often exists and may leak, and shall not be adjacent to the preceding places. If they are adjacent to the preceding places, the adjacent partition walls shall be waterproofed to prevent leakage and condensation. To prevent water pipe burst or water leakage from damaging electrical equipment, hot water pipes, steam pipes, or air conditioner water pipes with pressure shall not be deployed in the lithium-ion battery room.

5.3.3.2. Deployment Requirements

To facilitate fire rescue, requirements for the position of the lithium-ion battery room, relationship and spacing between buildings, fire lanes and internal and external roads, and fire water sources must be met to reduce the fire interaction between the building to be constructed and surrounding buildings, ensure that the fire engine has access and can effectively spray water, and prevent secondary disasters.

5.3.3.2.1 Remote Deployment

In the remote deployment scenario, the fire safety distance of the lithium-ion battery room must be properly determined based on the height of the lithium-ion battery room or the height of the building in which the lithium-ion battery room is located, the fire resistance rating, and the fire hazard. The fire safety distance shall ensure that the heat intensity radiated by the fire from the adjacent building to any side of the building wall is less than the critical ignition radiant heat intensity. If the lithium-ion battery room is deployed remotely, the recommended fire safety distance and fire resistance rating are as follows:

(a) If the fire resistance limit of a remotely deployed skid-mounted container, structure, or building is not less than 1 hour, the fire safety distance between the container, structure, or building and other buildings shall be not less than 3 m.

(b) If the fire resistance limit of the wall of a remotely deployed skid-mounted container, structure, or building opposite to other buildings is greater than or equal to 2 hours, and the fire resistance limit of the other sides is greater than or equal to 1 hour, the fire safety distance between the container, structure, or building and other buildings must be greater than or equal to 1 m.

5.3.3.2.2 Battery Room Deployed in the Building Where the Data Hall Is Located

When the lithium-ion battery room is deployed in the building where the data hall is located, the capacity of a single lithium-ion battery room shall not exceed 600 kWh. The lithium-ion batteries shall be deployed in a room against an exterior wall. The fire resistance limit of beams, columns, walls, and sealed holes in the room shall not be less than 2 h, and that of the top and bottom floors shall not be less than 1.5 h. The evacuation door shall be a fire door that can withstand fire for at least 1.5 h. Protective measures, such as a vestibule, shall be provided at the junctions between stairways, outdoor stairways, or hazardous areas and adjacent areas. The wall of the vestibule shall be a fire wall with a fire resistance of at least 2 h, and the door shall be a fire door with a fire resistance of at least 1.5 h and shall not be installed in line with the staircase door.

The lithium-ion battery room shall not exceed 24 m above the ground and shall not be deployed in the basement or semi-basement. If the height exceeds 24 m, the lithium-ion battery room shall meet the local fire rescue equipment conditions. The lithium-ion battery room shall be effectively sealed and isolated from cable trays, air conditioning ducts, and smoke control and exhaust ducts in other related spaces. This will prevent secondary disasters such as fire, heat hazards, toxic and noxious gases, combustible vapors, flowing fire, and fire water from spreading to other building spaces.

The lithium-ion battery room shall be equipped with emergency facilities such as emergency exit, fire door, pressure relief and explosion protection device, emergency light, clear permanent lithium-ion battery room label, and capacity indication label, and tools such as breathing mask, cart water-based fire extinguisher, removal tool, and insulated gloves.

If the lithium-ion battery room is deployed against the exterior wall of the building where the data hall is located, an opening shall be reserved in the fire rescue direction, and clear permanent labels shall be set inside and outside the opening. The opening shall be designed according to the local fire safety specifications. It is recommended that the opening be deployed in the middle of the exterior wall of the lithium-ion battery room. The distance between the bottom of the opening and the bottom floor of the lithium-ion battery room shall be greater than or equal to 2 m. The width and height shall not be less than 1 m. When the exterior window is used for fire rescue, safety glass shall be used. When the door is used for fire rescue, the net width shall not be less than 0.8 m.

5.3.4. Automatic Fire Extinguishing System (Equipment)

5.3.4.1. Overview

According to global physical fire tests and related standards, water is the first choice for suppressing lithium-ion battery fires. Dry powder, carbon dioxide, and inert gas cannot effectively cool lithium-ion batteries down in case of thermal runaway, posing a risk of reignition. Singapore updated its fire safety act in 2023, stipulating that an automatic water spray fire sprinkler system must be installed in lithium-ion battery rooms.

Based on global regulations and specifications, related experimental verification, and firefighting and rescue experience, the following requirements are proposed for firefighting facilities in the lithium-ion battery room of a data center.

5.3.4.2. Extinguishant Selection

If thermal runaway occurs in a lithium-ion battery, the impact spreads throughout the battery module in a short period of time. Thermal runaway can spread rapidly and is prone to reignition if the batteries cannot be cooled continuously and effectively. In addition, adjacent battery modules may even catch fire due to heat conduction.

Therefore, to extinguish a lithium-ion battery fire, the open flame of the battery must be extinguished quickly, and the extinguishant must have strong cooling and heat dissipation capabilities to prevent reignition. By physical status, fire extinguishants can be classified into gas extinguishant, dry powder extinguishant, and water extinguishant.

(1) Gas Extinguishant

The gas extinguishant is non-conductive, non-corrosive, non-persistent, and fast-flowing. It can be used in confined spaces for better extinguishing effect.

Carbon dioxide extinguishant: It is cheap, easy to prepare, liquefy, and store, and environmentally friendly. Carbon dioxide evaporates immediately after being released into the fire area, producing a large amount of gaseous carbon dioxide that reduces the oxygen concentration around combustibles and suppresses flames. However, carbon dioxide can only physically suppress a fire and has a limited cooling effect. It is difficult to extinguish a lithium-ion battery fire, and the battery is prone to reignition.

Heptafluoropropane extinguishant: Its extinguishing mechanisms include physical suppression and chemical suppression. Gasified and decomposed heptafluropropane can absorb ambient heat, reduce the temperature of the fire area, and dilute the oxygen concentration. In addition, it decomposes products at high temperature, which can trap combustible free radicals, interrupt the combustion chain reaction, and suppress the flame. However, it has an obvious greenhouse effect and a limited cooling effect on a lithium-ion battery fire, posing a risk of reignition.

Perfluorohexanone extinguishant: It has excellent fire extinguishing performance and is non-conductive. It is mainly used to extinguish battery fires by physical and chemical suppression. Perfluorohexanone is a liquid at room temperature with a boiling point of about 49°C and has a relatively high latent heat of vaporization. In addition, it decomposes at high temperature, which can remove free radicals during combustion and interrupt the combustion chain reaction. Therefore, after perfluorohexanone extinguishant is released into a confined space, it can absorb a large amount of heat, reduce the temperature of the fire area, and isolate oxygen to suppress the flame.

Although perfluorohexanone has excellent fire extinguishing performance and good cooling performance, it is difficult to continuously reduce the temperature of lithium-ion batteries, and there is a risk of reignition. In addition, as hydrofluoric acid is generated when the extinguishant is used, protective measures must be taken.

Aerosol extinguishant: Aerosol is a gaseous dispersion system composed of solid or liquid particles suspended in the gas medium. The particles can be suspended in the air for a long time without being affected by obstacles. Aerosol particles are generated by burning an aerosol-forming agent and do not require a pressurized container. Metal ions generated by aerosol decomposition can eliminate free radicals needed to sustain combustion, thereby interrupting the chain reaction. In addition, the vapor and carbon dioxide generated by the decomposition of metal oxides and carbonates reduce the oxygen concentration and suppress the flame. With its excellent fire extinguishing efficiency, low persistence, and non-conductivity, it is widely used in high-risk places. However, the cooling effect of the aerosol extinguishant is poor, and the efficiency of suppressing the re-ignition of lithium-ion battery fires is not satisfactory.

(2) Dry Powder Extinguishant

Dry powder is solid powder formed by drying, crushing, and mixing inorganic fire-extinguishing salt and a small amount of additives. ABC dry powder is applicable to extinguishing Class A, Class B, and Class C fires.

The main component of ABC dry powder is ammonium phosphate, which extinguishes flames by isolation, smothering, cooling, and chemical suppression. After dry powder is released into the fire area, it decomposes products at high temperature, which can trap combustible free radicals and interrupt the combustion chain reaction. In addition, the decomposition of dry powder absorbs heat and produces ammonia and water vapor to dilute the oxygen concentration in the fire area. Moreover, dry powder falls onto the surfaces of high-temperature combustibles and melts to form a glass coating to isolate oxygen and smother the combustibles. However, dry powder cannot effectively cool lithium-ion batteries down. Even if the open flames are extinguished, the batteries may reignite.

(3) Water Extinguishant

The water extinguishant has a large heat capacity and latent heat of vaporization. It absorbs a large amount of heat through phase transition in the fire area. After vaporization, its volume expands to reduce the oxygen concentration, providing excellent fire extinguishing and cooling performance. Because it is also inexpensive and easy to use, it has a wide range of applications.

Based on the particle size of liquid droplets, common fire extinguishing systems based on water extinguishant can be divided into automatic water sprinkler fire extinguishing system, water spray fire extinguishing system, and water mist fire extinguishing system.

Automatic water sprinkler fire extinguishing system: The particle size of water droplets is large. After sprinkling, the droplets gain sufficient momentum and force to penetrate the flame and high-temperature smoke to the root of the flame and the surfaces of combustible materials, thereby effectively cooling the batteries. The system has good fire extinguishing and cooling effects for lithium-ion battery fires. However, sprinkling water is conductive and can cause insulation failure in the battery system. Therefore, the power supply must be disconnected before extinguishing the fire, and check and take insulation measures after extinguishing the fire to reduce the negative effects of water sprinkling.

Water spray fire extinguishing system: Based on the centrifugal or collision principle, the water spray nozzle breaks down the water flow into fine water mist droplets for fire extinguishing and cooling protection under a certain water pressure. The water spray nozzle sprays out misty water with a particle size of less than 1 mm. It can be used to put out solid fires, liquid fires with a flash point higher than 60°C, and oil-immersed electrical equipment fires. Extinguishing fires produces a large amount of water vapor, which can facilitate extinguishing by cooling, smothering, emulsifying, and diluting the fire.

Water mist fire extinguishing system: The diameter of mist droplets is small. Compared with the same volume of water, mist droplets have a much larger surface area, which increases the heat exchange efficiency and achieves a good cooling effect. After absorbing heat, the fine water mist evaporates quickly, causing the volume to expand greatly. This reduces the oxygen concentration in the air, suppresses the oxidation reaction rate during combustion, and contains the fire.

In addition, the fine water mist has excellent performance in blocking heat radiation transfer, and can effectively block heat radiation from flames and high-temperature objects. Fine water mist features insulation, as well as excellent fire extinguishing, cooling, and environmental protection performance, and can properly suppress lithium-ion battery fires. However, the particle size and momentum of the fine water mist are relatively small, making it susceptible to ventilation and obstacles. And when the heat release rate is relatively high, it is difficult for the fine water mist particles to reach the surface of batteries due to heat buoyancy, which weakens the cooling effect.

In summary, water extinguishant shall be used for the fire extinguishing system in data center lithium-ion battery rooms.

5.3.4.3. Design Requirements

The lithium-ion battery room in a data center shall be equipped with a fire extinguishing system that uses the water extinguishant. Water pipes and nozzles shall not be installed right above Lithium-ion battery cabinets. Based on related test data, the water spray fire extinguishing system is preferred, followed by the automatic water sprinkler fire extinguishing system and the water mist fire extinguishing system.

The spraying capacity of the water spray fire extinguishing system shall be greater than or equal to 20 L/(min·m2). The fire water storage capacity in the campus shall be greater than or equal to 2 h. Surrounding water sources shall be able to supply water continuously for 7 h. Nozzles shall be designed and arranged in accordance with local standards to provide all-round protection.

The sprinkling capacity of the automatic water sprinkler fire extinguishing system shall be 12 L/(min·m2), and the fire water storage capacity in the campus shall be greater than or equal to 2 h.

Surrounding water sources shall be able to supply water continuously for 10 h. Nozzles shall be designed and arranged to provide all-round protection. Water pipes and nozzles shall be installed in front of the battery cabinets. The maximum height of nozzles shall be less than or equal to 7.8 m.

The operating pressure of the water mist fire extinguishing system shall be greater than or equal to 5 MPa, and the spraying capacity shall be greater than or equal to 1.2 L/(min·m2). The fire water storage capacity in the campus shall be greater than or equal to 4 h. Surrounding water sources shall be able to supply water continuously for 10 h. Nozzles shall be designed and arranged in accordance with local fire safety regulations or relevant international standards to provide all-round protection.

5.3.5. Ventilation and Smoke Control and Exhaust

5.3.5.1. Overview

Lithium-ion batteries do not generate combustible gases during normal operation. However, hydrogen, carbon monoxide, and a small amount of hydrogen fluoride are released during valve opening and water spraying in the event of thermal runaway. Therefore, an emergency ventilation system is required to vent these gases to the outside in a timely manner to prevent them from mixing with air to form explosive compounds. This ensures fire safety in the lithium-ion battery room.

5.3.5.2. Design Requirements

The lithium-ion battery room in a data center shall be equipped with an independent ambient temperature and humidity control system and explosion-proof ventilation device. A manual exhaust switch shall be installed outside the room. The emergency ventilation system shall be linked to the combustible gas detection and alarm device and the ambient temperature and humidity control system.

The air ducts, air vents, valves, and thermal insulation materials of the air conditioning system in the lithium-ion battery room shall be flame-retardant or non-combustible. The emergency ventilation volume shall comply with related regulations and the number of emergency ventilation times shall be greater than or equal to 12 times/h.

If an in-room gaseous fire extinguishing system is used, the emergency fan shall stop after the fire extinguishing system is activated. If an automatic water spray fire extinguishing system, automatic water sprinkler fire extinguishing system, or water mist fire extinguishing system is used, the emergency fan shall be always on after the fire extinguishing system is activated. However, it is not mandatory to activate the emergency fan if lithium-ion batteries are deployed remotely in an outdoor skid-mounted container.

The emergency fan shall be explosion-proof and devices of the emergency ventilation system shall not be deployed in the basement or semi-basement. The air intake and exhaust vents shall be set in accordance with local safety regulations or relevant international standards. In addition, the emergency ventilation systems of fire safety zones shall be isolated from each other. A fire damper of at least 150°C resistance shall be installed in the fire safety zone through where an air duct is routed. If the air duct is directly routed outdoors, no air damper is required and the fire safety zone shall not share an air damper with the ventilation system in the main service room.

5.3.6. Thermal Runaway Detection and Alarm

5.3.6.1. Overview

The lithium-ion battery room in a data center shall be equipped with an automatic fire alarm system, which can also be connected to the automatic fire alarm system of the building where it is located for centralized management. The fire alarm controller and fire detector shall comply with local fire safety regulations and relevant international standards.

It is advised to use a dedicated fire detection and alarm system that is specially developed for lithium-ion battery fires and has obtained mandatory certification.

Lithium-ion batteries release combustible gases or vapors such as hydrogen and carbon monoxide only when the valves are opened due to thermal runaway. Normally, the emergency fan does not operate. When the detector detects that the concentration of combustible gases reaches the alarm and action thresholds, the fan is activated to exhaust the combustible gases from the battery room. An alarm threshold of 10% lower flammability limit (LFL) and an action threshold of 25% LFL shall be set for the combustible gas detectors.

5.3.6.2. Design Requirements

Fire detectors such as combustible gas detector, heat detector, and smoke detector shall be installed in the lithium-ion battery room of a data center. The lithium-ion battery room shall be equipped with at least one type of combustible gas detector. Carbon monoxide or hydrogen detectors are recommended. The number of each type of detector shall be at least two per room. The gas detectors shall be linked with the ventilation system, automatic fire alarm system, gas concentration display, and alarm devices. The lower explosive limit (LEL) set for combustible gas detectors shall be consistent with the declaration of thermal runaway characteristics for lithium-ion batteries.

Gas detectors shall be properly installed based on the characteristics of different types of gases, air flow rates, effective coverage, detector principles and performance, and maintenance and calibration requirements. As required by the installation specifications, the carbon monoxide detector shall be installed near the battery cabinet. If it is an in-cabinet model, the carbon monoxide detector shall be installed inside the battery cabinet. The hydrogen detector shall be mounted on the ceiling (if there is a suspended ceiling, install one on each side of the ceiling).

In addition to combustible gas detectors, the lithium-ion battery room can also use reliable and advanced methods such as composite fire detectors, active gas detection tubes, and thermal imaging to report early thermal runaway alarms..

5.3.7. Drainage

5.3.7.1. Overview

If the lithium-ion battery room in a data center is equipped with an automatic water spray fire extinguishing system, automatic water sprinkler fire extinguishing system, or water mist fire extinguishing system, the drainage system design must consider the ability to drain fire water in a timely manner after the fire extinguishing system is activated. This will prevent secondary hazards such as water accumulation, overflow, and leakage from spreading to adjacent functional spaces and causing unnecessary loss.

5.3.7.2. Design Requirements

The floor, walls, doors, and cable trays of the lithium-ion battery room in a data center shall be waterproofed. If gravity drainage is used in the lithium-ion battery room, the height of water barriers shall not be less than 50 mm, and the recommended height is 100 mm. If other drainage methods are used, the corresponding drainage volume requirements must be met. If the irrigation-type destructive water fire extinguishing is used, the drainage port shall be higher than the highest battery, and a fire hydrant port shall be reserved for water supply.

Water pumps or natural drainage can be used. The drainage capacity shall not be less than the spraying capacity of the automatic fire extinguishing system, and the margin coefficient shall not be less than 10%.

5.3.8. EPO

5.3.8.1. Overview

Lithium-ion battery cabinets shall be equipped with independent EPO dry contacts, and the EPO dry contacts of battery cabinets in the parallel system shall be connected in parallel and then be linked to the EPO button in the equipment room to disconnect the non-fire extinguishing power supply in the lithium-ion battery room. This reduces the risk of ignition due to circuit overload or sparking, thereby blocking the path of fire spread. Note that the normal lighting power supply must be disconnected before the automatic sprinkler system and fire hydrants are activated.

5.3.8.2. Design Requirements

The fire linkage controller shall be able to disconnect the non-fire extinguishing power supply in the fire area and associated areas. If it is necessary to disconnect normal lighting, it is recommended that the lighting be disconnected before the automatic sprinkler system and hydrant are activated. A dedicated EPO button for fire rescue and extinguishing shall be installed outside the lithium-ion battery room, and protective measures shall be taken to prevent misoperations.

The emergency fan shall be powered by the fire extinguishing power supply. If non-fire extinguishing devices obtain power from the power distribution box (PDB), it is recommended that a shunt release be configured in the upstream PDB to remotely power off the circuit breaker. Lithium-ion battery cabinets in the battery room shall have independent EPO dry contacts and support one-click disconnection of lithium-ion battery devices in the room.

5.3.9. Explosion Protection and Pressure Relief

5.3.9.1. Overview

Lithium-ion batteries release combustible and explosive components (hydrogen, methane, carbon monoxide, and ethyl methyl carbonate) when the valve is opened due to thermal runaway. If these components cannot be vented to the atmosphere in a timely manner when the concentration reaches the LEL, there is a risk of explosion if a spark is ignited. The explosion creates shock waves that first break through points with weak pressure resistance in the lithium-ion battery room. High pressure is instantly released, causing damage to the building and people in the area.

5.3.9.2. Design Requirements

The lithium-ion battery room shall be equipped with pressure relief and explosion protection devices or pressure relief channels (such as glass windows and magnetic lock doors) with equivalent areas. If side pressure relief is used, a protection fence or wall shall be installed outside the pressure relief channels and fire warning labels shall be attached to the fire doors used for pressure relief. These may not be installed if the combustible gas concentration in the lithium-ion battery room can be controlled within 25% of the LEL, or if the explosion resistance of the room is greater than the internal explosion pressure.

Based on parameters such as the structure layout, battery type, and interior space of the lithium-ion battery room, a numerical explosion model of the data center can be built in a numerical simulation manner, and the location and area of the explosion relief opening can be optimized to provide safety assurance for mitigating the consequences of the battery room explosion.

The lithium-ion battery room shall have a non-sparking floor. If insulation materials are used, take ESD measures. Trenches are not recommended. If trenches are required, they must be tightly covered. Effective measures shall be taken to prevent the accumulation of combustible gases, vapors, dust, and fibers. In addition, fire-resistant materials must be used at the joints between trenches and adjacent buildings.

In summary, the fire safety requirements for batteries deployed in a remote skid-mounted container, remote independent room, or the building where the data hall is located are shown in the following table.

<table>
<tr><th>Item</th><th>Sub-item</th><th>Fire Safety Requirement</th><th>Remote Skid-mounted Container</th><th>Remote Independent Room</th><th>Building Where the Data Hall Is Located</th></tr>
<tr><td rowspan="6">Plane Layout</td><td rowspan="3"></td><td>Independent lithium-ion battery room</td><td>Optional</td><td>Recommended</td><td>Mandatory</td></tr>
<tr><td>When the battery room is deployed against an external wall, the wall in the fire extinguishing direction can be removed or a fire rescue window is reserved.</td><td>-</td><td colspan="2">Mandatory</td></tr>
<tr><td>Lithium-ion battery room height</td><td colspan="3">⩽ 24 m and not in a basement or semi-basement</td></tr>
<tr><td rowspan="3">Fire resistance level</td><td>Distance from other buildings ⩾ 3 m, overall fire resistance time</td><td>⩾ 1 h</td><td colspan="2">-</td></tr>
<tr><td>Distance from other buildings ⩾ 1 m, fire resistance time of the wall opposite to other buildings</td><td>⩾ 2 h</td><td colspan="2">-</td></tr>
<tr><td>Fire resistance time of beams, columns, and four walls</td><td>-</td><td colspan="2">⩾ 2 h</td></tr>
</table>

		Fire resistance time of the top and bottom floors	-	≥ 1.5 h
		Fire resistance time of sealed holes	≥ fire resistance time of the wall	
		Fire resistance time of the fire door	≥ 1.5 h	
	Peripheral requirements	Reachable by fire engines on peripheral roads	Mandatory	
Automatic fire extinguishing system	Fire extinguishing mode	Water spray fire extinguishing system, automatic water sprinkler fire extinguishing system, or water mist fire extinguishing system	Recommended	Mandatory
	Automatic water sprinkler/water spray fire extinguishing system	Surrounding water sources (fire engines, self-prepared water in the campus, or municipal water) can supply water continuously for 10 hours.	Recommended	Mandatory
		Spraying capacity and duration of the automatic water sprinkler fire extinguishing system	12 L/(min·m^2) and ≥ 2 h	
		Spraying capacity and duration of the water spray fire extinguishing system	≥ 20 L/(min·m^2) and ≥ 2 h	
		Nozzle layout	Distance ≤ 3 m and (when water sprinklers are used) height ≤ 7.8 m	
	Water mist fire extinguishing system	Surrounding water sources (fire engines, self-prepared water in the campus, or municipal water) can supply water continuously for 10 hours.	Recommended	Mandatory
		Operating pressure of water mist	≥ 5 MPa	
		Spraying capacity and duration of the water mist fire extinguishing system	≥ 1.2 L/(min·m2) and ≥ 4 h	
Ventilation and smoke control and exhaust	Emergency ventilation	Times of emergency ventilation in the lithium-ion battery room	≥ 12 times/h	
	Linkage	Alarm linkage with combustible gas detectors	Mandatory	
Thermal runaway detection and alarm	Number of detectors	Combustible gas detector (hydrogen or carbon monoxide)	≥ 2/room or 2/cabinet	
	Installation	Carbon monoxide detector installation position	Close to battery cabinets	
		Hydrogen detector installation position	Ceiling-mounted installation (installed on each side if a suspended ceiling is used)	
Drainage	Drainage flow	Drainage capacity ≥ Spraying capacity of the automatic fire extinguishing system, and margin coefficient ≥ 10%	Mandatory	
	Spread prevention	Water barrier height in the lithium-ion battery room	-	≥ 50 mm, recommended: 100 mm
EPO	Power-off	Remote one-click disconnection of non-fire extinguishing devices	Mandatory	
Explosion protection and pressure relief	Explosion relief measures	Pressure relief and explosion protection devices or pressure relief channels (such as glass windows and magnetic lock doors)	Recommended	
		If side pressure relief is used, a protection fence or wall shall be installed outside the pressure relief channels and fire warning labels shall be attached to the fire doors used for pressure relief.	Mandatory	

5.4. Li-ion battery Transportation and Installation

5.4.1. Transportation Requirements

Li-ion batteries must be handled with care during transportation to prevent shocks, vibrations, or exposure to sunlight, rain, or extreme conditions. Batteries must always remain upright and free from pressure or inversion.

5.4.2. Storage Requirements

Upon delivery, Li-ion batteries should be inspected for intact packaging, correct specifications, and the presence of all accessories. If installation is delayed, batteries must be stored in clean, dry, and well-ventilated areas, away from conductive dust or corrosive substances. Ideal storage conditions are 0–40°C with relative humidity below 95%. Batteries stored for over nine months must be charged.

5.4.3. Installation Requirements

Installation must adhere to approved designs and technical specifications. The construction and auxiliary facilities should be completed and accepted before installation begins. Batteries should be visually inspected for cracks, leaks, or terminal damage. During assembly, insulated tools and protective gear must be used to ensure safety.

Additional guidelines include:

- Racks must be grounded and securely hold batteries without deformation.
- Wiring must be correct and tightened to the torque specified in technical documents.
- Seismic features must be implemented where required.

5.4.4. Quality Acceptance

During acceptance, the Li-ion battery room's environment, installation, and construction quality must meet design and product standards. Insulation resistance should be ⩾2 MΩ, and proper documentation (manuals, certificates, and quality reports) must be provided.

5.5. Regulatory Description and Trends

The safety design of Li-ion battery energy storage systems must account for various factors, including battery safety, thermal safety, electrical safety, functional safety, electromagnetic compatibility, system installation, and transportation safety. Globally, standards such as those from IEC, UL, and UN are commonly referenced. Key safety standards across major regions are summarized in Table 8 below [12]:

Table 8 Safety standards for lithium-ion battery energy storage in major regions around the world

Country and Region	Lithium-ion Battery Energy Storage Safety Standard No.						
	Battery safety	Thermal safety	Electrical safety	Functional safety	Electromagnetic compatibility	system/Installed	Transportation safety
European Union	IEC 62619		IEC/EN 62477-1; IEC/EN 62109-1/-2	IEC 61508; IEC 60730-1	EN 61000-6-4/2	IEC 62040-1	UN38.3(globally available)
United States of America	UL 1973; UL 1642	UL 9540; UL 9540A	UL 1741	UL 1998; UL 991	FCC(Fifteenth) Part A)	NFPA 855	
Japan	JIS C 8715-2		JIS C 8715-1				
China	GB/T 36276	GB/T 36276				GB50174	

Currently, lithium-ion battery standards primarily address safety from two key perspectives: battery safety performance and environmental adaptability. For stationary energy storage applications, the emphasis is on battery safety and thermal safety standards directly related to the battery itself. The table below outlines the relevant test items:

Table 9 Contents of Lithium-ion Battery Energy Storage Safety Standard at Home and Abroad

No.	Standard No.	Standard Name	Main content
1	IEC 62619:2017 [13]	Secondary monomer cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for secondary lithium batteries and batteries for industrial equipment.	Safety tests for cell, battery and system safety and environmental suitability are proposed.
2	UL 1642:2015 [14]	Lithium-ion battery safety standard	The safety of cells and batteries in various use environments, including fault conditions, heavy pressure conditions and combustion conditions, is comprehensively investigated.
3	UL 1973:2018 [15]	Batteries for stationary, vehicle auxiliary power and lightweight electric rail (LER) applications.	Comprehensive review of the electrical, mechanical, and environmental safety of cells and batteries.

4	UL 9540:2016 [16]	Safety standards for energy storage systems and equipment	Evaluate the electrical, mechanical, and environmental safety at the energy storage system level.
5	UL 9540A: 2018 [17]	Test method for evaluating battery thermal runaway flame propagation in battery energy storage systems.	Evaluates the thermal runaway characteristics of the battery energy storage system and selects appropriate fire and explosion protection mechanisms based on test data.
6	JIS C 8715-2:2012 [18]	Test method for evaluating battery thermal runaway flame propagation in battery energy storage systems.	Focus on product use safety and environmental adaptability safety
7	GB/T 36276-2018 [19]	Lithium-ion battery for electric energy storage	Focus on product use safety and environment adaptability safety Focus on product use safety and environment adaptability safety.

The development of Li-ion battery safety standards has traditionally lagged behind the rapid progress in the industry. However, a comprehensive safety framework is now emerging. Initially focused on cells and battery modules, standards are now extending to the system level. Testing is also becoming increasingly stringent, simulating extreme use conditions. This evolution reflects the maturing Li-ion battery industry, which is gradually adapting to higher safety demands.

6. Future Trends

The energy storage landscape for data centers is evolving rapidly, driven by advances in battery technology, safety systems, and energy management. Emerging trends indicate that Li-ion batteries, particularly LFP variants, will continue to dominate due to their superior performance, safety, and sustainability.

6.1. Advancement in Battery Technology

6.1.1. Solid-State Batteries

- Solid-state batteries, which use solid electrolytes instead of liquid ones, are emerging as the next generation of energy storage. These batteries offer significantly enhanced safety by eliminating flammability risks and increasing thermal stability.
- Expected to revolutionize data center energy storage by providing higher energy densities and faster charging times, solid-state batteries could be ideal for high-performance applications. Mass production is anticipated within the next few years.

6.1.2. Enhanced Li-ion Chemistries

- Research into sodium-ion and other next-generation chemistries is underway, which could lower costs and improve sustainability while maintaining or enhancing the performance of traditional Li-ion systems.
- Hybrid systems combining lithium with other materials (e.g., magnesium or aluminum) are under development, which may offer higher capacity and longer lifespans.

6.2. Innovations in BMS

6.2.1. Real-Time Monitoring and Predictive Analytics

- BMS technology will continue to evolve, offering real-time monitoring of all battery parameters, including voltage, temperature, SOC, and SOH.
- Using AI and machine learning, future BMS solutions will be capable of predicting potential battery failures before they occur, enabling preventive maintenance and enhancing system reliability.

6.2.2. Integration with IoT and Cloud-Based Systems

- The incorporation of Internet of Things (IoT) technologies will enable real-time data collection and remote monitoring, allowing operators to track battery performance and conditions from any location.
- Cloud platforms will offer robust data storage and advanced analytics, allowing data centers to optimize battery operations and improve efficiency using large datasets and AI-driven insights.

6.3. Safety Innovations

6.3.1. Enhanced Fire Protection

- Research into fire suppression systems that do not rely on water, such as perfluorohexanone or other clean agents, is gaining traction. These systems will be ideal for data centers where traditional water-based systems might cause damage to critical infrastructure.
- The development of new thermal insulation materials and active cooling systems will help to mitigate the risk of thermal runaway, ensuring that even in extreme cases, heat is contained safely.

6.3.2. Battery Protection with Advanced Materials

- New solid or gel-based electrolytes are being developed to reduce volatility and enhance battery stability. These innovations will further improve safety, particularly in extreme operating conditions.
- Research into self-healing materials for batteries, which can repair small damages autonomously, could lead to longer-lasting and more resilient energy storage systems.

6.4. Optimized Energy Management

6.4.1. AI-Driven Energy Storage Optimization

- AI and machine learning will be increasingly used to optimize energy storage systems, balancing load distribution, improving efficiency, and minimizing energy costs in real time.
- Future data centers will leverage advanced energy storage solutions to optimize energy consumption by shaving peak loads, integrating renewable energy sources, and reducing reliance on the grid during high-demand periods.

6.4.2. Energy-Efficient Data Center Design

- As sustainability becomes a key focus, future data centers will increasingly adopt energy-efficient designs, such as liquid cooling systems, low-carbon energy sources, and advanced battery storage solutions.
- The concept of a circular economy will gain traction, where end-of-life batteries are reused, refurbished, or recycled to minimize waste and environmental impact.

6.5. Regulatory and Standards Evolution

As the use of Li-ion and other advanced batteries expands, regulations and safety standards will continue to evolve. Enhanced global safety standards, such as those being developed by IEC, UL, and other agencies, will be increasingly focused on addressing the specific challenges of energy storage systems in high-demand environments like data centers.

7. Conclusion

The future of Li-ion battery technology in data centers holds great promise. With advancements in battery chemistry, safety systems, and AI-driven energy management, data centers will achieve not only greater reliability but also enhanced sustainability. Embracing these innovations will be crucial for operators to stay ahead of the curve in an increasingly energy-conscious and competitive market.

Through comparison and analysis, LFP is recommended for use in data centers due to its superior safety and reliability. However, ensuring the successful application of Li-ion batteries in data centers goes beyond material selection. It encompasses a comprehensive approach, addressing critical aspects such as battery management system requirements, Li-ion battery room design, and transportation, storage, and installation protocols. This holistic strategy is essential for enabling the widespread and secure adoption of Li-ion batteries in data centers.

The safety of Li-ion batteries is directly tied to the stable operation of data centers, the protection of personnel, and the safeguarding of significant assets. It is a shared responsibility among all stakeholders - operators, builders, regulators, and technology developers to recognize the critical role Li-ion batteries play. These systems protect not only data but also the trust and safety of countless individuals who depend on the uninterrupted operation of data centers.

A high priority shall be given to Li-ion battery security by implementing robust safety frameworks and adhering to stringent standards. This approach will reinforce data center resilience, minimize risks, and ensure compliance with evolving regulatory requirements. By adopting cutting-edge fire suppression systems, temperature monitoring technologies, and early detection mechanisms, data centers can mitigate potential hazards associated with Li-ion batteries.

Additionally, regular maintenance and periodic testing of battery systems are critical for maintaining performance and identifying early signs of wear or failure. Implementing predictive maintenance strategies using AI and machine learning can further enhance system reliability by anticipating issues before they escalate.

Collaboration between industry stakeholders is also vital to fostering innovation and standardization. Establishing universal guidelines for Li-ion battery integration, transportation, and recycling will not only improve safety but also contribute to environmental sustainability by reducing the carbon footprint associated with data center operations.

As the digital world continues to expand, the demand for high-performance and energy-efficient data centers will only grow. By investing in advanced Li-ion battery technologies and adopting a proactive approach to safety and sustainability, the industry can meet this demand while supporting global efforts to transition toward a greener and more resilient future.

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