UNIVERSIDAD POLITÉCNICA DE MADRID

POLITÉCNICA

Máster Formación Permanente Energías Renovables y Medio Ambiente

Universidad Politécnica de Madrid

XVIII Edición 2023-24

Máster ERMA

Módulo 15
Plantas híbridas y de almacenamiento

El Litio y la Seguridad de los sistemas de almacenamiento

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Huawei Spain Digital Power

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Learning Objectives

- To understand the basic concept and categories of energy storage technology, to understand the working principles, advantages, disadvantages and current application status of different energy storage technologies, and construct the overall cognition of energy storage technology.
- In-depth understanding of the working principle, material system, technology trends, and composition of lithium-ion battery energy storage system;
- Learn about applications of lithium-ion battery energy storage systems in multiple areas
- Learn about the safety, service life and other characteristics of lithium-ion battery energy storage systems .

Content

Huawei: Leading provider of ICT infrastructure and smart devices

Vision & mission

Bring digital to every person, home and organization for a fully connected, intelligent world

Devices	**Connectivity**	**Cloud**
Intelligent Automotive Solution	**Computing**	**Digital Power**

207,000 employees

55% employees work in R&D

170+ countries and regions

No. 5 in global R&D investment

140,000+ active patents held globally

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Global R&D teams and technology platforms: Leveraging the domain specific advantages globally to keep leading. Optimal professional person for optimal **Digital Power Solutions: PV, ESS, EV, DCF**

170 Countries

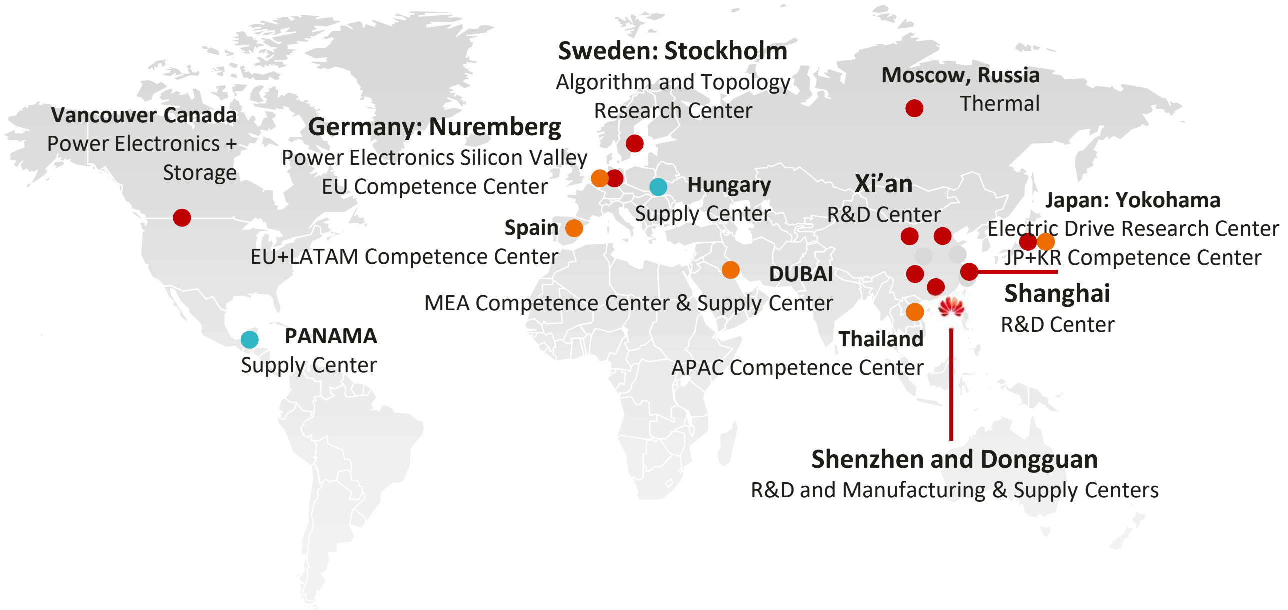
10000+ Employees
60%+ R&D

12 R&D Centers

20%+ R&D investment

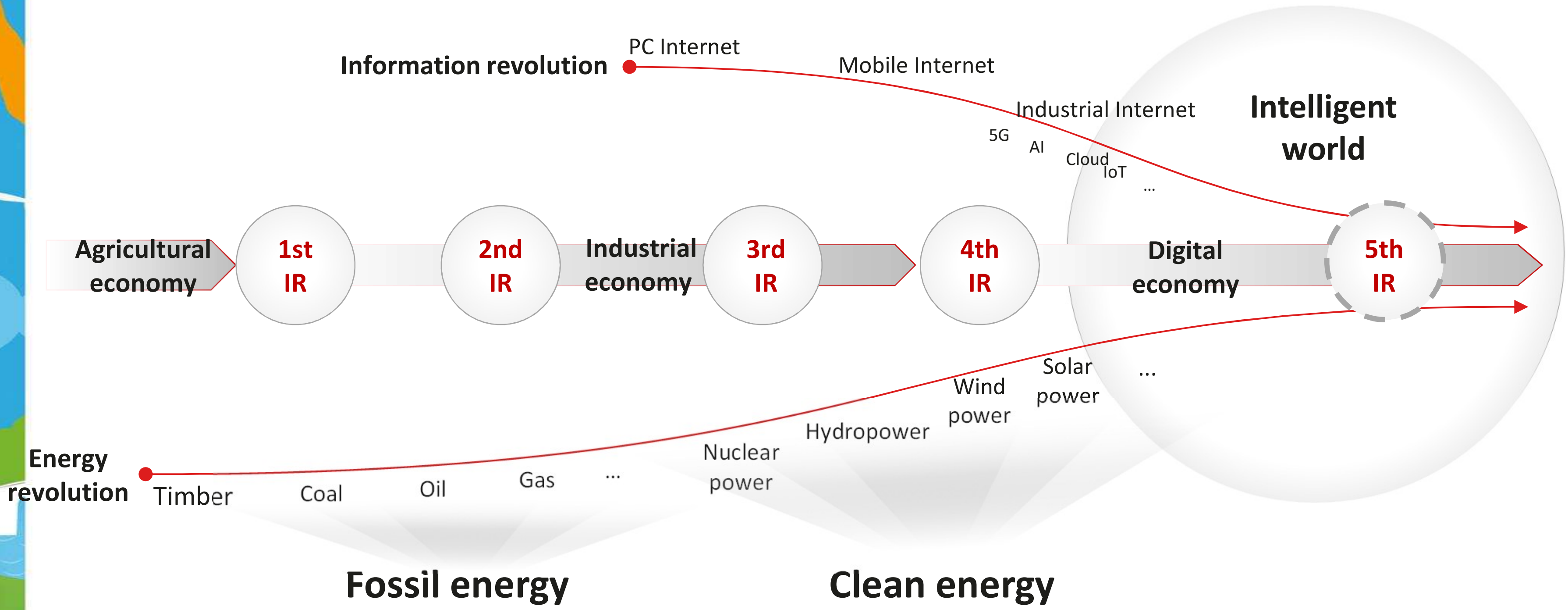
4 Supply Centers

2122 active Patent



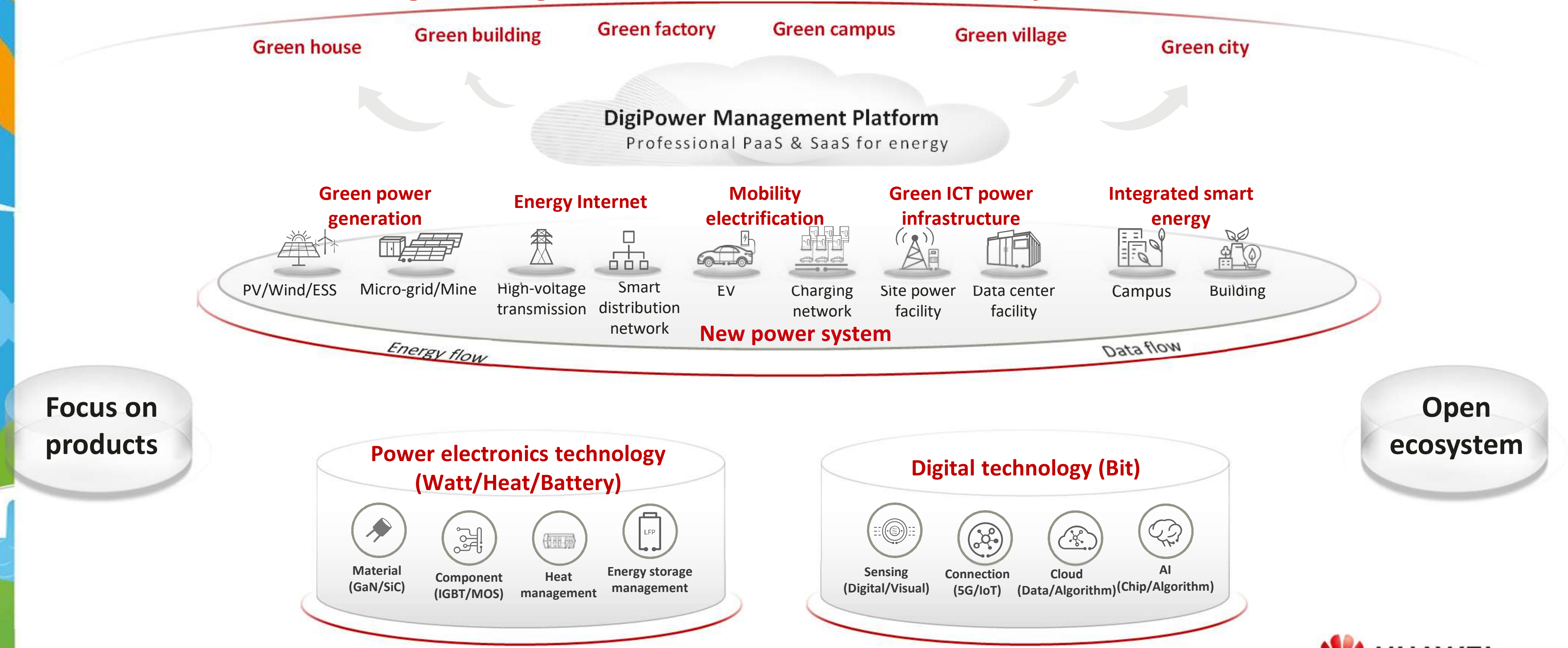
Watt:	Heat:	Battery:	Bit:
Sweden/Germany/Canada	Sweden/China	Canada/China	China/Germany

The 5th Industrial Revolution goes hand in hand with low-carbon, digital, and intelligent
The 5th Industrial Revolution goes hand in hand with low-carbon, digital, and intelligent
transformations, all of which bring us closer to the intelligent world



Huawei Digital Power: Integrating digital and power electronics technologies, developing clean power, and enabling energy digitalization to drive energy revolution for a better, greener future

Evolving from high carbon to low carbon, and finally to net-zero carbon



Carbon Neutrality has Become a Global Consensus, PV+ESS has Become the General Trend

Carbon Neutrality Has Become the Global Consensus. Top Enterprises are Practicing Green Transformation

Carbon Neutrality Targets for Major Economies

China	European Union	United States	Japan
2030 Carbon Peak **2060** Carbon Neutral	Released Green New Deal **2050** Carbon neutral	Return to the Paris Agreement **2050** Carbon neutral	Launch of Green Growth Plan **2050** Carbon neutral

The Top Enterprises Actively Practice Carbon Neutrality

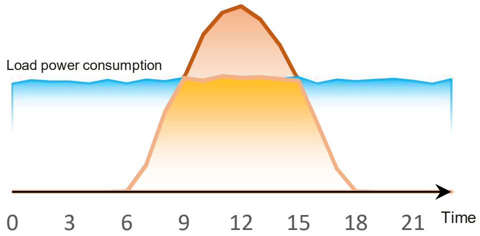
379 companies joined RE100 alliance, commit to use 100% green electricity

Well-known companies have proposed carbon-neutral goals

Google	ABB	Tencent
2020	2030	2030
Alibaba Group	**amazon**	**P&G**
2030	2040	2030

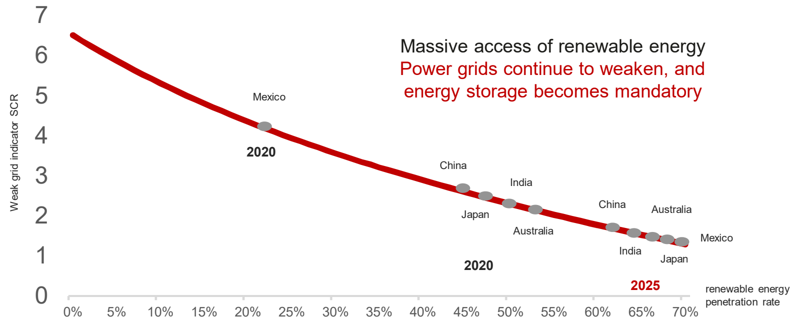
Energy Transformation Trend: From PV only to PV+ESS Solution

PV + ESS to Avoid Solar Energy Waste and Maximize the Revenue



- Only PV power cannot cover the 24h power supply
- PV+ESS synergy increases the proportion of green power supply

With the Increase of New Energy Penetration Rate, the Supply Grid Becomes Weaker. Adjustment Provided by ESS is Essential.



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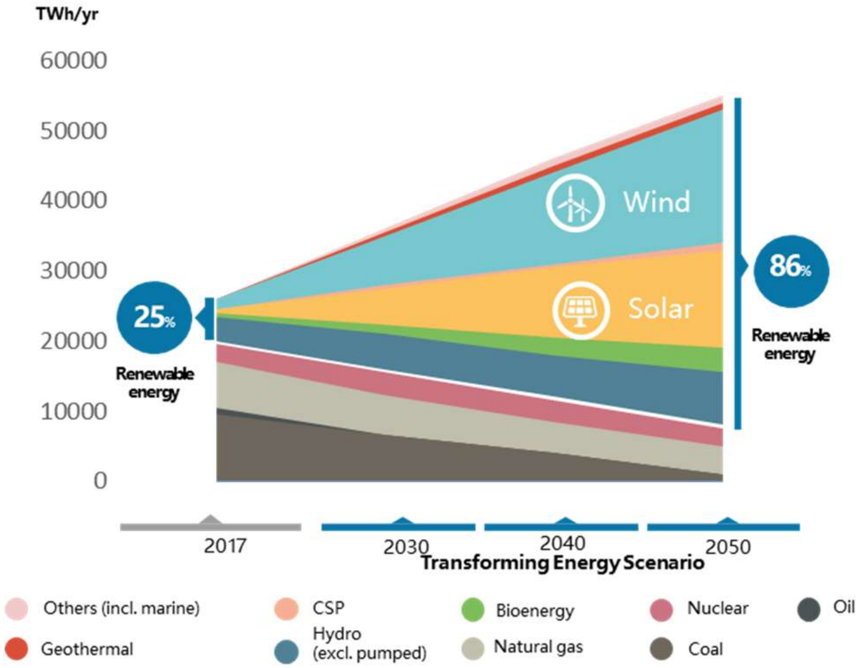
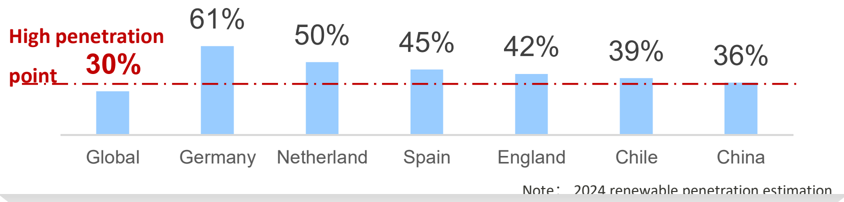
High penetration renewable energy has led to weak grid and the issue of stability of the power system

Rapid growth in proportion of renewable energy



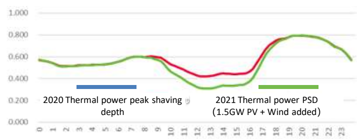
Source: *IEA Energy Outlook*

Renewable penetration severe challenges to the safe and stable



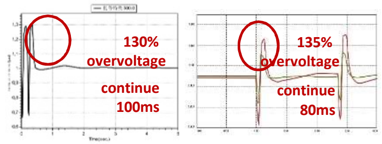
Peak/Frequency Regulation

Thermal power is close to the peak-shaving limit



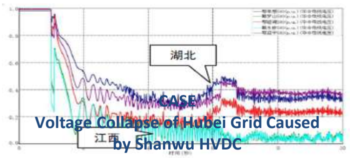
Transient Overvoltage

HVDC overvoltage issues Caused 130%+ overvoltage



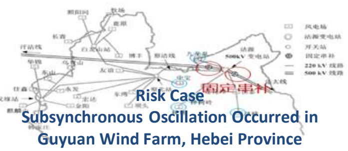
Voltage Stability Margin

HVDC is faulty causing voltage collapse



Broadband Oscillation

Risk of low frequency/ sub synchronous / super synchronous oscillations



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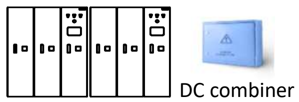
Convergence of PV & BESS industries towards string architecture

Solar

Central Inverter

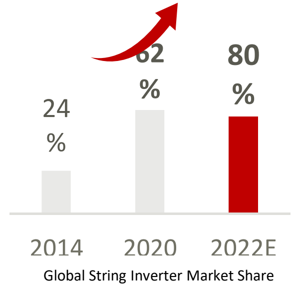


2000+ PV modules / MW

- 1 MPPT centralized Management
- Lower availability around 98%
- single failure recovery cost longer time
- Higher replacement cost
- More Spare parts, hard to find in lifecycle

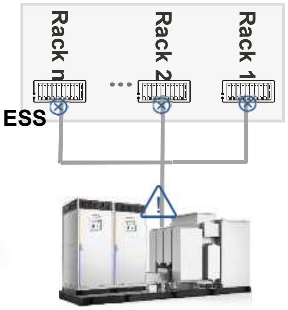
Smart PV Controller

- More MPPT, more yields
- 99.99% availability，more flexibility
- Single failure influence is limited
- Easy O&M and replacement
- Inverter is spare part



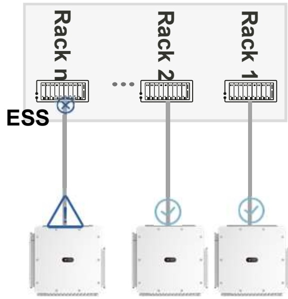
Energy Storage

Central ESS: Centralized rack extensive management



- One central PCS manages 2000 battery cells in series & parallel causes severe mismatch capacity
- Reduced usable capacity, quick degradation & massive O&M costs & poor safety.
- Failure recover take more time
- Lower availability

Smart String ESS: Distributed and refined rack management



- Independent control of battery packs & racks
- Isolation of faulty pack
- No need of SOC calibration
- Single failure influence is limited
- Higher availability

Challenges in Battery Energy Storage System Industry

Low Available Capacity

- Series & Parallel mismatch due to inconsistency between battery cells, which leads to lower available capacity according to Cannikin Law

Pack & Rack Optimizer

Complex O&M

- On-site battery installation wiring & commissioning
- Regular SOC calibration by professional staff

No need for periodic balancing
No need for experts to visit sites

Fire Risks

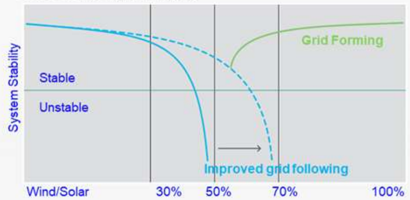
- Battery cell over-charge, over-discharge ,or other faults
- Key components(circuit boards, contactors, etc.) failure cause sparking and arcing

Cell to system safety protection
Avoid thermal runaway

Grid Forming

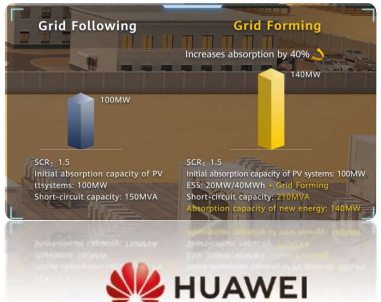
EU considers grid forming as a key to high wind/solar penetration

2020 EU MIGRATE Project



The European Power Grid Code (RfG) raised requirements of Grid Forming for Type A-D power generating modules

Grid forming increase absorption of PV capacity by 40%



Network security directly challenge grid stability

Cyber Attack Causes Large Power Outages

First power system cyber attack in Eastern Europe all over the world

- Hackers hacked into SCADA systems of three power distribution companies.
- Some substations were disconnected,
- causing power failure for six about 225,000 users.

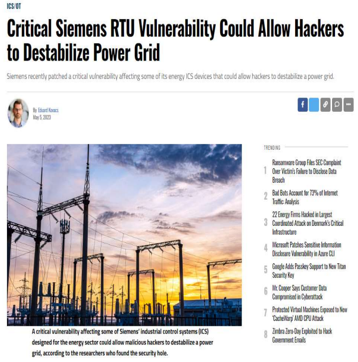
Device Vulnerability

A German solar inverter vulnerability seriously threatens European grid

- According to Netherlands Volkskrant, it is claimed that the security vulnerability has affected thousands of inverters used in European grid. Once hackers take control inverters and shut them down, it can cause widespread blackouts across Europe.

Vulnerability of industrial control system

Remote transfer unit vulnerabilities Lead to grid unstability



- There is a company industrial control system (ICS) has a critical vulnerability, directly affecting remote transfer unit ;
- Unauthenticated attackers can take complete control of the device, even cause power outages by changing critical automation parameters.

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BESS system safety design challenge grid stability

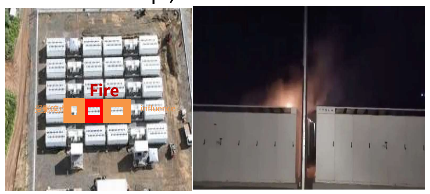
Risk source

- 1, 2 — **Non-battery risks**: Short circuit / Arcing / Open flame
- **External risks**: Vibration / Drop / Condensation
- **Electrical risks**: Insulation failure / Overvoltage and
- 3 — **Internal defects**: Burr/Bonding / Lithium plating
- **Control failure**: Sampling/Communication / BMS fault

BESS failure path causes safety risks

Sharp temperature rise/Open valve → Thermal runaway → Thermal runaway diffusion → Violent explosion

location	1 Elkhorn BESS Project in Moss Landing, California, USA **BESS runs for only half a year**
Fire reason	The main cause is that the umbrella valve warping caused rainwater to drip into BESS
Loss	Around 2 Million USD
Pic.	Sep., 2023 

location	2 Bouldercum Battery Project Queensland, Australia **BESS is in the charging state**
Fire reason	External water flows into the busbar copper bar
Loss	Around 3 Million USD
Pic.	Sep., 2023 

location	3 Guangtong Logistics Park Zhuhai, China **BESS runs for only 2 years**
Fire reason	The positive copper foil of the battery is not evenly coated, which is mismatch in cells caused battery thermal runaway.
Loss	Around 0.5 Million CNY
Pic.	Aug., 2023 

Grid Forming is considered a Vital Technology for Weak Power Systems

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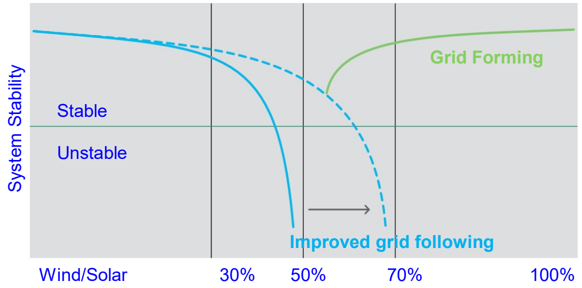
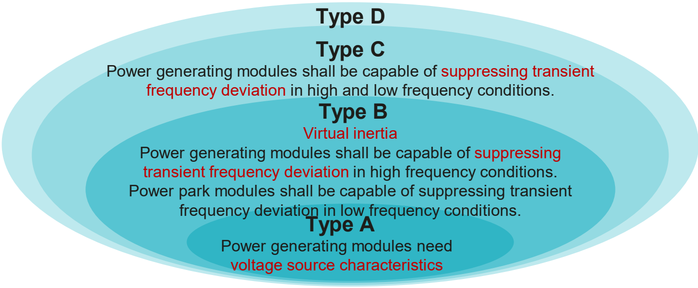
EU considers grid forming as a key
to high wind/solar penetration

2020 EU MIGRATE Project



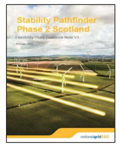
The European Power Grid Code (RfG) raised requirements of Grid Forming for Type A-D power generating modules



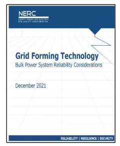
Guidelines and pilot projects are emerging

① China、UK、USA、Australia has released guidelines for GFM

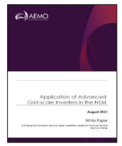
2023. Jul, China
Grid Forming standard



2021. Feb, UK
Grid Forming standard



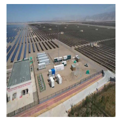
2021. Dec, USA NERC
Guideline for Grid Forming



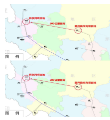
2021.Aug, Australia, AEMO
'Advanced grid-scale inverter'

② Huawei has participated in multiple GFM tests in real sites

2024, Xinjiang , China
25MW/100MWH
In SCR ≈ 2



2024, Qinghai , China
50MW/100MWH
In multi source PV/Wind/CSP



2024, Tibet , China
6MW/24MWH
In 70% penetration rate

③ Commercial BESS adopts GFM to enhance system strength

** Based on public news*

ZENOBĒ ENERGY

agl

- UK developer Zenobe **plans to build more bigger scale BESS projects (with GFM features) from 2023Q4-2024Q4**
- Australia: A system strength shortfall of 312MVA was identified, **AGL proposes to build 250MW/250MWh GFM BESS to support system strength.**

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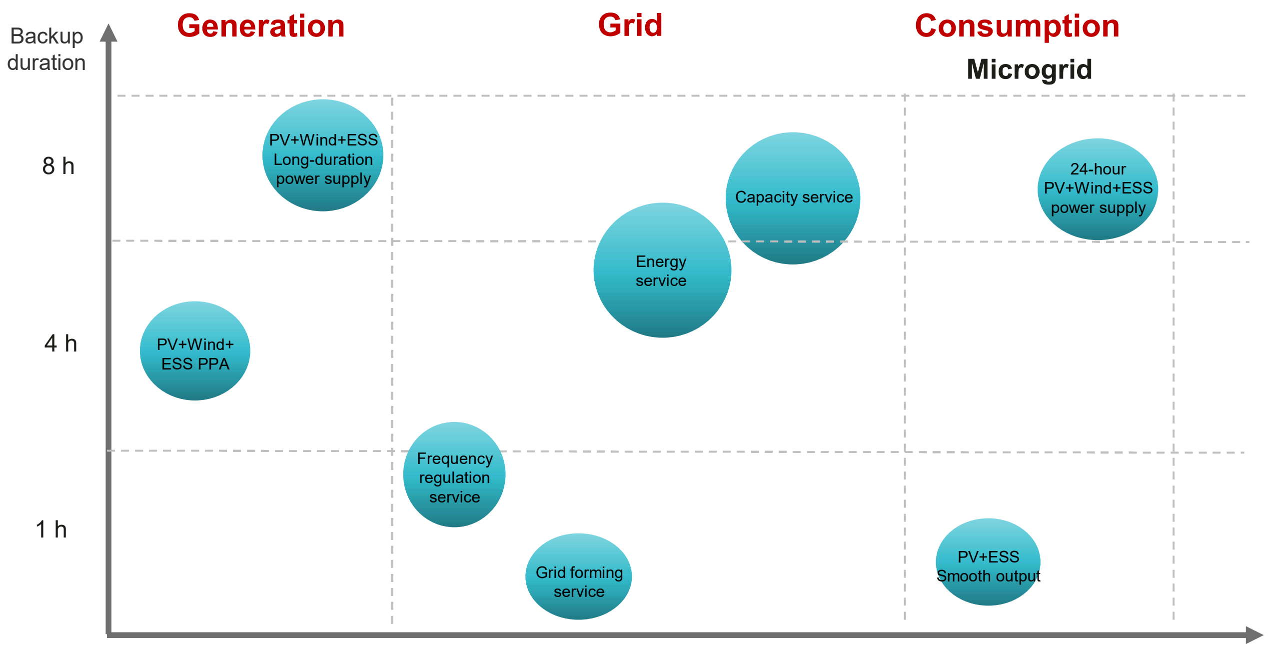
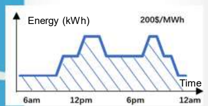
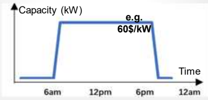
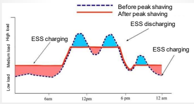
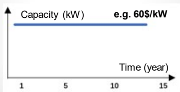
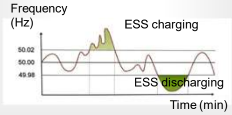
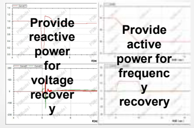
Cover Multiple Scenarios Such as Power Generation, Transmission, and Consumption, Improve Wind and PV Power Integration, Stabilize Power Grid Operation, and Reduce Power Consumption Costs

- Generation: Replace the conventional genset power supply with the joint operation of PV+Wind+ESS. Promote PV+Wind+ESS to optimize the PPA electricity prices of PV+wind.
- Grid: Leverage ESSs in power grid services to ensure the stability and balance of power grid operations.
- Consumption: Promote PV+ESS to improve self-consumption, facilitate time-of-use (ToU) arbitrage, and delay power distribution network revamping to reduce power consumption costs.



Seven Business Models for ESS Customers, Ensuring Safe, Stable, and Balanced Power Grid Operations

	Generation		Grid				Consumption
Scenarios	PV+Wind+ESS PPA	Long-duration PV+Wind+ESS power supply	Energy market	Capacity market	Frequency regulation market	Grid forming market	Microgrid market
Business models	1. Sign the **ToU PPA** to generate revenue based on the ToU arbitrage model. 	1. Generate power based on the **around-the-clock output** curve and obtain the PPA revenue. 2. If the output curve is not followed, corresponding **penalty rules** will apply. 	1. Obtain revenue based on the electricity price forecast and charge/discharge price differences between peak and off-peak periods. 	1. Compete with conventional generators in grid capacity compensation bidding. A fixed contract for 15 to 17 years will be signed if the bid is won. 2. A notice is sent in advance. If the capacity requirements are not met, a **penalty** will be imposed. 	1. Fair bidding for ESSs and conventional generators Power compensation will be achieved if the bid is won. Energy compensation will be available if required. 2. If the response time, adjustment precision, and compensation requirements for adjustment are not met, **penalties** will be imposed. 	1. Fair bidding based on grid forming service technical requirements for condensers, retired thermal power facilities, and grid-forming ESSs 2. **Penalties** will be imposed if the response time, inertia/reactive support capability, and availability requirements are not met. 	1. In PPA mode, the IPP sells electricity only during the period with sufficient irradiance (8 am to 18 pm) in the daytime. The ESS configuration is reduced as much as possible, the initial investment is reduced, and the payback period is shortened. Only the ROI of the PV+ESS system is considered. 2. The customer-built mode is used to reduce the comprehensive power supply cost. The construction can be performed in batches, and the PV+ESS substitution rate will be gradually increased.
Scenario characteristics	• Low LCOE of PV+ESS power generation • The actual charge and discharge curves match the curves in the quotation. • **Output based on power grid dispatching requirements**	• Low LCOE of PV+ESS power generation • **Stable supply of constant power** based on constant power to loads • More accurate wind+PV power generation curve	• More accurate electricity price prediction in the power market • The actual charge and discharge curves match the curves in the quotation. • **Charge when the electricity price is low and discharge when the electricity price is high based on the power grid dispatching requirements.**	• The discharge capacity at the POC remains unchanged within the contract period of **15 to 17 years**. • The system keeps **online around the clock at constant power** and can be dispatched by the power grid at any time.	• Keeping **online around the clock**, ensuring high availability in all scenarios • More accurate prediction of frequency regulation prices • Fast frequency regulation: high requirements on response time • Primary frequency regulation: requirement for a wide range at constant power; secondary/tertiary frequency regulation: high efficiency requirement, directly affecting the revenue proportion	• Keeping **online around the clock**, real-time grid inertia and transient voltage support • A longer inertia adjustment process and stronger reactive support indicate greater revenue.	• Applies to areas with no or weak power grids to replace gensets, ensuring power supply and reducing the overall power consumption cost.
Key requirements	• Capacity usage • Round-trip efficiency (RTE) • Availability	• Capacity usage • RTE • Availability	• Capacity usage • RTE • Availability	• Capacity usage • Discharge efficiency • Flexible augmentation • Availability	• Online around the clock, high availability • SOC range at constant power • High SOC precision • Shorter response and adjustment time	• Online around the clock, high availability • Meeting admission requirements for the grid forming market • Enhanced reactive overload capability and inertia duration	• Full-stack solution • Availability and reliability • Easy commissioning and O&M
Regions	Chile, North America, etc.	South Africa, UAE, Philippines, etc.	China, Europe, North America, etc.	Italy, Poland, and Belgium UK, Ireland, and North America	West Europe (France, Germany, Czech, Belgium, etc.), North Europe, HI region, Singapore, UK, Ireland, etc.	China and Germany UK, Australia, etc.	China, Northern and Southern Africa, Latin America, etc.

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Content

Definition of Energy Storage Technology

Wikipedia: Energy storage or energy storage technology refers to the technology that stores energy and uses it when needed.

Generalized energy storage: energy storage is a cyclic process in which energy such as electric energy, thermal energy, and mechanical energy is stored from the same form or converted into another form, and then released in the form of specific energy when used in the future.

Energy storage in a narrow sense: refers to a series of technologies and measures that use chemical or physical methods to store electrical energy and release it when needed.

Common Energy Storage Products and Applications

Consumer domain

Transportation field

Electric power field

Classification of energy storage technologies

According to different energy conversion and storage forms, energy storage technologies can be divided into five categories: mechanical energy storage, electrochemical energy storage, thermal energy storage, electromagnetic energy storage and chemical energy storage. In terms of energy release, except thermal energy storage, other energy storage technologies generally release energy in the form of electric energy.

energy storage technology

mechanical energy storage

- Pumped storage hydropower
- flywheel energy storage

The use of mechanical systems to convert electrical energy into potential or kinetic energy for storage.

electrochemical energy storage

- Lead-acid battery energy storage
- Li-ion battery energy storage
- liquid flow battery energy storage
- Other new battery energy storage

The use of battery devices to convert electrical energy into chemical energy for storage.

electromagnetic energy storage

- supercapacitor energy storage
- superconducting magnetic energy storage

Electric energy is converted into electric energy or magnetic field energy by means of electric field or magnetic field device and stored

chemical energy storage

- Hydrogen and synthetic natural gas energy storage

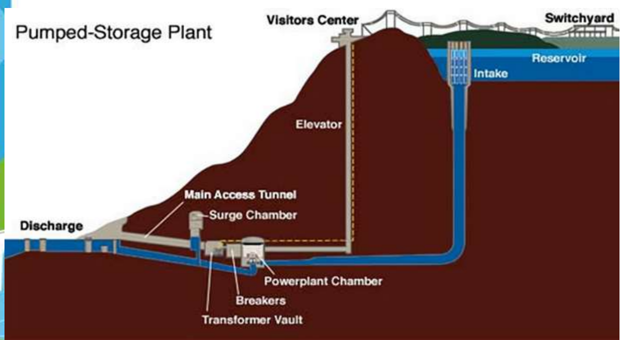
The use of chemical equipment to convert heat or electrical energy into chemical energy for storage.

thermal energy storage

- sensible heat energy storage
- latent heat energy storage

Heat energy is stored in the form of sensible heat or latent heat by means of heat storage medium (such as water and molten salt).

Mechanical energy storage - pumped storage hydropower



Basic Principles	When surplus of electricity, the excess power is used to pump water from low-level reservoir to high-level reservoir, and the electric energy is converted into gravity potential energy for storage. The water from the high-level reservoir flows back to the low-level reservoir during peak power consumption to push the turbine generator to generate electricity.
Advantages	1) Large-scale (GW/GWh) and centralized energy storage technology; 2) Long service life, usually up to 40-60 years
downsides	1) The selection of plant site depends on geographical conditions (two reservoirs with different elevation levels are needed) and has certain difficulties and limitations; 2) Long construction period of pumped storage hydropower station (It takes 7-8 years from start-up to commissioning of all units); 3) It may have some influence on ecological environment.
Application Status	1) Mainly applied to large power grid regulation, together with nuclear power and thermal power for peak regulation, phase regulation, frequency regulation and power system backup; 2) By the end of 2019, the global installed capacity of pumped storage hydropower was 171.0GW, accounting for 92.6% of the global installed capacity of electric energy storage. 3) By the end of 2019, the accumulated installed capacity of pumped storage hydropower in China was 30.29GW, accounting for 93.4% of the total installed capacity of electric energy storage.

Mechanical energy storage - flywheel energy storage

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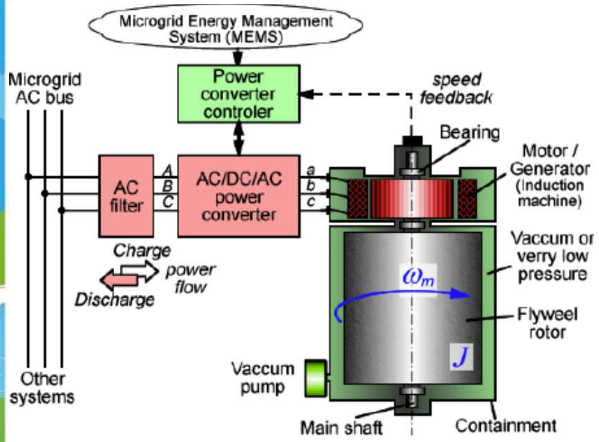


Basic Principles

When surplus of electricity, the motor drives the flywheel to rotate at high speed, converting the electric energy into kinetic energy storage; When electrical is in shortage, the motor is switched to generator operation, which converts the kinetic energy of the flywheel into electrical energy. That is, the flywheel energy storage realizes the storage and release of electric energy through the acceleration and deceleration of the rotor.

Advantages

1) High power density (up to 4 kW/kg);
2) Durable with long lifecycle (million level);
3) High charging and discharging efficiency (over 90%);
4) Less maintenance and good stability;

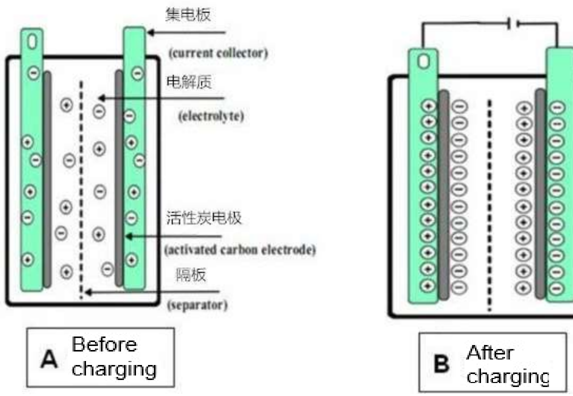
Downsides

1) The energy density is low (20-80 Wh/kg), and the discharge lasts only a few seconds to a few minutes;
2) High self-discharge rate due to bearing wear and air resistance.

Application Status

1) Flywheel energy storage is a typical power-based energy storage technology and is applicable to power distribution network for frequency adjustment and data center UPS scenarios.
2) By the end of 2019, flywheel energy storage accounted for 0.2% of the total installed electricity energy storage capacity worldwide.

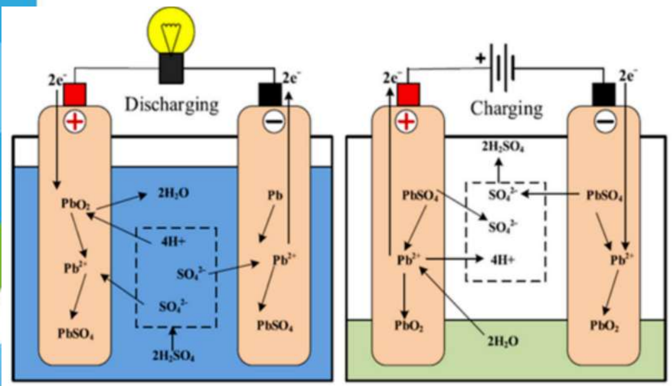
Electromagnetic energy storage - supercapacitor energy storage



electric double layer supercapacitor

Basic Principles	**Double-electric layer supercapacitor**: When the electrode is charged, the electric charge on the surface of the electrode attracts the heterogeneous ions in the surrounding electrolyte, and the ions attach to the surface of the electrode to form a double electric charge layer, forming a potential difference between the two solid electrodes, thereby realizing energy storage. Double-layer capacitors store energy through electrostatic interaction. **Faraday pseudocapacitor**: It is an electrochemical action (Faraday reaction) to realize energy storage. The electroactive material has reversible chemisorption or redox reaction in the two-dimensional surface or three-dimensional space of the electrode body phase.
Advantages	1) High power density (5-30 kW/kg) 2) Many cycles, up to one million 3) charging and discharging efficiency > 90%;
downsides	1) Low mass energy density (usually <20Wh/kg); 2) High initial investment cost;
Application Status	1) It is used for braking energy recovery and instantaneous high power scenarios. 2) It is applied in the fields of diesel locomotives, tramcars, subways and port hoisting machinery;

Electrochemical energy storage-lead-acid battery energy storage



Basic Principles

Lead-acid batteries are one of the most widely used batteries in the world. The positive electrode (PbO2) and the negative electrode (Pb) in the lead-acid battery are immersed into the electrolyte solution (sulphuric acid), and the battery is charged and discharged through the following reaction:

(positive electrode) (electrolyte) (negative electrode)

PbO2 + 2H2SO4 + Pb --->PbSO4+2H2O+PbSO4 (discharge reaction, negative electrode oxidation, positive electrode reduction)

(positive electrode) (electrolyte) (negative electrode)

PbSO4 + 2H2O + PbSO4--->PbO2+2H2SO4+Pb (charge reaction, negative electrode reduction, positive electrode oxidation)

Advantages

1) simple structure, safe and reliable;
2) Mature application, low price, and high cost-effectiveness

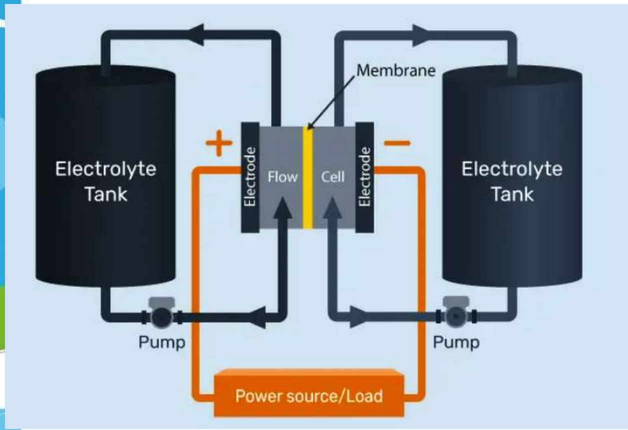
downsides

1) poor discharge performance at large discharge C-rate;
2) low energy density (40-80Wh/kg);
3) Relatively less cycles (~1000 times)

Application Status

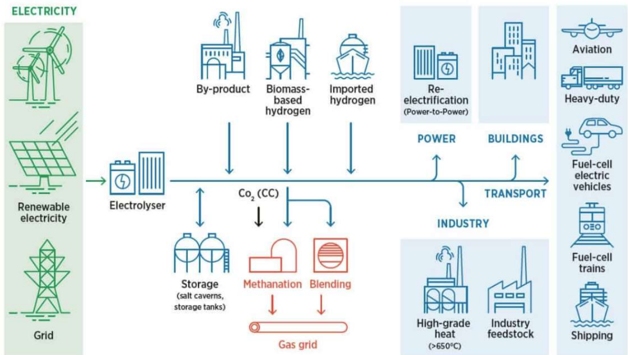
Lead-acid batteries are mostly used for starting power supply of automobiles and backup power supply of electric power system. There is a trend of accelerated replacement by lithium-ion batteries.

Electrochemical energy storage-flow battery energy storage



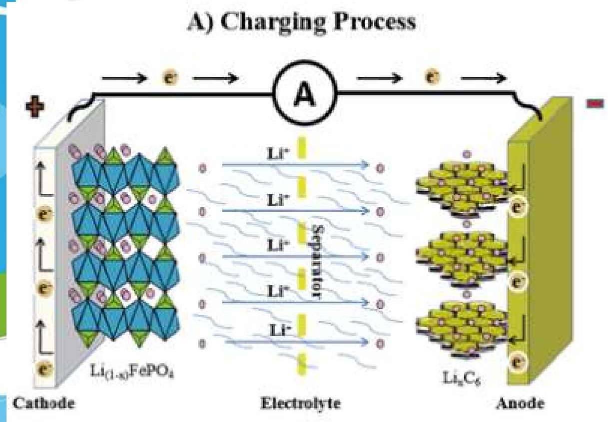
Basic Principles	In a flow battery system, it usually consists of two containers and a stack in which the electrolyte is stored (Energy stored in electroactive substances of liquid electrolytes) The electrolyte in the container is pumped into the battery stack by a pump. The electrolyte converts electric energy and chemical energy through an oxidation-reduction reaction at the diaphragm.
Advantages	1) The system capacity and power can be decoupled based on the application scenario requirements. (Capacity depends on electrolyte storage and power depends on the area of the stack diaphragm); 2) The number of cycles exceeds 10,000;
downsides	1) The price of energy storage systems is high. 2) low energy density and power density; 3) Low charging and discharging efficiency;
Application Status	1) Flow battery has various electrolyte systems, and all-vanadium flow battery is most widely used at present; 2) By the end of 2019, there were more than 200 all-vanadium flow battery energy storage demonstration projects worldwide, with a total installed capacity of about 86 MWh.

Chemical energy storage - Hydrogen



Basic Principles	Hydrogen obtained by thermochemical Processes Of natural gas, biomass, coal and electrolysis of water, can be purified and directly used as energy carrier; Alternatively, hydrogen is re-reacted with carbon dioxide to form synthetic natural gas (methane), which is used as another secondary energy carrier. Energy is stored as chemical bonds in hydrogen or methane.
Advantages	1) the energy storage capacity is large, which can reach the TWh level; 2) Hydrogen can be stored for a long time, up to several months
downsides	1) The energy efficiency of the entire chain is low (only 30% to 40%). 2) High cost of hydrogen or synthetic natural gas production
Application Status	Hydrogen or natural gas fueled thermoelectric cogeneration or cold-heat-electric cogeneration systems has mature usage in distributed power generation and microgrid.

Electrochemical energy storage - lithium ion battery energy storage

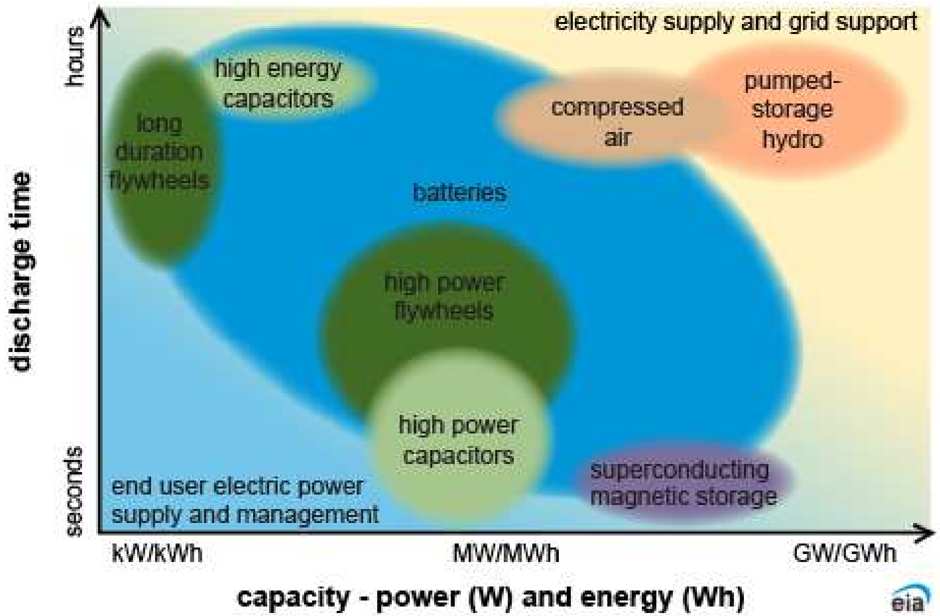


Basic Principles	When the battery is charged, lithium ion is removed from the positive electrode material, enters the electrolyte under the action of electric field force, passes through the diaphragm, migrates to the surface of the negative electrode material, and then is intercalated in the negative electrode material. When the battery is discharged, the transfer direction of lithium ion is opposite to that of charging.
Advantages	1) high energy density up to 300Wh/kg; 2) the charging and discharging efficiency is up to 90%; 3) cycles, up to 5000 times
Downsides	1) The initial investment is higher than that of lead-acid batteries; 2) Safety problems such as high heat and fire caused by improper management of over-charge and discharge
Application Status	1) Lithium-ion batteries have excellent comprehensive performance and are widely used in portable and mobile devices such as electric vehicles, laptops, and mobile phones, and have become the most widely used batteries in the world; 2) Lithium-ion battery production is rising, prices are falling, and application space is expanding. In 2019, the installed capacity of power batteries for new energy vehicles is about 115.2 GWh, while the installed capacity of batteries in global electricity storage capacity is 8.5 GWh.

Energy storage technologies for electriciy generation by type, rango of capacities, and general applications

Aspects of storage technologies:

- Range of application of storage technologies: Power output (MW) & Energy Storage (MWh)
- Storage technologies capacity in terms of discharge time at rated power which defined the system power ratings: Power Quality & UPS, Bridging Power and Energy Management
- Efficiency and lifetime of storage tecnologies (RTE – Lifetime)
- Mass and volumen densities of storage technologies
- CAPEX and OPEX



Source: U.S. Energy Information Administration, adapted from Energy Storage Association
Note: This is a general representation of the range of capacities and duration of electricity discharge for the types of energy storage technologies for electricity generation that are currently deployed in the United States. Excludes hydrogen, which potentially could encompass the entire range of capacities and discharge times. Some types, especially batteries, include technologies with a range of capacities and applications. kW is kilowatts; H is hours, MW is megawatts; GW is gigawatts.

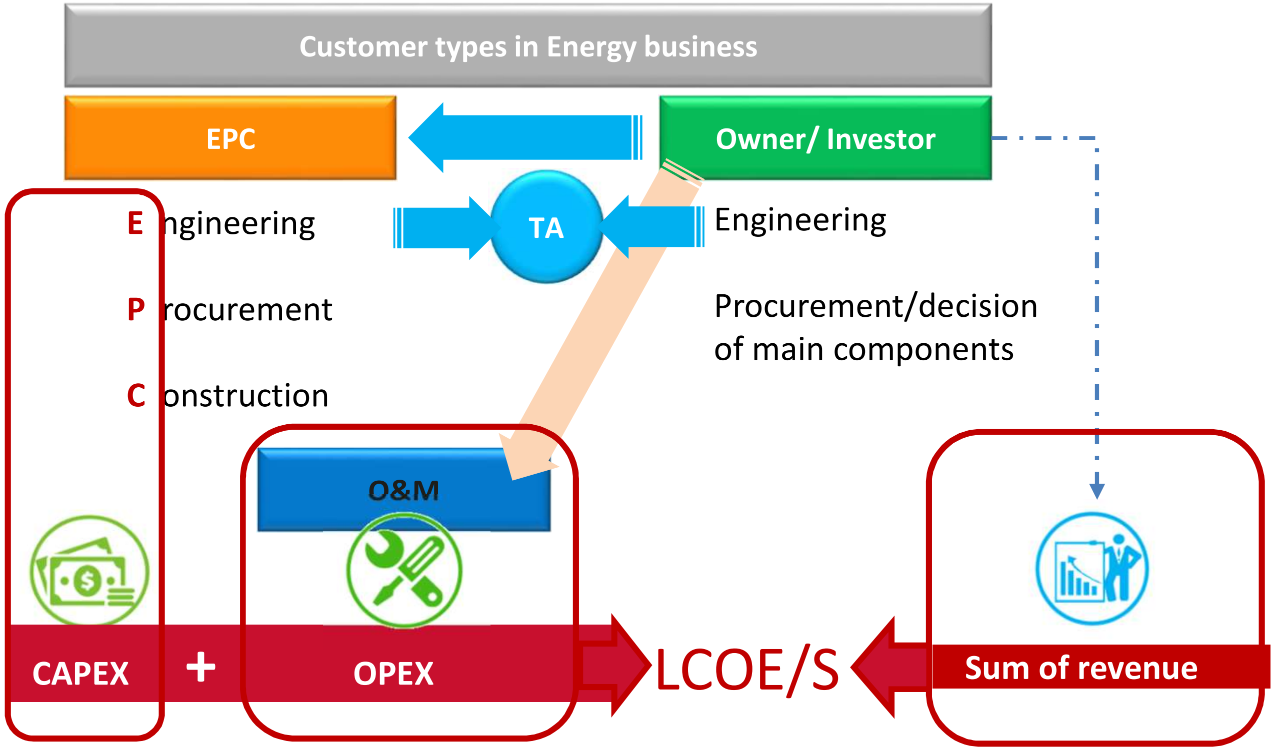
Comparison of energy storage technology characteristics

Indicators	electrochemical energy storage		mechanical energy storage		electromagnetic energy storage
	Lead-acid battery energy storage	Lithium ion battery energy storage	pumped storage hydropower	flywheel energy storage	double-layer supercapacitor
Capacity scale	100 MWh	100 MWh	**GWh**	MWh	MWh
Power scale	Dozens of MW	100 MW	**GW**	Dozens of MW	Dozens of MW
Energy density / Wh. Kg-1	40 - 80	**80 - 300**	0.5 - 2	20 - 80	2.5-15
Power density/W.Kg-1	150 - 500	**1500 - 3000**	0.1-0.3	> 4000	**1000 - 10000**
Response Time	milliseconds	milliseconds	**minutes**	milliseconds	milliseconds
Number of cycles	- 1000	2000 - 10000	> 10000	**million times**	**million times**
service life	5 - 8 years	10 to 15 years	**40 - 60 years**	20 years	15 years
charge and discharge efficiency	70 - 80%	> 90%	70% - 80%	85% - 95%	> 90%
Advantages	High security and low investment	**high energy density, many cycles,** high charge and discharge efficiency	Large capacity and power scale, **Long service life**	High power density, many cycles, and high charge/discharge efficiency	High power density, more cycles and good safety
disadvantage	**The discharge performance of large C-rate is poor,** Low energy density and fewer cycles	Improper charging and discharging management leads to safety problems, High initial investment	**Slow response, limited by environment, long construction period, and impact on ecology**	Small capacity and high investment, Low energy density and high self-discharge rate	Small capacity and high investment **Low energy density**
Application Areas	Vehicle starting power supply, standby power supply	Terminals, electric vehicles, and electric energy storage	Electric energy storage	Grid Power storage (grid frequency modulation), UPS	Rail transit (braking energy recovery, start-up)

Players and key concepts to understand key metrics for Energy Storage Tecnology

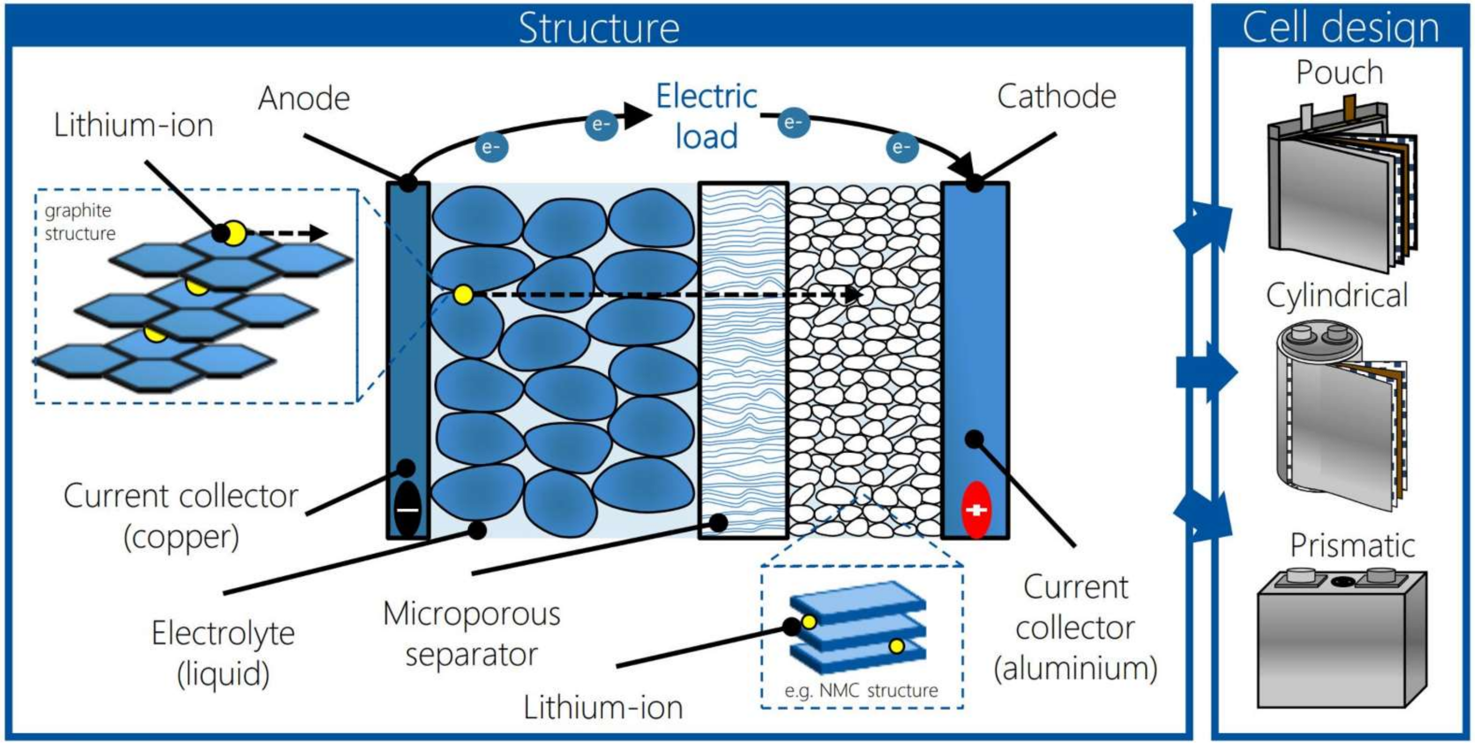
Ultra Safety

Stable
Grid Forming

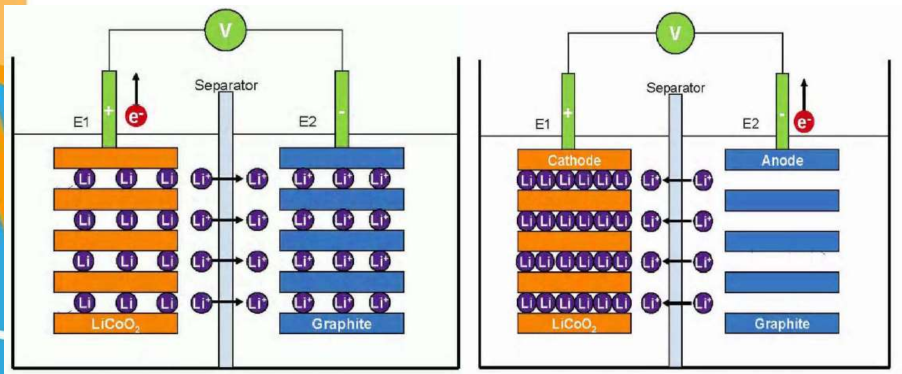


Content

Operating Principle of a lithium-ion battery cell



How Lithium-ion Battery Works



Charged Electrode

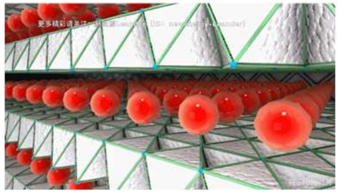
Discharged Electrode

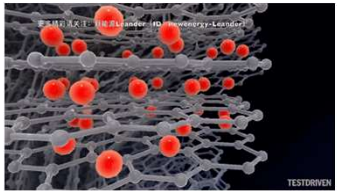
Cathode Reaction $:LiCoO_2 \underset{discharge}{\overset{charge}{\rightleftharpoons}} Li_{1-x}CoO_2 + xLi^+ + xe^-$

Anode Reaction $:6C + xLi^+ + xe^- \underset{discharge}{\overset{charge}{\rightleftharpoons}} Li_xC_6$

Overall Reaction $:6C + LiCoO_2 \underset{discharge}{\overset{charge}{\rightleftharpoons}} Li_{1-x}CoO_2 + Li_xC_6$

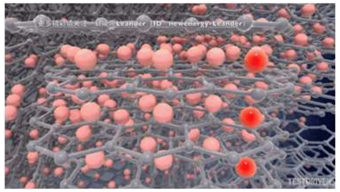
Charging process

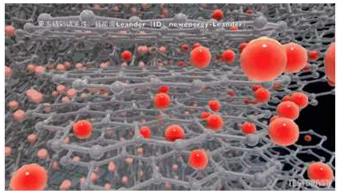




- During charging, the positive electrode material loses electrons, and lithium ion is de-intercalated from the positive electrode material.
- Lithium ions reach the negative electrode through electrolyte and diaphragm and are intercalated in graphite layer, while electrons reach the negative electrode through outer circuit until charging is completed.

discharge process



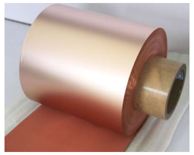


- During discharge, electrons exit from the negative electrode material and flow to the positive electrode through the outer circuit. Lithium ions also exit from the graphite after losing electrons.
- The de- intercalated lithium ions return to the positive electrode through the electrolyte and the diaphragm again, and combine the electrons that reach the positive electrode through the outer circuit to form a relatively stable lithium- intercalated positive electrode material;

Important materials for lithium-ion batteries

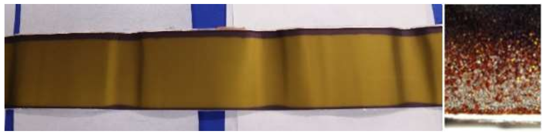
- Active material (graphite)
- binder
- dispersant
- conductive agent

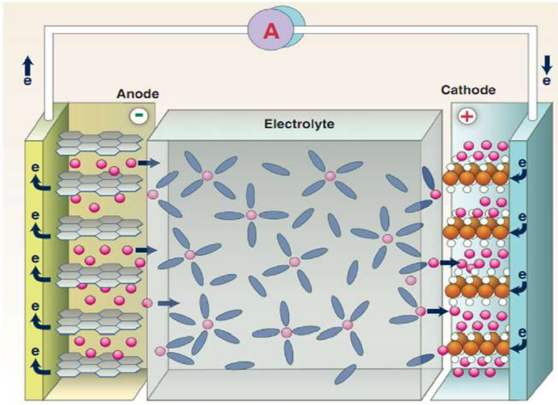
negative electrode



Negative electrodes current collector (copper foil)

The negative electrodes sheet is golden in full charge state





Separator

- lithium salt
- mixed solvents
- Additives

electrolyte

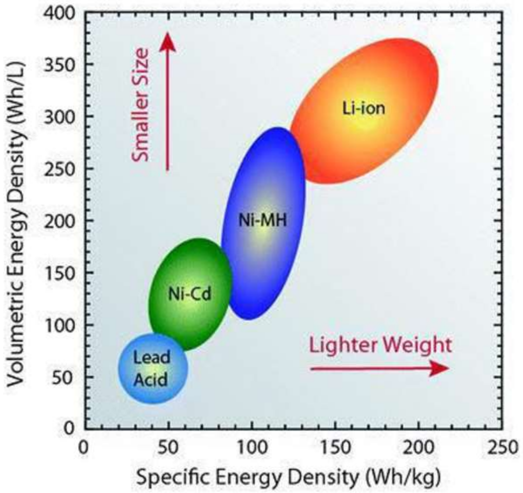
positive electrode

- Active material ($LiCoO_2$)
- conductive agent
- binder

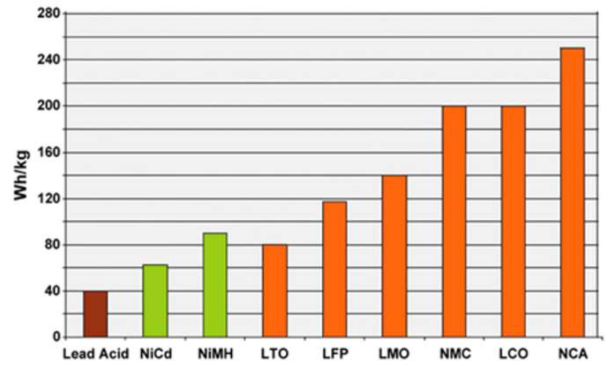
Positive electrodes current collector (aluminum foil)

What make batteries different?

Comparison of Energy Density



Comparison of Lithium-ion Battery



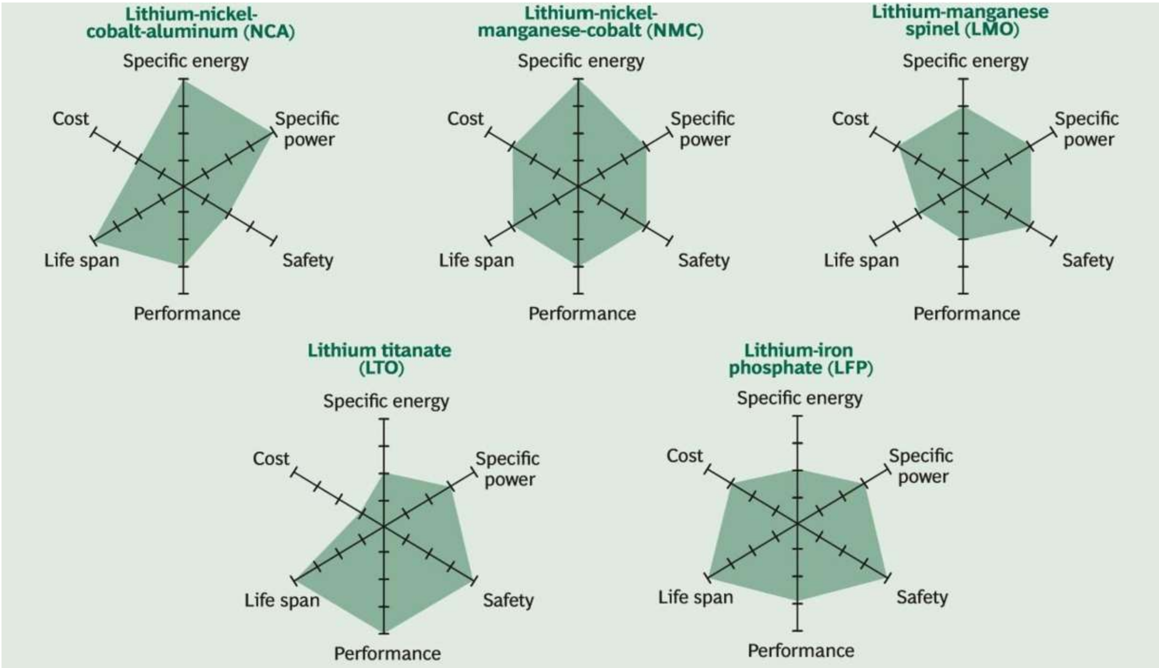
Energy density is one of the key indices

Customer concerns

- Specific Energy & Power
- Efficiency
- Life span
- Safety
- **Cost**

Technologies

- Battery chemistry
- Cell type design
- Manufacturing process
- Quality control



Source: BCG Research

Lithium Ion Battery Performance Comparison

Currently, graphite is used as a negative electrode material for lithium ion batteries, and there are mainly lithium cobalt oxide batteries, ternary (NCM, NCA) lithium batteries, lithium iron phosphate batteries, and lithium manganese oxide batteries according to different positive electrode materials used. When lithium titanate is used as the negative electrode material, it is called lithium titanate battery.

Battery Type	lithium cobalt oxide Batteries	Lithium metal oxide (NCA or NMC) Batteries	Lithium iron phosphate battery	Lithium manganese oxide Batteries	Lithium titanate battery Ternary/Lithium iron phosphate/Lithium manganate+Lithium titanate
Voltage (V)	> 3.7	3.65	3.2	3.75	2.2
Volume Energy Density (Wh/L)	> 700	300 - 600	200 - 450	250 - 500	150 - 300
Mass Energy Density (Wh/kg)	> 200	> 200	120 ~ 180	100 ~ 120	80 ~ 100
Number of cycles	~ 1000	~ 2000	> 5000	1000 ~ 2000	> 10000
Operating temperature	- 20 ~ 60 ° C	- 20 ~ 60 ° C	- 20 ~ 60 ° C	- 20 ~ 60 ° C	- 20 ~ 60 ° C
Price (RMB/W)	1.5 ~ 2	0.6 to 1.0	0.5 to 0.8	0.5 to 0.8	3 ~ 5
Advantages and disadvantages	High volume energy density High price Poor security Few cycles	High mass energy density High price Poor security	Many cycles Low price Good security	Low mass energy density Low price Few cycles	Many cycles High security Low mass energy density High price
Application Scenario	3C	Electric vehicles (passenger cars), electric energy storage	Electric vehicles (bus, logistics), electric energy storage	electric bicycle	Electric bus
Major Suppliers	ATL, Samsung SDI , LG, Murata, Lishen	CATL, Samsung, LG, Matsushita, BYD, Lishen, Gotion	CATL, BYD, Lishen, Gotion, EVE	Xingheng (phylion)	Toshiba, Microvast, JEVE, Yinlong

Lithium batteries mainly used in new energy vehicles and energy storage

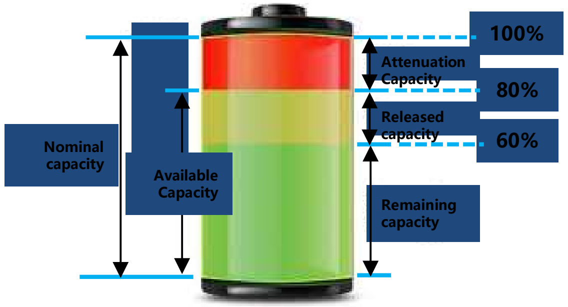
key specifications of Lithium-ion battery status

SOH

- The State of Health (SOH) indicates the ability of the current battery to store energy relative to the new battery. Currently, the SOH is not defined in a unified manner. The most common SOH is the percentage of the current available battery capacity to the nominal battery capacity.
- Accurately measuring the SOH of lithium batteries helps you know the battery health status in time.
- The ambient temperature,charge/discharge ratio and depth of charge/discharge are the main factors affecting SOH. When the battery temperature is too high or too low, the charge/discharge ratio is too large, and the charge/discharge ratio is too high, the SOH of lithium battery will be rapidly reduced.

SOC

- The State of Charge (SOC) indicates the current energy storage state of the battery, that is, the percentage of the remaining battery capacity to the total available battery capacity.
- SOC is the most important parameter of lithium-ion battery management. It not only reflects the remaining power of the battery, but also the estimation input of other parameters of the battery status, but also the important criterion of BMS (battery management system) control strategy.
- The SOC of lithium batteries cannot be measured directly. It can only be estimated by using the estimation model, such as battery cell voltage, charging and discharging current, temperature, and internal resistance.

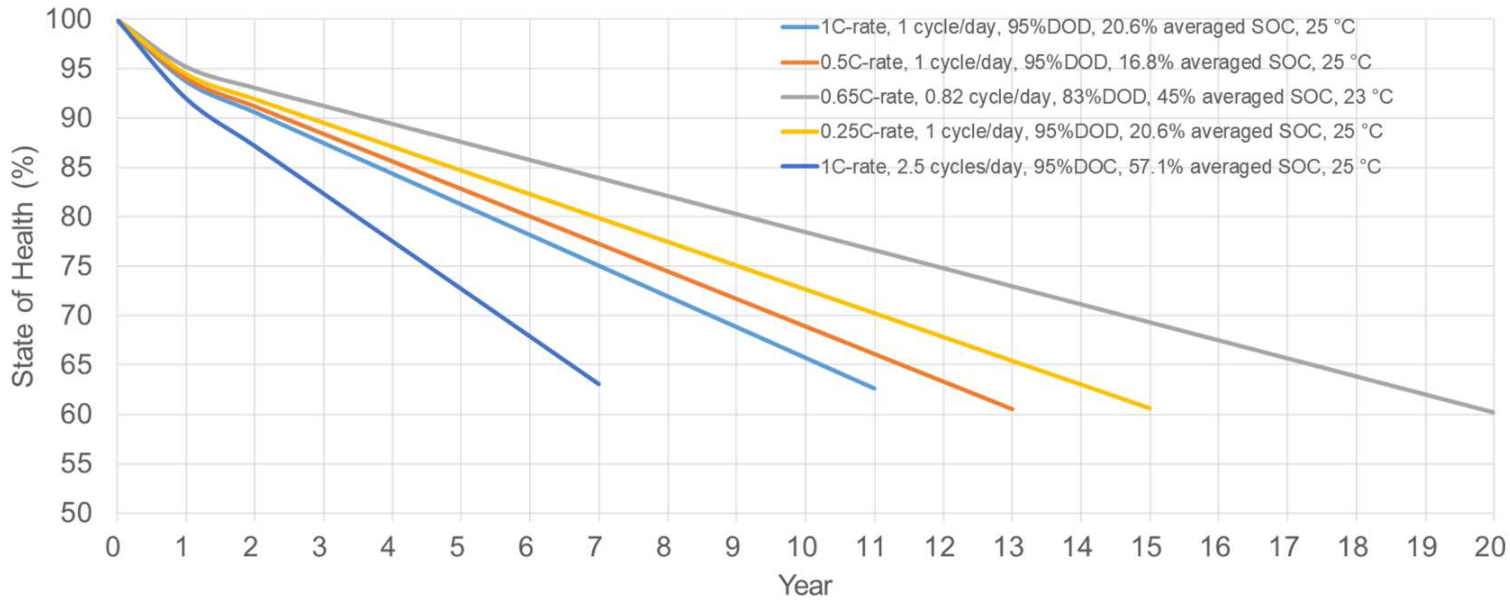


In the preceding example:

$$\text{SOH}=\frac{Abalibale\ capacity}{Normianl\ capacity}\text{x}100\% = 80\%$$

$$\text{SOC}=\frac{Remaining\ Capacity}{Abalibale\ capacity}\text{x}100\% = 75\%$$

C-rate, cycle/day, DOD, avg SOC, and temp are key factors



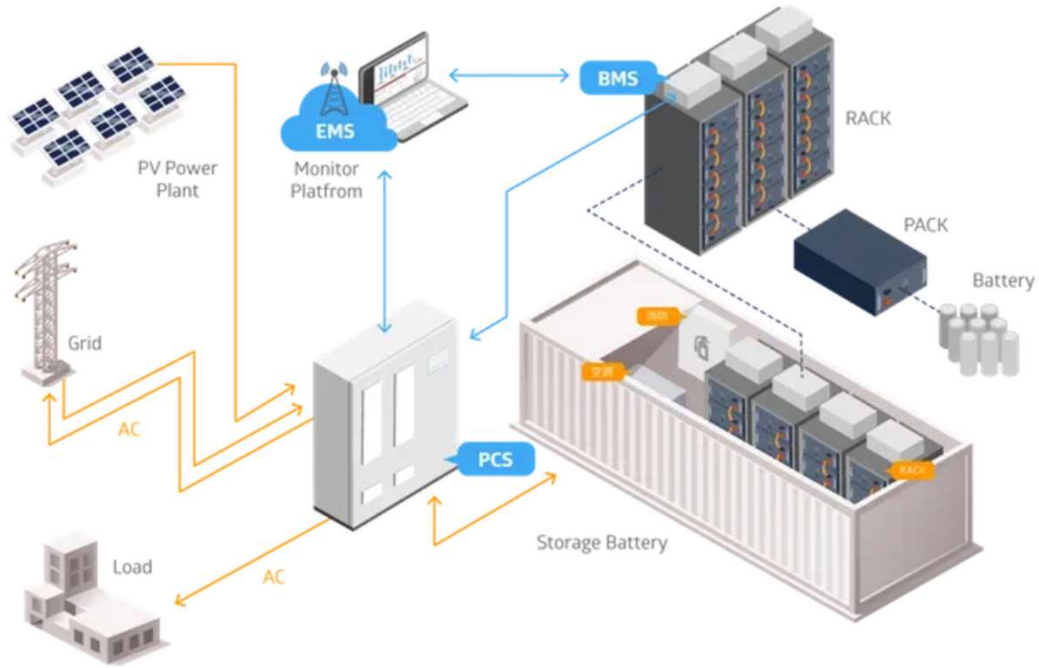
An example of SOH Attenuation Baselines

Content

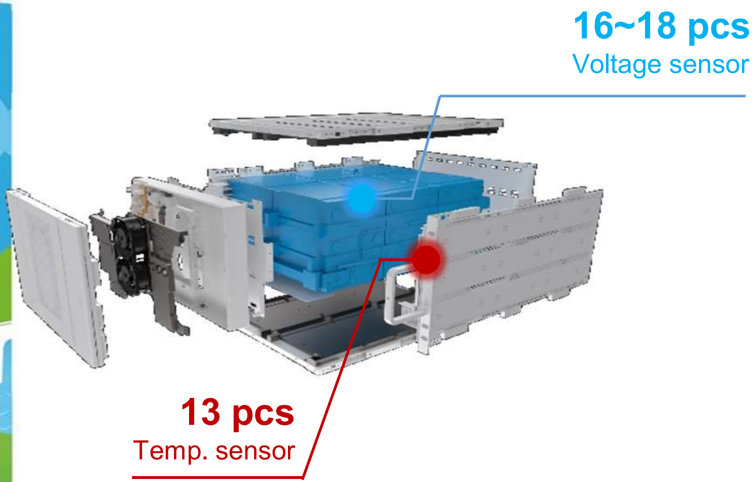
Composition of Lithium Ion Electric Energy Storage System

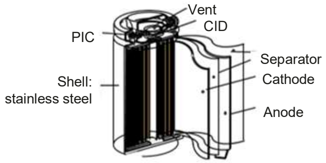
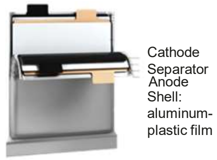
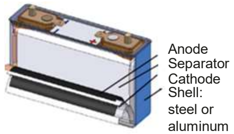
Lithium Ion electric energy storage system

- Battery Packs and Rack
- Battery Management System (BMS)
- Power Conversion System(PCS)
- Energy Management System (EMS)
- Power distribution, temperature control, and fire control



Classification of lithium batteries by shell and appearance



Type	Appearance	Structure	Advantage	Disadvantage
Cylindrical			• Small size • Low cost • Good consistency	• Poor heat dissipation in a string • Heavy weight
Pouch			• Flexible size • Light weight • Small internal resistance	• Low mechanical strength • Difficult sealing process • Difficult heat dissipation design and high cost
Prismatic			• Good heat dissipation • High reliability • High safety • High stiffness	• Regular shape • High cost • Various models

Energy Storage Subsystem – Battery Pack and BMS

The PACK&battery cluster is the energy storage component of the energy storage system. When designing energy storage system, the cell and its grouping mode should be selected according to the voltage grade, capacity, power and PCS matching of energy storage

The battery management system (BMS) is used to monitor battery system status, estimate battery status SOX, balance (passive equalization and active equalization), manage battery heat, alarm, protect system, and manage communication.

Lithium ion cell

Cell unit

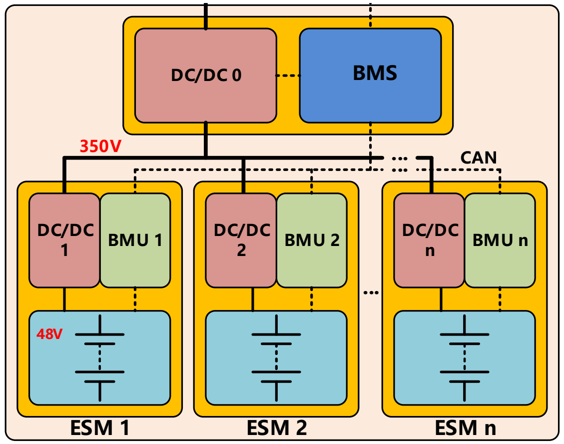
Battery Pack

Battery cluster

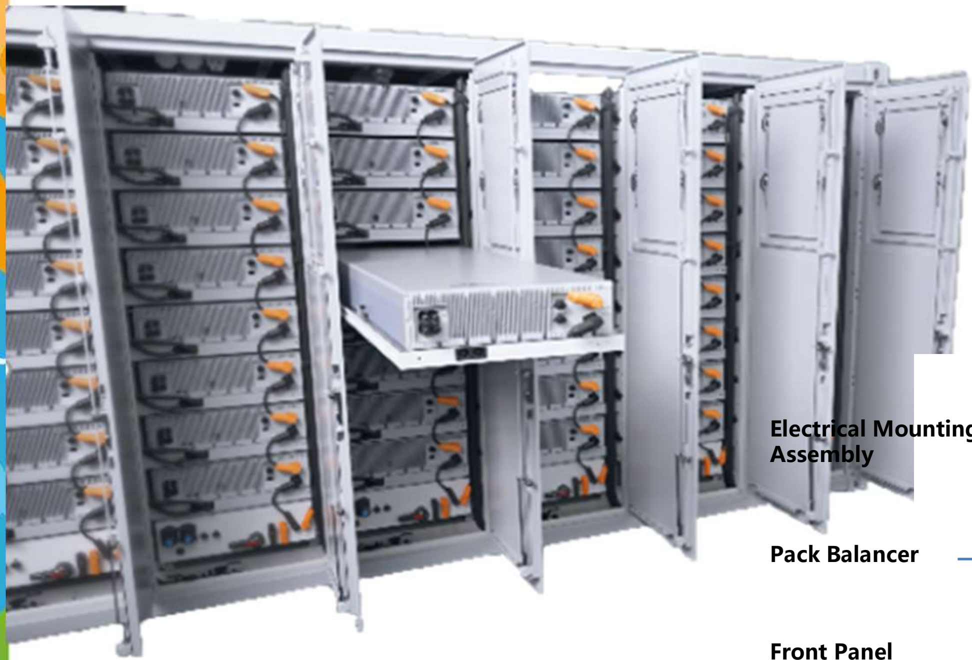
cell management system

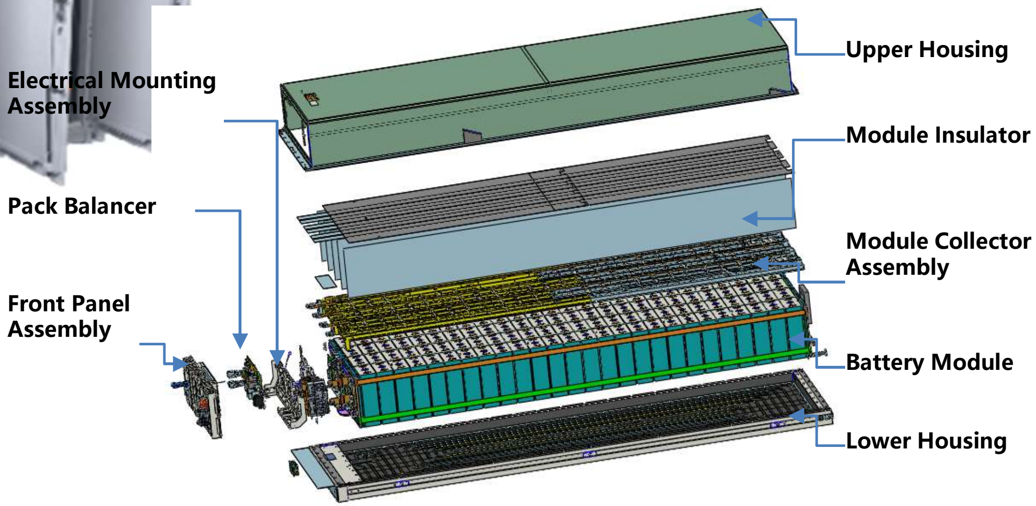
Battery cluster management system

Battery Pack Management Unit



Liquid solution with prismatic LFP cells

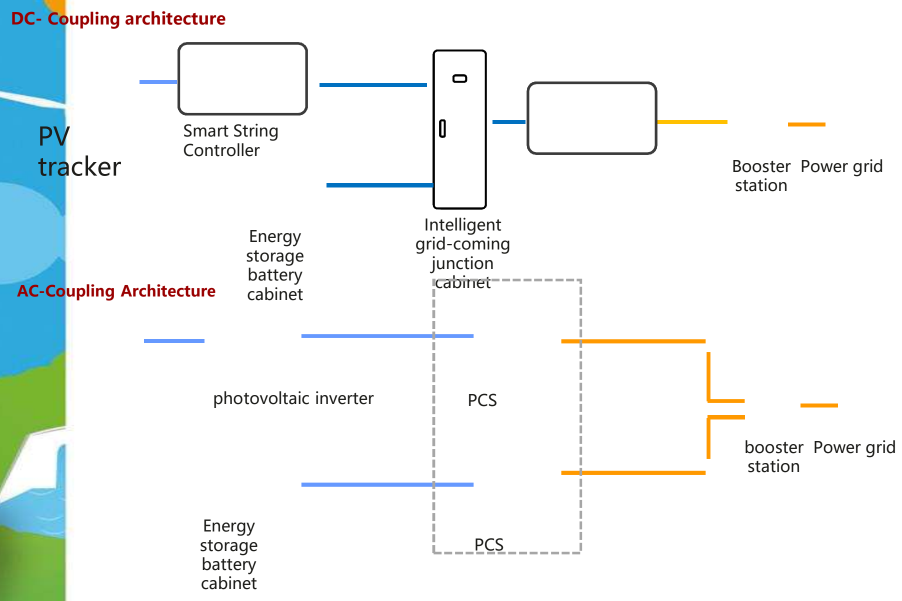


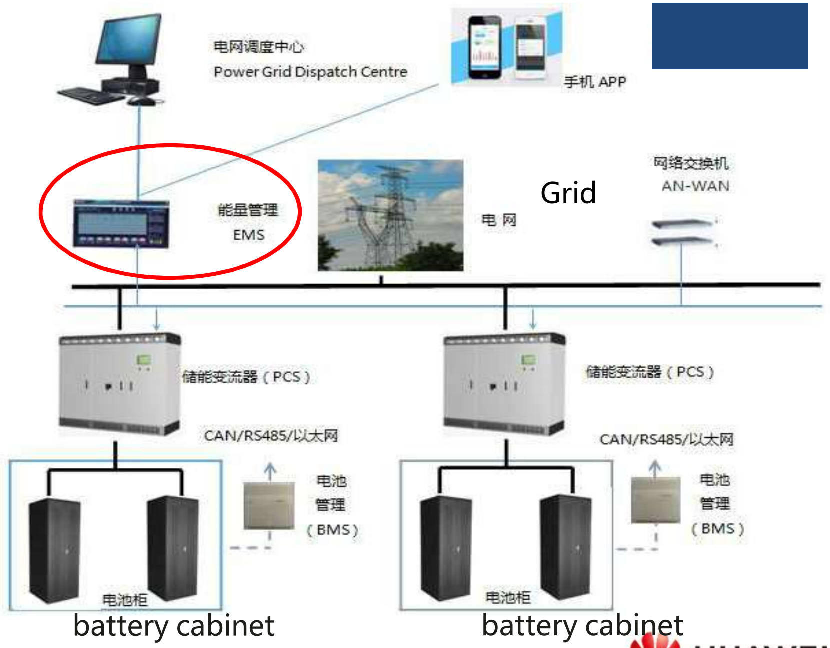


Energy Storage Subsystem - Power Conversion system (PCS) and Energy Management System (EMS)

The Power Conversion system (PCS) is responsible for the energy interaction between the energy storage system and grid. According to the access mode of the power grid, can be divided into two types: DC coupling and AC coupling.

The energy management system (EMS) makes control strategy according to load prediction, battery status and electricity price rules, and realizes energy management through PCS and BMS.





Interpretation of energy storage system specifications

Specifications of the XXX energy storage system (example)

AC voltage	400-480Vac
Rated capacity	2958 kWh
Rated power	739.5 kW
discharge ratio	0.25C
Power backup duration	4h

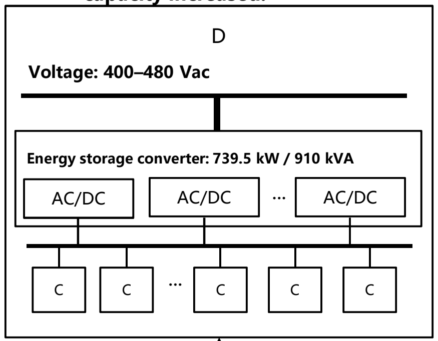
- 126 Vdc —DCDC+DCAC→ 400-480 Vac
- 18.5 Wh Cell —46 and 34, 6 and 17→ 2958 kWh
- Determined by power conversion system
- 739.5 kW ÷2958 kWh = 0.25C
- 2958 kWh ÷739.5 kW = 4h

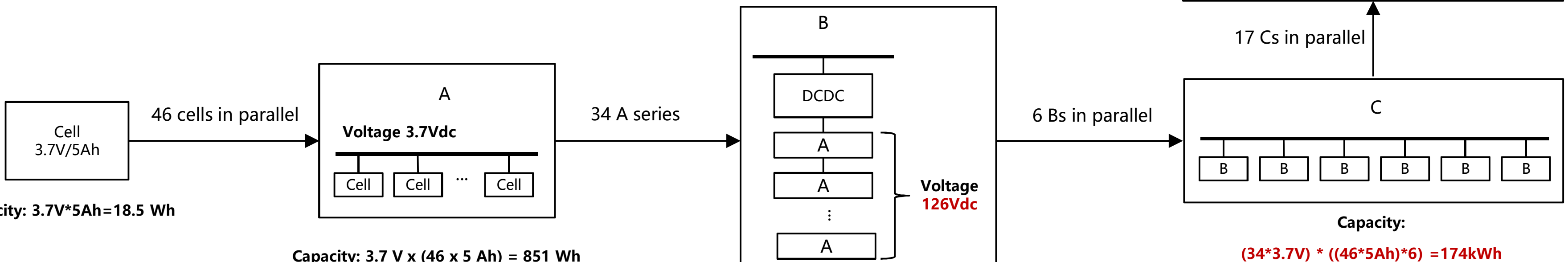
1C indicates the current when the battery is fully charged or fully charged in 1 hour .

Capacity:

(34*3.7V) * (((46*5Ah)*6) * 17) =2958 kWh

The parallel connection make voltage constant but the capacity increased.





Capacity: 3.7V*5Ah=18.5 Wh

Capacity: 3.7 V x (46 x 5 Ah) = 851 Wh

The parallel connection make voltage remains unchanged, the current and capacity increase.

Capacity: (34*3.7V) * (46*5Ah) =29 kWh

The serial connection make current remains unchanged, the voltage increases, and the capacity increases.

Capacity:

(34*3.7V) * ((46*5Ah)*6) =174kWh

The parallel connection make voltage remains unchanged, but the current and capacity increase.

HUAWEI

Energy Storage Cell Technical parameters

25℃, DOD100%

No.	Project	Bidder's Guarantee
1	Battery Type	Lithium iron phosphate
2	Nominal Voltage (V)	3.2 V
3	Nominal capacity (Ah)	280 Ah
4	Nominal charge current (A)	280 A
5	Maximum charge current (A)	280 A
6	Nominal Discharge Current (A)	280 A
7	Maximum Discharge Current (A)	280 A
8	Voltage Range (V)	2.0 V - 3.65 V
9		2.5 V - 3.65 V
10	Number of cycles	0.5C rated magnification/25°C EOL 60%, DOD 100%, cycle times ≥ 12,000
11	Energy efficiency	≥ 94%
12	Dimensions (W x D x H mm)	173.7 mm *72.0mm *207.5mm (**2.59 dm3** (l))
13	Internal resistance (mΩ)	≤0.4 mΩ
14	Weight (kg)	5.42 kg
15	Storage temperature range (°C)	-40-65°C
16	Nominal Energy (KWh)	0.8961

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ESS 1.0

Air cooling system

6*21*1*18*0.8961=

2032 kWh

6*21*1*18=2268CELLS

2.59l * 2268= 5874 l = 5.87 m^3

15.8% of container volume is cell space

ESS 2.0

Liquid cooling system

6*8*2*52*0.8961=

4472 kWh

6*8*2*52=4992CELLS

2.59l * 4992= 12.92 m^3

34.9% of container volume cell space

20HC Container internal dimensions:
Length: (5.89 meters) Width: (2.34 meters) Height: (2.69 meters) → 37m^3

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Thermal Design Calculation

(1) Heat consumption during battery charging and discharging(76.6KW)

$$Q_{Pack} = Q_{Cell} + Q_{BMS} + Q_{Busbar}$$

Q Pack=62.4KW (According to the 0.5CP charge rate and efficiency)
Q BMS=1.6KW (including the BMU and active equalization module)
Q Busbar=12.6KW (The copper aluminum bar of the battery module)

(2) Heat consumed by battery temp rise caused by battery heat(32KW)

$$Q_{absorb} = 0.5 * Q_{Pack}$$

Q Pack about 50% of the cells are used to cause the temperature rise of the battery cells, and the other 50% are scattered into the cabin environment. Calculation value are 32.2 kW.

(3) Heat transferred from solar radiation to the container (0.92KW)

$$Q_{Irradiation} = 0.047 * Ab * A * K * E$$

- Ab is the absorption coefficient of solar radiation, taken as 0.3
- A area on three sides of the container, 37.56 m2
-- K Heat transfer coefficient of the battery compartment, 2.3 W/(m2 x K)
- E solar radiation intensity, 753 W/m2

(4) Heat infiltrated from the outside environment through the combined transfer of convection and heat conduction(2.44KW)

$$Q_{leakage} = A_{Total} * (T_{out} - T_{in}) * H$$

--A_{Total}, total heat transfer area, calculated as 70.64 m2
- $T_{out}T_{in}$- Average temperature difference in the outer compartment of the battery compartment. The values are 45°C and 30°C.
-- H, comprehensive heat transfer coefficient, take 2.3 W/(m2*K)

(5)Heat consumption of the cluster control box: Q control=1.1KW

(6)Power cable and quick-connect terminal: Qline=1.3KW

(7)Heat absorption of mechanical parts in the battery compartment:

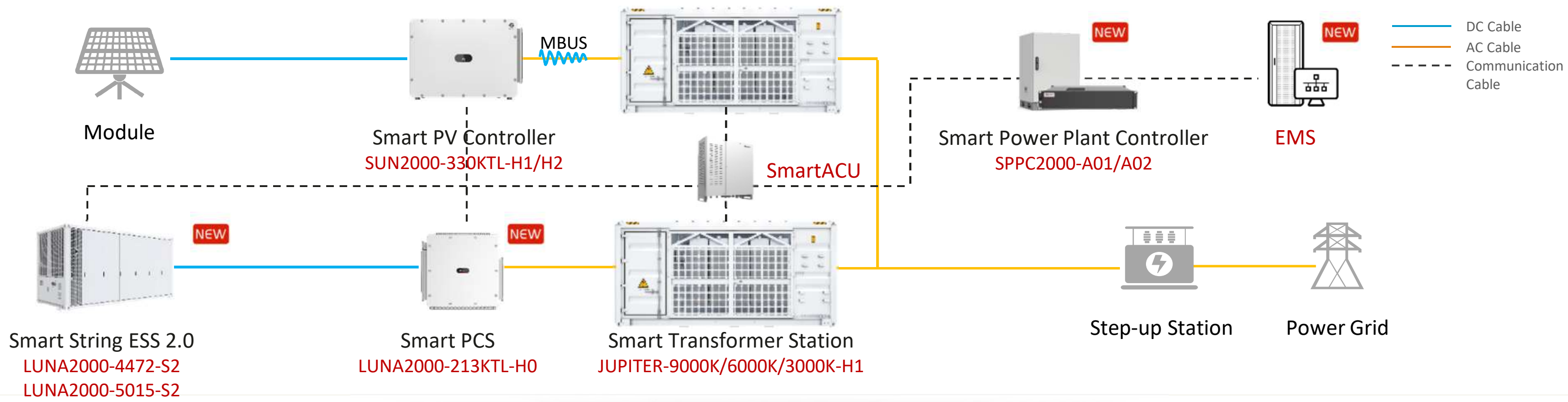
Q structure =4.011KW

Q Total=(1)-(2)+(3)+(4)+(5)+(6)-(7)=**46.35KW**

The test rate is 10% of the design margin and the required cooling capacity Q Final=1.1*Q Total=50.98KW

According to the design parameters of the liquid-cooled unit, the external temperature is 45°C, the water temperature is 22.5°C, the cooling capacity of the liquid-cooled unit is 53 kW, and the total cooling capacity is **53kW >50.98kW**, meeting the design requirements.

FusionSolar 8.0： Optimal BOS, Higher Yields, Smart O&M, Safe & Reliable
Smart String ESS Solution 2.0: Upgrade for optimal LCOS and active safety



Grid Forming

- Redefine Voltage Stability: Realizes 3 times the reactive current
- Redefine Frequency Stability : Realize fast response support of equivalent Virtual inertia
- Redefine Phase Angle Stability : Effective suppression of wide frequency oscillation
- Millisecond-level plant scheduling response NEW

Safe & Reliable

- **Cell Safety:** 100+ cell performance test
- **Electrical Safety:** Active and passive protection
- **Structural Safety:** Separate compartment layout and high protection level of battery packs
- **System Safety:** All-round protection; AC and DC real-time insulation detection; pack-level directional smoke exhaust, preventing packet-level faults from spreading NEW

Optimal Investment

- Pack-level optimization, rack-level optimization, 6% higher energy
- 90.3% RTE @800Vac (including Aux.power) – 0.5C NEW
- 91.5% RTE @800Vac (including Aux.power) – 0.25C NEW
- Constant output power @ full SOC range, CAPEX save 10% NEW
- Up to 99.9% higher system availability

Smart O&M

- High-precision automatic SOC calibration, no need for onsite O&M by experts NEW
- Multi-dimensional ESS health diagnosis, comprehensive management of power station operation NEW

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Content

Application of Lithium-ion Battery Energy Storage System

Consumer Electronics	Electric two-wheeler	Automotive power battery

Application of Lithium-ion Battery Energy Storage Systems in Digital power Company

digital power storage system

Data Center

Provides standby energy storage for data centers.

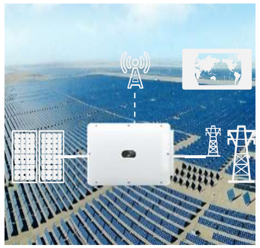
Smart Li

Site

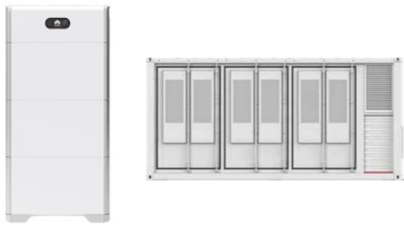
Provides standby power/
Cyclic energy storage

Cloud Li

Smart PV



For users and industrial and commercial parks
cyclic energy storage



LUNA2000

mPower

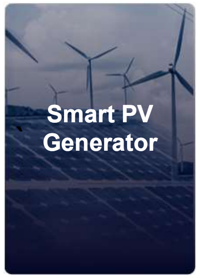
For electric vehicles
Vehicle-mounted and cloud-based battery management system

Cloud BMS

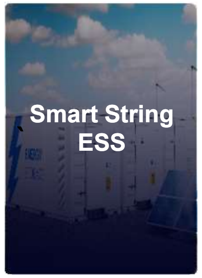
Smart PV & ESS, building a clean energy generation network

Digital Power Cloud
Professional PaaS & SaaS for energy

5 Solutions



Grid Forming
LCOE reduced by 5%



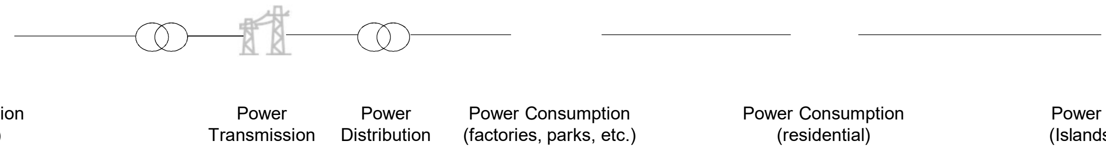
Active Safety
LCOS reduced by 20%

Panel-level optimization in different rooftops
Arc protection, safe shutdown
Virtual power plants with unified management

Independent networking
Concurrent & Separable

PV & Storage Synergy

Fusion of Energy Flow And Information Flow



Application of Li-ion Battery Energy Storage System in Grid

Energy storage on the generator side | Grid-side energy storage | User-side energy storage

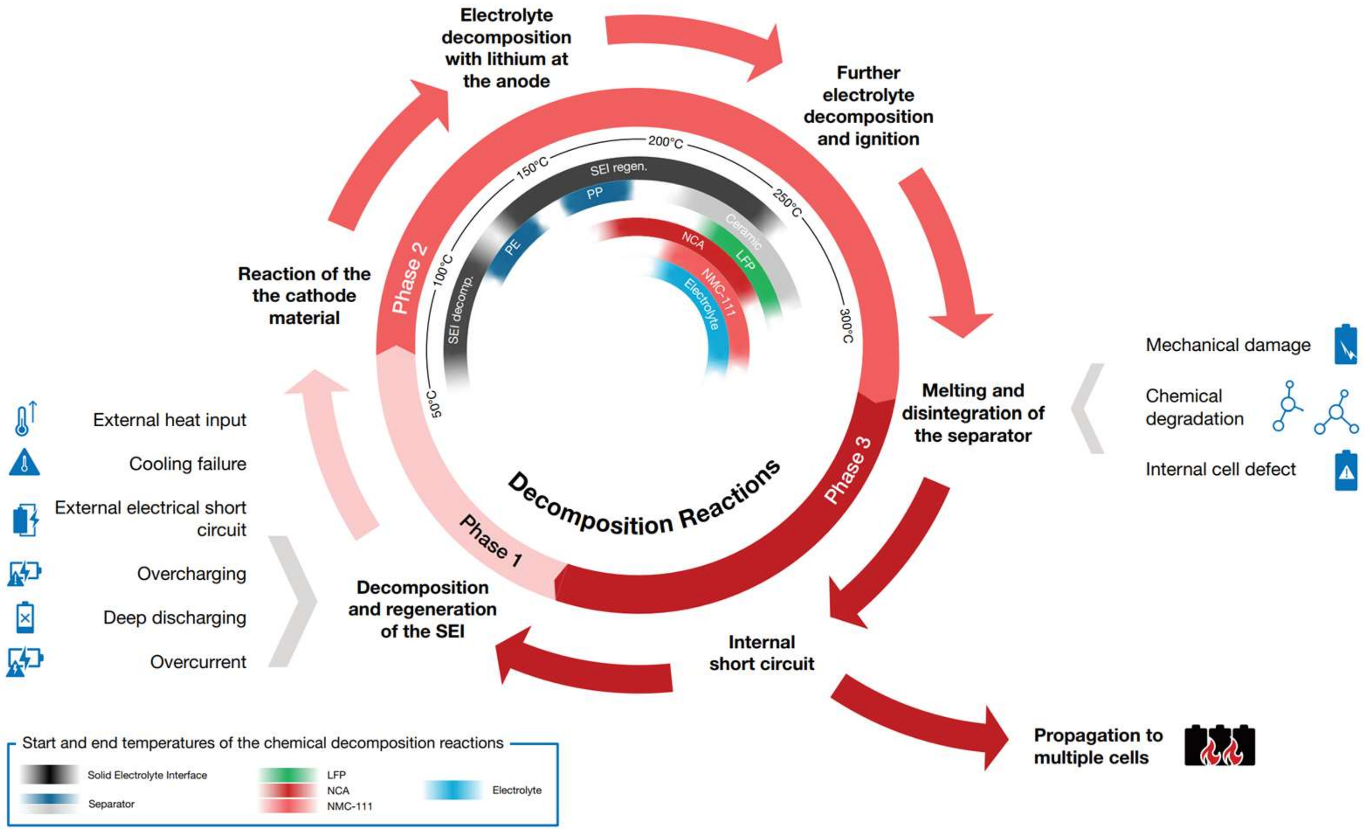
- Smooth output
- Auxiliary services (peak and frequency modulation)
- Benifit from Peak-valley electricity price
- virtual inertia
- Ease capacity expansion urgency
- Emergency power supply
- Capacity fee
- Spontaneous self-use

← Power generation side → ← Grid side → ← User side →

Typical Scenarios	PV + storage power station	thermal power + storage station	Grid energy storage	industry and commerce	Off-grid	Households
capacity	100kW-30MW	10MW-20MW	5MW-100MW	20kW-5MW	30KW-10MW	Below 20 kW
Scenario						

Content

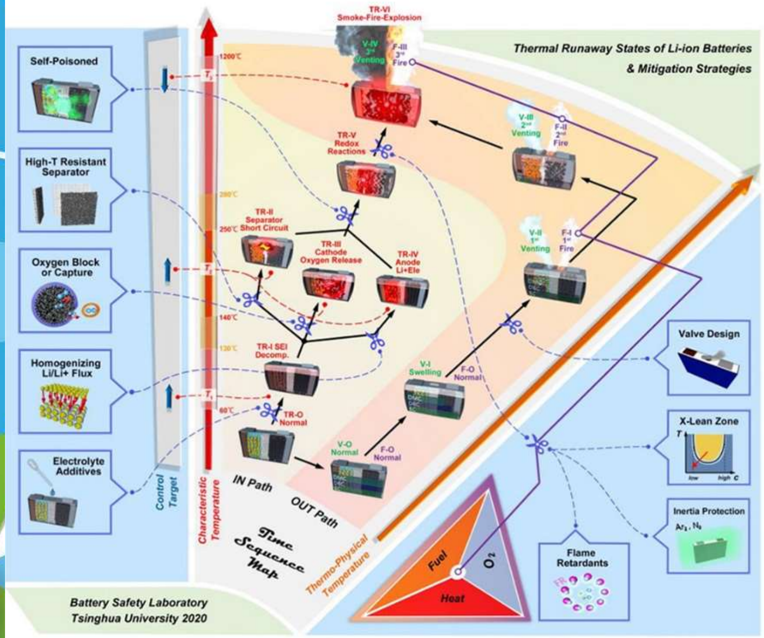
What is thermal runaway?

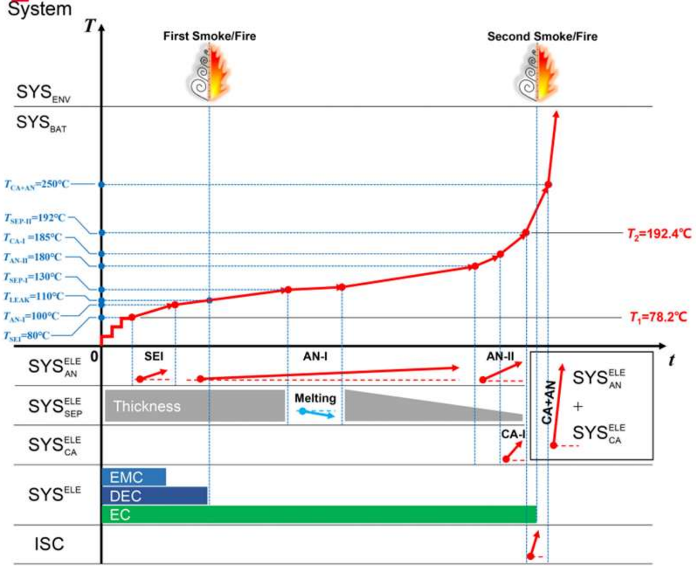


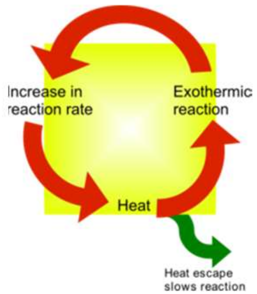
Lithium Battery Characteristics - Thermal Runaway

Definition of thermal runaway: The temperature of the battery increases due to internal or external factors and triggers a chain reaction. As a result, the battery temperature continuously increases, causing a safety accident.

- **SEI Decomposition**
- **Separator melting**
- **Internal short circuit**
- **Positive electrode / electrolyte Decomposition**
- **Negative electrode / electrolyte burning**

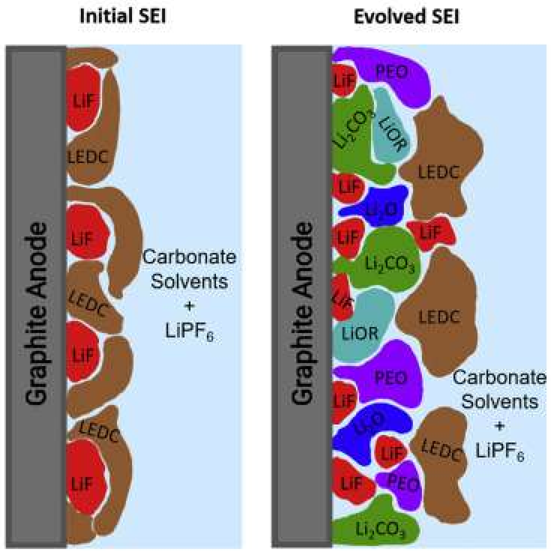






SEI Layer

A solid electrolyte interphase (SEI) is generated on the anode of lithium-ion batteries during the first few charging cycles. The SEI provides a passivation layer on the anode surface, which inhibits further electrolyte decomposition and affords the long calendar life required for many applications

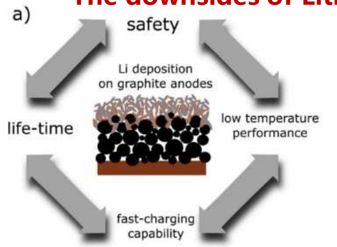


The SEI layer on the anode is important for the safety of the battery. When the cell is heated above a threshold value, the SEI layer can begin to chemically decompose. This exposes the lithiated graphite to the non-aqueous electrolyte. The resulting chemical reaction is exothermic, releasing a continuous heat flow into the battery. This raises the internal battery temperature, which causes a runaway thermal reaction at the cathode when the cathode threshold temperature is exceeded.

Battery Characteristics - lithium dendrite

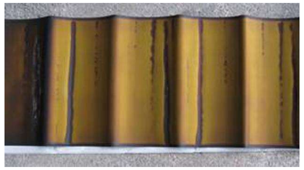
The root cause of Lithium precipitation : part current density > part Li-ion intercalating rate into graphite

The downsides of Lithium



Lithium precipitation at large rate charge

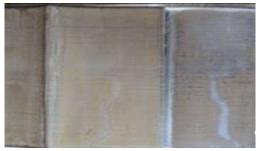
Lithium precipitation at cell Deformation



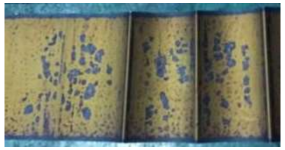
Electrolyte missing

Positive electrode capacity > Negative electrode capacity

Lithium precipitation by overcharge

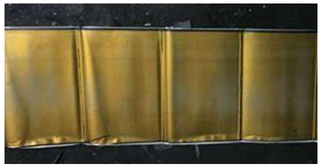


Lithium precipitation by improper formation



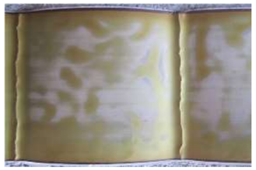
Lithium precipitation with horizontal stripes due to uneven application

Lithium precipitation due to charging in low temperature



Lithium precipitation due to separator wrinkling

Negative electrode compaction beyond limit



Lithium precipitation by Vertical Stripes due to cell Deformation

There are countless reasons for lithium dendrite formation, but there is only one way to avoid it: batteries should be used within their working boundary over the whole battery life.

Energy storage system safety

From 2017 to 2021, there were 30 fires from energy storage power stations in South Korea, involving total battery capacity ~210MWh and direct economic loss of CNY 238 million. In 2020, the installed capacity of ESS in South Korea decreased by 33.9% (vs. the global increase of 37.9%).

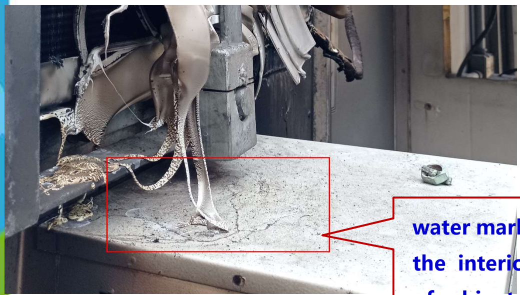
On April 16, 2021, a fire at the Dahongmen Energy Storage Power Station in Fengtai, Beijing caused a 18 MWh battery system burn out and a direct economic loss of ove CNY 16,000,000. Two firefighters were killed, one station employee was killed and one firefighter was injured.

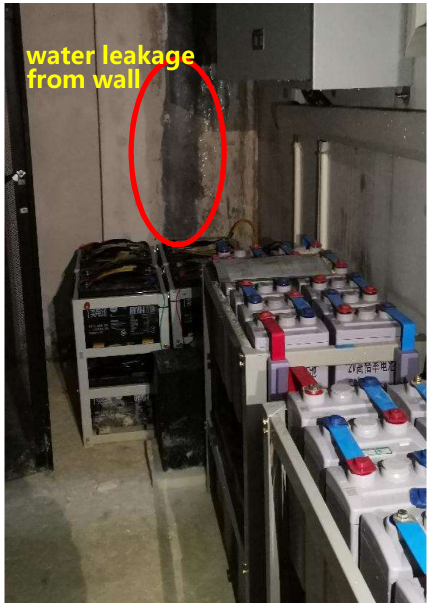
On July 30, 2021, a fire broke out at the Tesla Megapack Energy Storage Power Station near Geelong, Victoria, Australia, during the test process. The fire burned for 4 days before went out.

ESS TOP 3 Fire Causes:

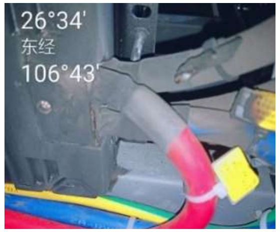
- **No. 1** **Mis-operation in ESS Installation**
- **No. 2** **environmental tolerance erosion**
- **No. 3** **large current shock**

Energy Storage System Safety Cases





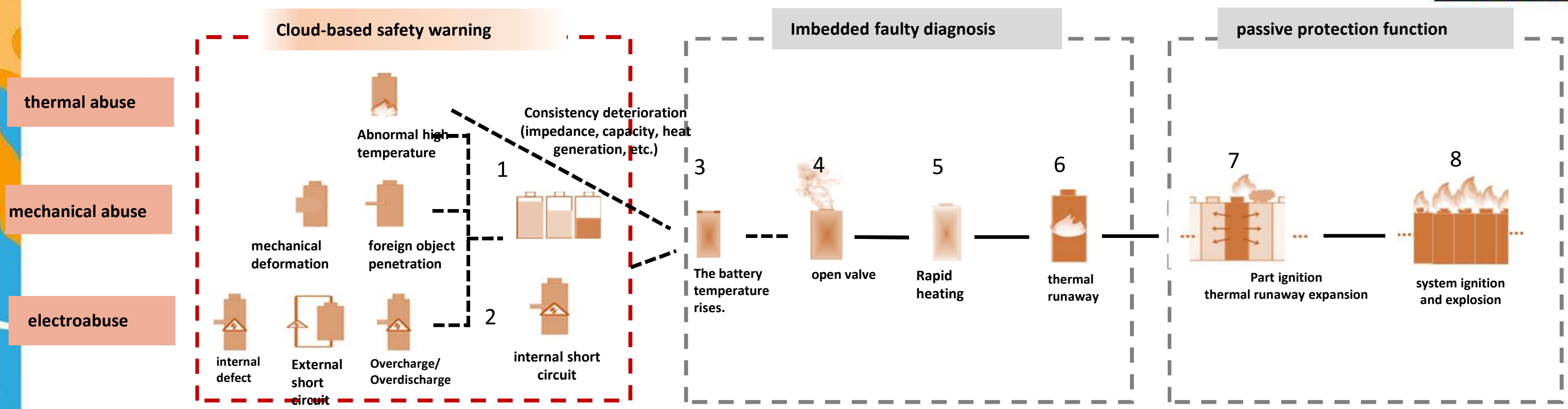
Installation performed incorrectly or the tool is incorrectly used. As a result, multiple modules are short-circuited.

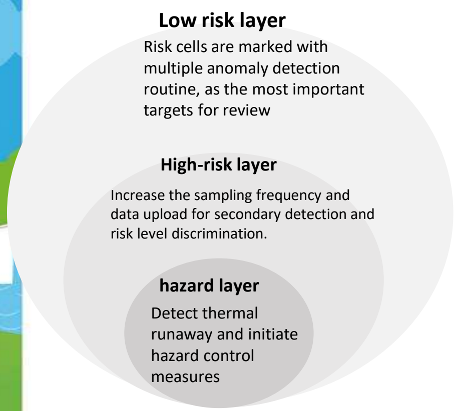


Cables are not properly installed or not maintained for a long time. As a result, the cable ends are overheated over a long time usage.

Environmental Stability, good maintenance for Energy Storage Systems is extremely important

Energy storage system safety protection strategy





Pre-warning: Early detection of exceptions and risk identification

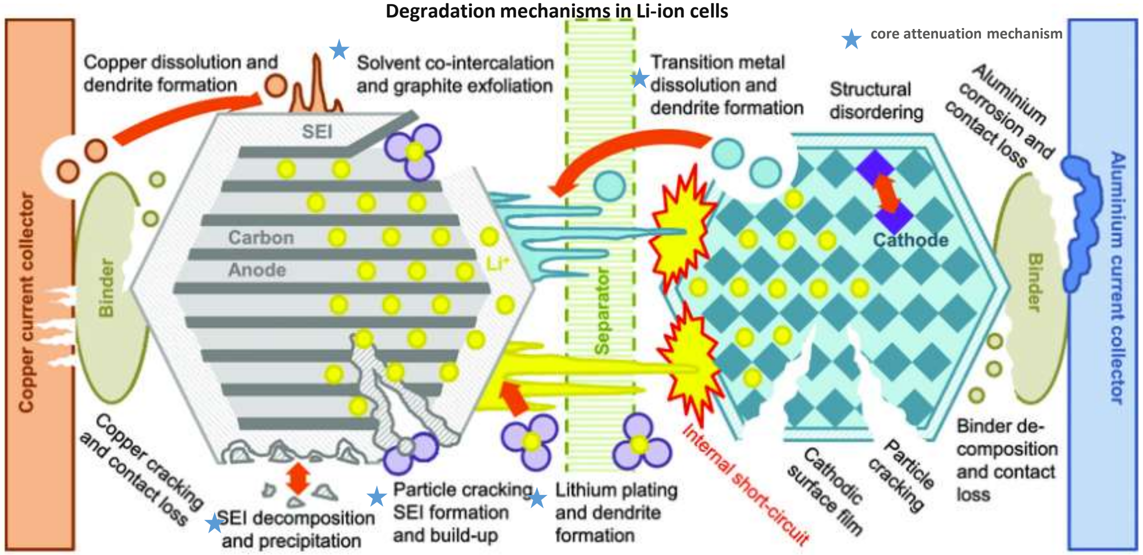
Detection: Thermal runaway signal detection to control hazards

Isolation: Enhances hardware robustness, isolates hazards, and does not spread.

Firefighting: Hierarchical Fire Fighting System Reduces Direct Loss

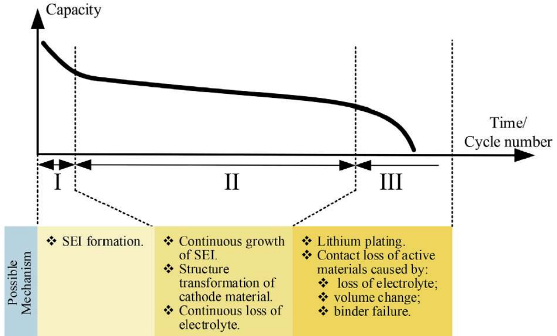
Life characteristics of lithium-ion batteries

Degradation mechanisms in Li-ion cells



Degradation factor

- Positive electrode ⇒ Structural changes during cycling
- Negative electrode ⇒ SEI formation; SEI growth; lithium precipitation
- electrolyte ⇒ Loss, dissolution, decomposition
- Non active material ⇒ Binder failure / Corrosion of current collector



Degradation mechanisms

- loss of active lithium ion
- Loss of active materials In postive electrode
- Loss of active materials in negative electrode

When comparing a battery to two glasses of water, the active materials determines the capacity of the cup and the active lithium ion determines the amount of water in the cup.

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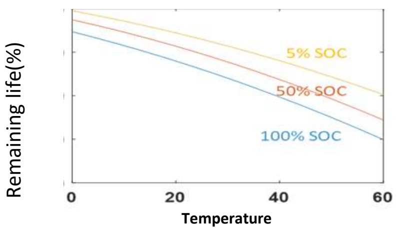
Factors influencing cell life

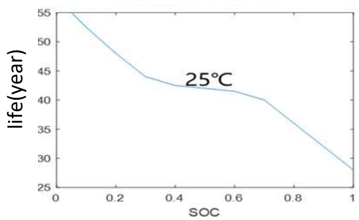
Calendar Life

Calendar life degradation vs. temperature



The higher the temperature, the faster the calendar life decays
(described by Arenius formula)

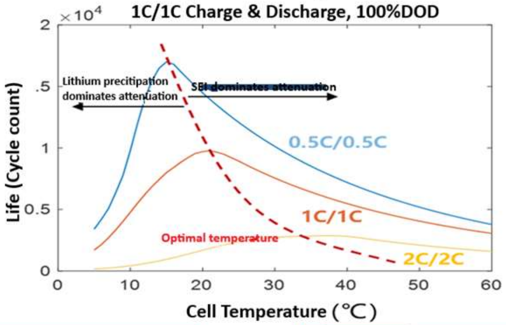
Calendar life vs. SOC

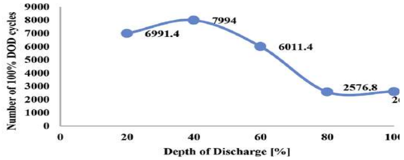


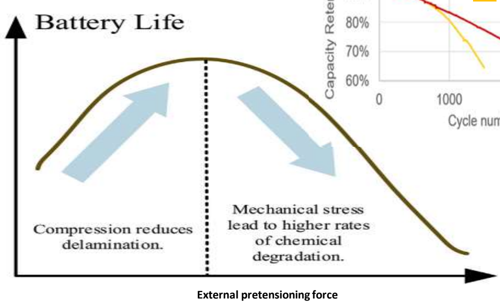
The higher the average SOC, the faster the calendar life decay
(Theoretical calculation can be performed based on negative electrode potential)

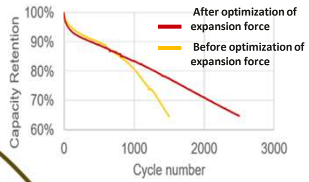
cycle life

Cycle life VS Temperature
1C/1C Charge & Discharge, 100%DOD









Temperature

The higher the temperature, the faster the cycle decay under the condition of lithium.

charge/discharge ratio

1. For the traditional charging mode, the higher the magnification, the faster the attenuation.
2. The cycle life can be increased by improving the charging and discharging modes (under research).

charge/discharge interval

Charge/discharge interval = Average SOC + Charge/discharge depth (in research)

1. The greater the depth of charge and discharge, the faster the attenuation
2. The higher the average SOC, the faster the attenuation.

External binding force (expansion force)

The external binding force significantly affects the cell life, and there is an optimal initial binding force condition, but it is not possible to accurately and quantitatively judge the cell life (in research).

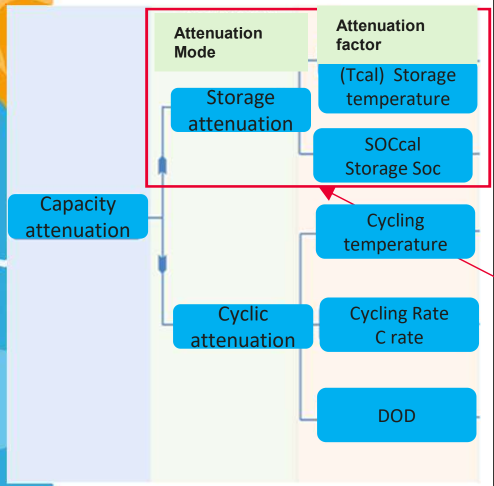
SOH Guarantee

The basic logic of each vendor's model is the same.

The general difference lies in whether temperature rise and storage attenuation are considered.

Other vendors usually do not consider storage attenuation and temperature rise in packs.

Degradation Coefficient Decomposition



Degradation coefficient calculation logic

$Qloss = Qloss_{cal} + Qloss_{cycle}$

Storage Decay: Arrhenius Decay Law

$Qloss_{cal} = kTStorage * kSOC * t^{z1}$

① kT storage. T storage is the average storage temperature.

$k_T = kref_{cal} * e^{-\frac{Ea\_cal}{R}(\frac{1}{T_{Storage}} - \frac{1}{Tref})}$

② kSOC. SOC is the average SOC.

③ t is the running time, including storage and cycle time, i.e. the calendar decay when both storage and cycle are considered

④ z1 is the storage degradation coefficient, which is related to the storage specifications under different SOHs.

Cyclic Decay: Arrhenius Decay Law

$Qloss_{cycle} = kTcycle * kcrate * kDOD * Q^{z2}$

① kT cycle, T cycle takes the average temperature of the cycle

$k_{TCycle} = kref_{cycle} * e^{-\frac{Ea\_cycle}{R}(\frac{1}{TCycle} - \frac{1}{Tref})}$

② kcrate, affected by the charge rate

According to the empirical formula, kcrate and charging rate are logarithmic functions. The specific values are related to the cycling performance at different rates.

③ kDOD, affected by the charge and discharge depth, fluctuates around 50% SOC. The empirical formula in the reference literature, kDOD and the depth of discharge are cubic functions.

$kDOD = 3.57 * (DOD - 0.6)^3 + 0.77$

④ Q is the discharge amount, which reflects the growth of SEI film.

5 z2 is the cyclic degradation coefficient, which is mainly related to the cyclic specifications under different SOHs.

Other Venders: The temperature rise of electrochemical cells in the pack is not considered.

$$Qloss_{cal} = kref_{cal} * e^{-\frac{Ea\_cal}{R}(\frac{1}{Storage} - \frac{1}{Tref})} * kSOC * t^{z1}$$ ---- 1 Storage degradation

$$Qloss_{cycle} = kref_{cycle} * e^{-\frac{Ea\_cycle}{R}(\frac{1}{Cycle} - \frac{1}{Tref})} * kcrate * kDOD * Q^{z2}$$ ---- 2 Cycle degradation

Other vendors: The storage degradation is not considered.

- Input: operating temperature, charge/discharge temperature rise, charge/discharge ratio, depth of discharge, EOL, average SOH, and daily cycles
- Output: cycle degradation curve from the specified working condition to the specified SOH, including the number of cycles and service life

Huawei considers 19 factors to simulate the attenuation curve

SOH Guarantee

Fitting Model		Industry	Huawei	Impact
Two Main Factors		**3 to 5** factors	**19** factors	more factors considered, more accurate result
Cyclic degradation	**Cell Degradation**	Cell cycle: 300-500 cycles	Cell cycle: **1250** cycles	More the number of times, the more the working conditions, the more accurate.
		Test conditions/Quantity: 1 working condition	Test conditions/quantity: **2 to 3** working conditions, 3 PCS for each type	
	Pack Degradation	Temperature rise: The temperature rise of the cell in the pack **is not considered.**	Temperature rise: The temperature rise of the cell in the pack must be considered.	Temperature is one of the top factors.
		Consistency: Generally, consistency differences are **not considered** and there is no design to prevent.	Consistency: Package Optimization and rack management avoid differences	Consistency is one of the top factors.
Storage degradation		Cell storage: degradation **is not usually considered**	Cell storage: test for 6 months + fitting, with degradation considered	Storage degradation accounts for about **33%** of the lifetime degradation.

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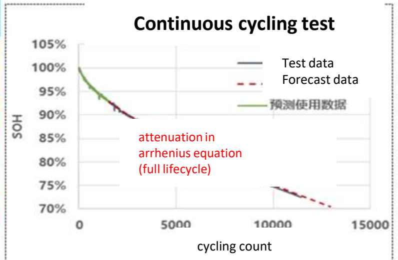
SOH Guarantee

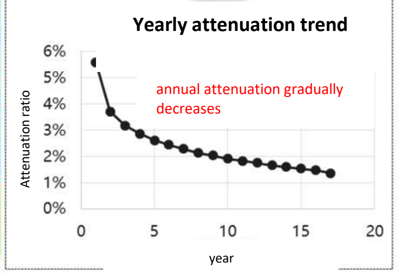
	Category		warranty model	Data volume/time limit requirements	Note 1	Note 2
1	**Cell data**	Storage Degradation Data	SOH storage degradation data in 100% SOC at 25°C.	≥ 6 months data (at least 6 data records)	Provide data + fit curve	Data storage volume ≥ 6 months, at least two temperature points (temperature difference ≥ 10°C)
2			SOH storage degradation data in 100% SOC at 45°C.	≥ 6 months data (at least 6 data records)	Provide data + fit curve	
3			SOH storage degradation data in 50% SOC at 25°C.	≥ 6 months data (at least 6 data records)	Provide data + fit curve	
4			SOH storage degradation data in 50% SOC at 45°C	≥ 6 months data (at least 6 data records)	Provide data + fit curve	
5		Cycle data	SOH cycle degradation data at 25°C (1/2 max rate)	≥ 1 / 8 cycle specification + 50 turns	Provide data + fit curve	The number of cycles is greater than or equal to 1/8 + 50, and at least three temperature points (temperature difference is greater than or equal to 5°C). The maximum rate and 1/2 maximum rate data are required.
6			SOH cycle degradation data at 35°C (1/2 max rate)	≥ 1 / 8 cycle specification + 50 turns	Provide data + fit curve	
7			SOH cycle degradation data at 45°C (1/2 max rate)	≥ 1 / 8 cycle specification + 50 turns	Provide data + fit curve	
8			SOH cycle degradation data at 25°C (max rate)	≥ 1 / 8 cycle specification + 50 turns	Provide data + fit curve	
9			SOH cycle degradation data at 35°C (max rate)	≥ 1 / 8 cycle specification + 50 turns	Provide data + fit curve	
10			SOH cycle degradation data at 45°C (max rate)	≥ 1 / 8 cycle specification + 50 turns	Provide data + fit curve	
11	**Pack data**	Consistency	Consistency of cells in the same container, including capacity and internal resistance	Data of each electrochemical cell during shipment. Cell → pack → container corresponds to each other.		By apply pack optimization & Rack management can avoided this degradation. Competitors do not consider this function
12			Temperature difference consistency of the PACK in different positions			
13		Temperature rise	Temperature rise curve of the cell in the pack at an ambient temperature of 25°C and 0.5CP charge and discharge			Some competitors do not consider this part.
			Temperature rise curve of the cell in the pack at an ambient temperature of 25°C and 0.33CP charge and discharge			
14			Temperature rise curve of the cell in the pack at an ambient temperature of 25°C and 0.25CP charge and discharge			
15	**Operating condition data**	Working condition data (provided by the customer)	Operating ambient temperature		Calculated by Huawei based on the average dimension and temperature rise.	
			Daily cycle times		Calculated by Huawei based on the customer's working conditions	
16			Charge/discharge ratio		Huawei calculated based on the customer's working conditions	
17			Storage SOC		Huawei uses 50% SOC storage.	
18 19			DOD		Huawei calculates the DOD based on 100%.	

Lifespan of energy storage systems

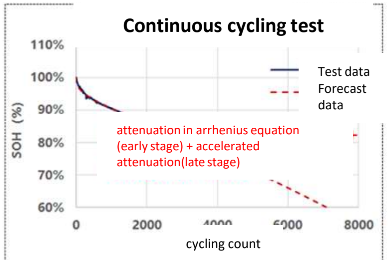
Live test shows life aging curve meets either rule 1 or rule 2

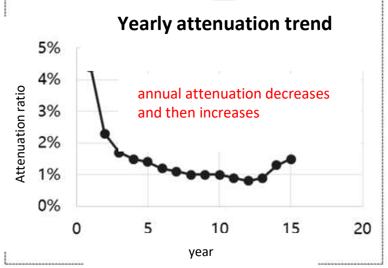
life aging rule 1 [1]





life aging rule 2 [2]





1. Maik Naumann et., al. Analysis and modeling of cycle aging of a commercial LiFePO4/graphite cell. Journal of Power Sources 451 (2020) 227666.

2. Damian Burzyński*, Leszek Kasprzyk,et,al. A novel method for the modeling of the state of health of lithium-ion cells using machine learning for practical applications. Knowledge-Based Systems 219 (2021) 106900.

CAPEX
1. Cost of equipment (ESS, PCS)
2. Installation cost
3. Other cost

1. 储能系统、PCS 等设备成本
2. 施工成本
3. 其他成本

OPEX
1. preventative maintenance & fault maintenance cost
2. O&M labor cost
3. Warranty Expenses and the power generation loss during fault

1. 巡检及故障运维费用
2. 运维中人力成本
3. 质保费用及故障带来的发电损失

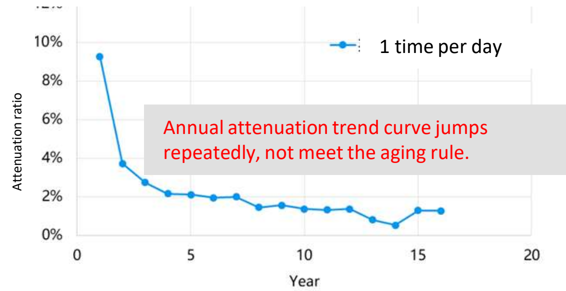
Total electricity charge fee in life cycle
生命周期内总充电电费

$$LCoS = \frac{\sum_{n=1}^{N} NPV\,(CAPEXt) + \sum_{n=1}^{N} NPV\,(OPEX_t) + \sum_{n=1}^{N} NPV\,(FUEL_t)}{\sum_{n=1}^{N} NPV\,(放电量_t)}$$

Total electricity discharged in life cycle

SG	United Kingdom energy storage project, 1C	
Year	1 time per day	annual attenuation SOH (n years)-SOH (n+1 years)
0	100.00%	
1	90.73%	9.27%
2	87.01%	3.72%
3	84.26%	2.75%
4	82.10%	2.16%
5	79.98%	2.12%
6	78.02%	1.96%
7	76.02%	2.00%
8	74.56%	1.46%
9	73.00%	1.56%
10	71.62%	1.38%
11	70.29%	1.33%
12	68.91%	1.38%
13	68.11%	0.80%
14	67.57%	0.54%
15	66.28%	1.29%
16	65.01%	1.27%

Comparison of Annual Degradation Trends Curve for XX Projects



Conclusion: It can be concluded that some integrators provide a manually changed degradation curve

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TOP cell suppliers / energy storage manufacturers in the industry

TOP EV Batteries Manufacturers

(2021 with 562 GWh)

Rank	Company	2021 Market Share	Country
#1	CATL	32.5%	China
#2	LG Energy Solution	21.5%	Korea
#3	Panasonic	14.7%	Japan
#4	BYD	6.9%	China
#5	Samsung SDI	5.4%	Korea
#6	SK Innovation	5.1%	Korea
#7	CALB	2.7%	China
#8	AESC	2.0%	Japan
#9	Guoxuan	2.0%	China
#10	PEVE	1.3%	Japan
n/a	Other	6.1%	ROW

Note: The data source of vehicle loading capacity is the automobile production certificate, and the loading capacity for multi-supplier of the same vehicle is calculated in avaergae.

TOP three battery makers — CATL, LG and Panasonic — combine for nearly 70% of the EV battery manufacturing market

Table 1: Energy storage manufacturers meeting BloombergNEF's tier 1 criteria as of 4Q 2024

Firm/Brand	Headquarters	Firm/ Brand	Headquarters
ZTT Energy Storage	China	Kehua	China
ZOE Energy Storage	China	Jinko	China
Windey Energy	China	JD Energy	China
WEIHENG	China	Invinity	UK
Wartsila	Finland	Hyperstrong	China
Trina Storage	China	Huawei	China
Tesla	US	Hithium	China
Tecloman	China	Great Power	China
SUNWODA	China	Gotion High-Tech	China
Sungrow	China	Fox ESS	China
Sermatec	China	Fluence	US
Samsung SDI	South Korea	FlexGen Power Systems	US
Rocho Energy	China	Eve Energy	China
Robestec/Shanghai Ronghe	China	Eos Energy	US
Risen Storage	China	Envision Energy / AESC	China / Japan
REPT BATTERO	China	Cubenergy	China
RelyEZ	China	CRRC Zhuzhou	China
RCT Power	China	Cornex	China
Pylontech	China	CLOU Electronics	China
Powin Energy	US	CHINT	China
PotisEdge	China	CATL (Contemporary Amperex Technology)	China
NHOA Energy	Italy	Canadian Solar e-STORAGE	Canada
Narada	China	CALB	China
Linyang	China	BYD	China
LG Energy Solution	South Korea		

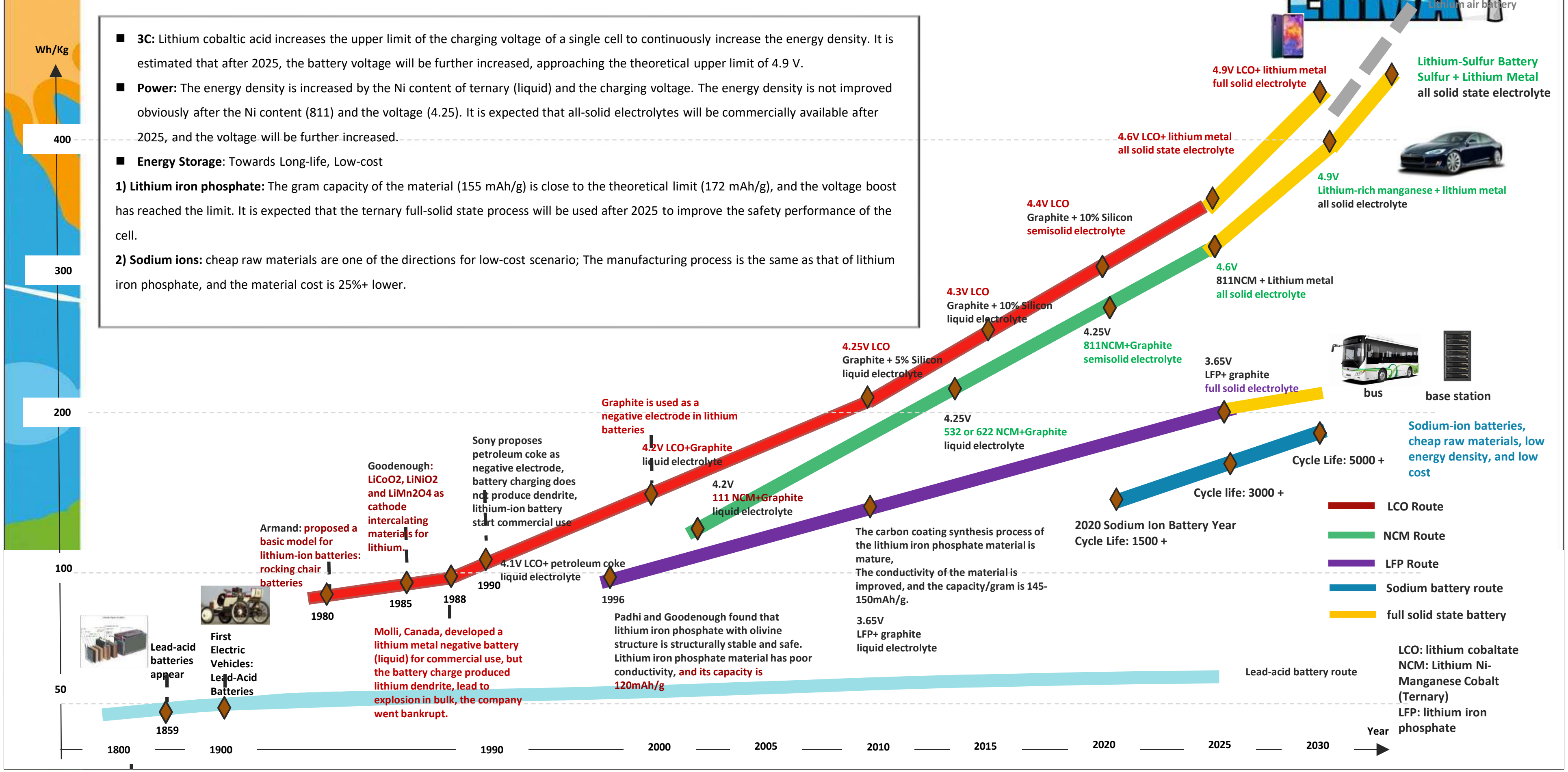
Source: BloombergNEF. Note: Methodology is here. List is in reverse alphabetical order to avoid giving the impression that the order is relevant. We currently consider both cell providers and system integrators as energy storage manufacturers/ brands.

Development Trends of Lithium Ion Battery Technology: Safety, High-density, Large C-Rate, Long Life, Low Cost

- **3C:** Lithium cobaltic acid increases the upper limit of the charging voltage of a single cell to continuously increase the energy density. It is estimated that after 2025, the battery voltage will be further increased, approaching the theoretical upper limit of 4.9 V.
- **Power:** The energy density is increased by the Ni content of ternary (liquid) and the charging voltage. The energy density is not improved obviously after the Ni content (811) and the voltage (4.25). It is expected that all-solid electrolytes will be commercially available after 2025, and the voltage will be further increased.
- **Energy Storage**: Towards Long-life, Low-cost

1) Lithium iron phosphate: The gram capacity of the material (155 mAh/g) is close to the theoretical limit (172 mAh/g), and the voltage boost has reached the limit. It is expected that the ternary full-solid state process will be used after 2025 to improve the safety performance of the cell.

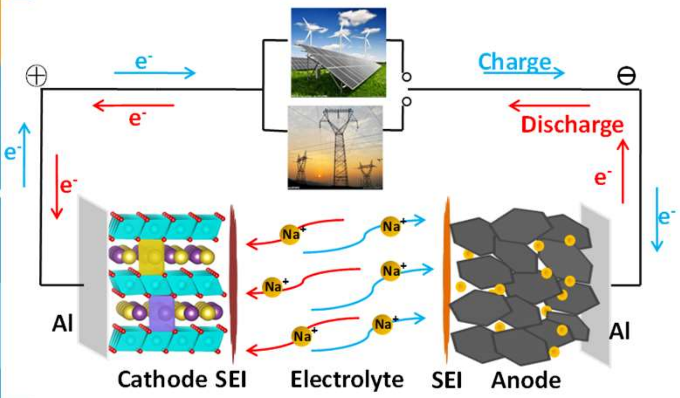
2) Sodium ions: cheap raw materials are one of the directions for low-cost scenario; The manufacturing process is the same as that of lithium iron phosphate, and the material cost is 25%+ lower.



Introduction to Sodium Ion Battery

- Sodium-ion batteries have similar working principles to lithium-ion batteries. The positive and negative electrodes are composed of two different sodium-ion intercalated compounds.

Working principle diagram



- Na+ reversibly be intercalated and de- intercalated in the positive and negative electrodes
- During charging, Na+ is removed from the positive electrode and intercalated in the negative electrode (electron).
- During discharge, Na+ is removed from the negative electrode and intercalated in the positive electrode (electron).

- **Positive electrode: materials with high voltage platforms such as sodium-transition metal oxides, those materials which have potential application prospects are mainly classified as layered oxides, polyanions, and Prussian blue compounds.**

type	Specific composition	Advantages	Disdvantages
layered oxide	NaCuFeMnO2 (Hina battery) NaNiFeMnO2 (Natron, Faradion)	1. The theoretical capacity is higher than Fe-Li, but the actual capacity is close. 2. The processing performance is similar to that of lithium batteries. 3. The precursor is mature materials in other industries, and the BOM cost is lower than that of lithium iron.	1. The transition metal is easy to catalyze electrolyte, which leads to poor cycling performance, material can be treated with surface to improve cycle performance. 2. Thermal runaway will decompose and generate oxygen; 3. The NaNiFeMnO2 material patent is not in China (Argon Laboratories).
Prussian Blue	NaFe[Fe(CN)6] (Starry Sky, Natron, CATL)	1. Use modified material from mature material in other industries, which is expected to have the lowest BOM cost. 2. good safety and no oxygen generation;	1. The material contains crystallized water, causes high water content which affects the self-discharge and cycling life; 2. Patents are not in China (Sharp)
polyanion	Na3V2(PO4)3 (Tiamat, Toyota)	1. Good compatibility with electrolyte; 2. The material stability is good and the cycling performance is good. 3. Stable structure and high safety.	1. Poor C-rate performance and low energy density 2. V is highly toxic and expensive, with low yield 3. Patents not in China (Kyushu University and NGK, Japan)

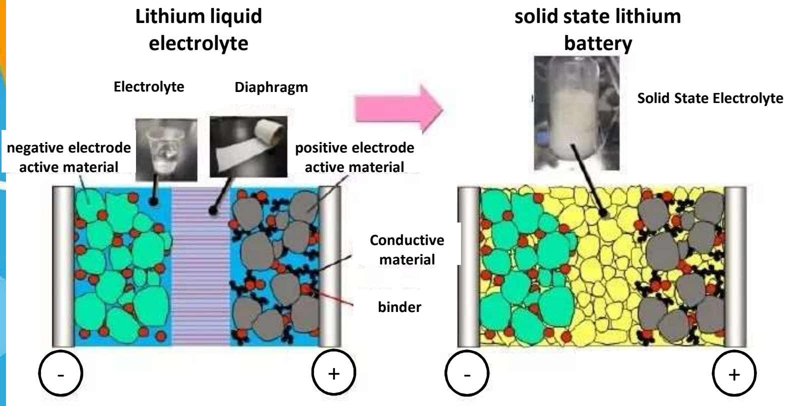
- **Negative electrode: Material having a low voltage platform such as carbon**

type	Advantages	Disdvantages
Anthracite (Hina battery)	Low BOM cost	Poor consistency and low capacity
Hard Carbon (Natron, Starry Sky, CATL)	Mature system and high capacity	High cost

- **Diaphragms: glass fiber, polypropylene or polyethylene, etc.**
- **Electrolyte: The sodium salt dissolved in a solvent.**

New Energy Storage Technology - Solid State Battery

Concept and Principle of Solid State Lithium Battery



Characteristics of Solid State Lithium Battery

Features	mechanism	Potential Applications
Security	Inorganic solid electrolytes are non-flammable, non-corrosive and non-leakage.	Electric vehicles, energy storage
High density	The negative electrode may be lithium metal, and the positive electrode may be high-voltage material.	Electric vehicles, consumer electronics
high temperature Application	No electrolyte, no side reaction between electrode material and electrolyte at high temperature, operating temperature up to 300° C	Application in high temperature areas

Content

1 Safety Challenges

What makes a BESS safe?

- IEC 62133
- IEC 62619
- IEC 62933
- IEC 61936
- EN 50522
- UL 9540A

Over 400 Standards
for batteries

What is safety?

- ☑ IEC 62133
- ☑ IEC 62619
- ☑ IEC 62933
- ☑ IEC 61936
- ☑ EN 50522
- ☑ UL 9540A

BESS System Failure Mode Analysis

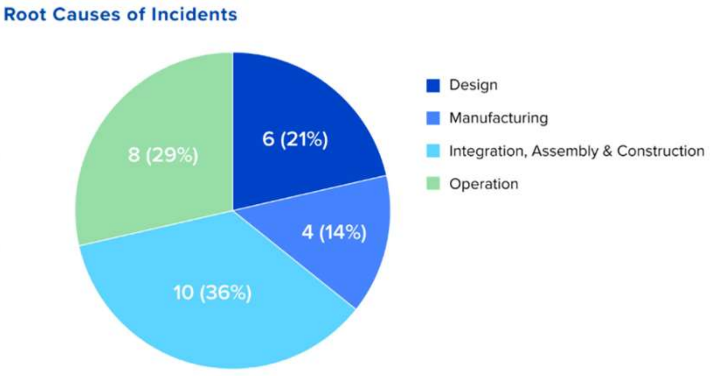
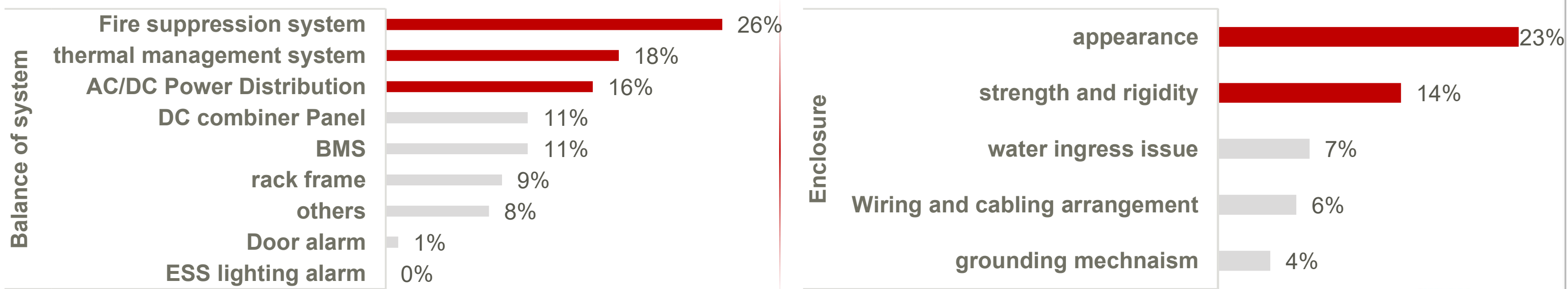


Figure 4. Breakdown of BESS Failures by Root Cause

Design, Manufacturing and Integration make up nearly ¾ of the failures in BESS systems.

Source - https://storagewiki.epri.com/index.php/BESS_Failure_Event_Database

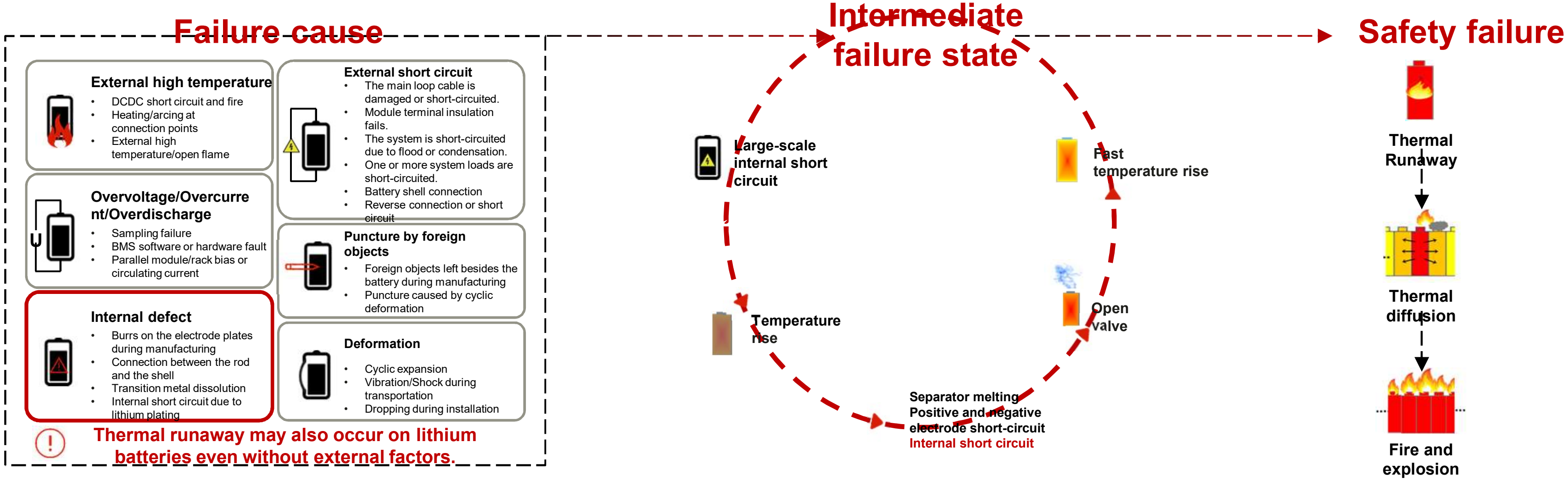
CEA Analysis: 30GWh BESS over the past 6 years and identified more than 1,300 issues, more come from refined management and BESS system integration design



Source: Clean Energy Associates

Evolution of Thermal Runaway in Lithium Batteries

Thermal runaway occurs when a large amount of heat is accumulated inside the lithium-ion battery because **much more heat is generated than dissipated**, which causes a chain of reactions, resulting in fire and explosion.



Thermal Runaway Evolution	Soft short circuit External heat Internal short circuit	Temperature rise due to an internal short circuit	Opening the valve to release gases	Rapid temperature rise	Thermal runaway Hard short circuit	Fire	Thermal diffusion	Explosion
Reaction Temperature / Evolution Time	≤ 69°C (t1 > 30 min)	90–110°C (t2 > 10 min)	110–150°C (t3 > 5 min)	150–170°C (t4 > 1 min)	160–220°C (t5 > 30s) t second-level	450–800°C (evolution time t)	≥ 600°C Tmax 800°C	

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2 Smart String BESS Safety Deep Dive

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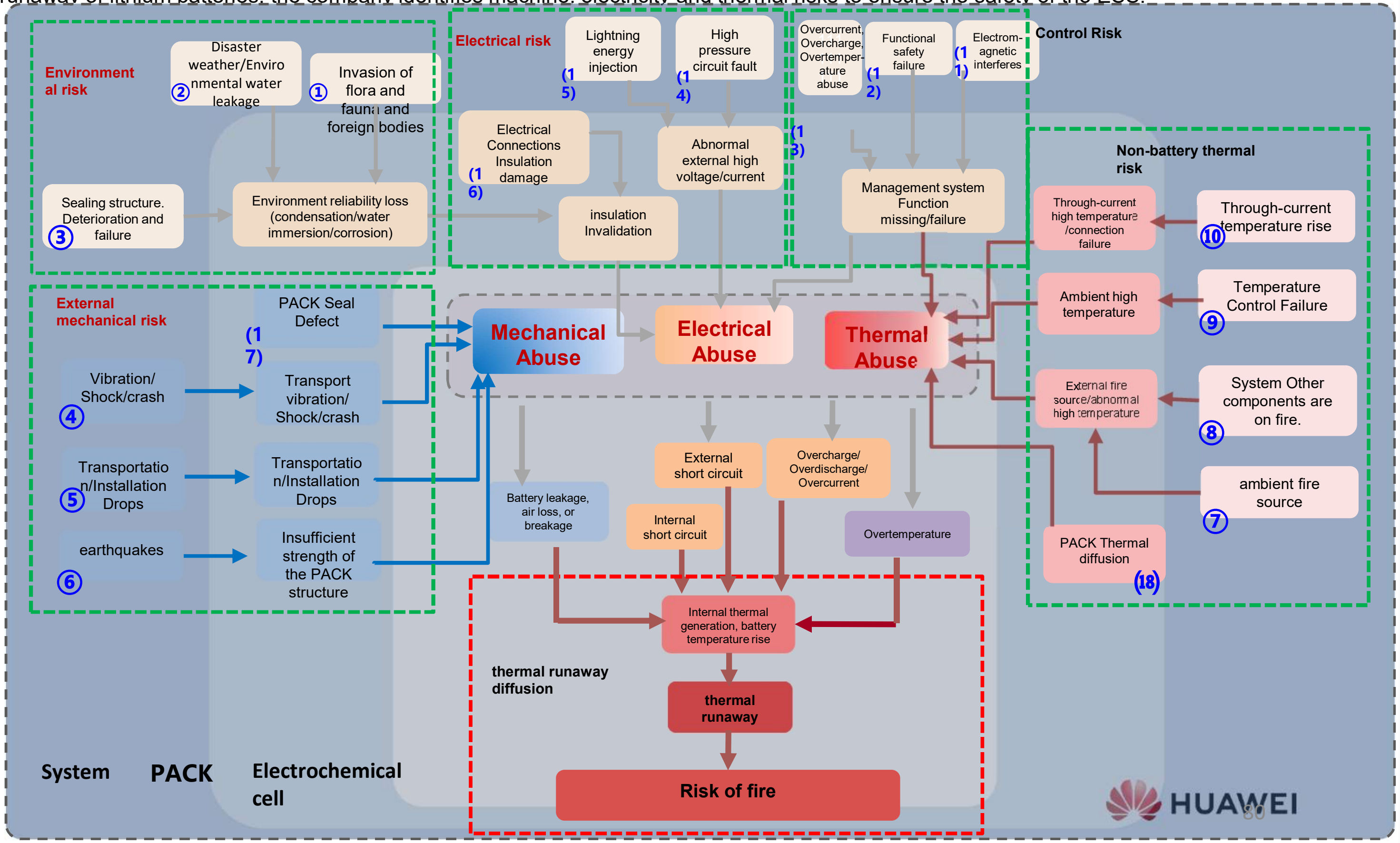
BESS safety: Identify and prevent mechanical, electrical and thermal risks

- With the goal of preventing thermal runaway of lithium batteries, the company identifies machine, electricity and thermal risks to ensure the safety of the ESS.

Service flow	Failure type	Corresponding factor
design	Machine	⑥⑰
	Electricity	①⑬⑭⑮⑯
	Thermal	⑦⑧⑨⑩⑪⑫
Test	Machine	⑥⑰
	Electricity	①⑬⑭⑮⑯
	Thermal	⑦⑧⑨⑩⑪⑫
Incoming material	Machine	④⑤
	Electricity	③
	Thermal	⑨
Process	Machine	④⑤
	Electricity	①⑯
	Thermal	⑦⑧
Transportation and storage	Machine	④⑤
	Electricity	⑬
	Thermal	⑦⑨
Delivery and O&M	Machine	⑤⑥
	Electricity	①②⑮⑯
	Thermal	⑦⑧⑪⑫



Cell to Grid Safety building C2G safety capabilities and system

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E2E system security from Cell to Grid.

Jointly defined and strict tested

Cell Level	Pack Level	Container Level	System Level	Grid Level
Thermal runaway proactive warning	Thermal runaway non-diffusion	Keep safe while thermal runaway	Risk-based proactive shutdown	Adapts to complex grid environments
100 Cloud BMS, 10+ fault warnings in advance	High Protection Pack	Physical isolation protection	24-hour AC/DC insulation impedance monitor	improves grid operation stability. Dual-stage , active power constant output in HV ride-through

E2E Process security from Procurement to Delivery.

Procurement
- Sourcing
- Standard
- Admission

Logistics
- Pack/Transport/Logistics
- Qualification
- Monitorability

Design
- 130+ Design patents；
- Lifecycle MBSE
- 3rd party challenge / defense lab

Manufacture
- Minimal-cable raft
- IQC lab
- Automation

Delivery
- Solution clarification, design, audit
- PMI and rectification

Partner
- HCSX certificate
- Logistics security mgmt.
- Online audit

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LFP Cell: Most Stable cell than Others, Less Fire Risk

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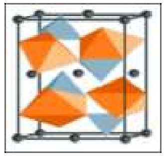
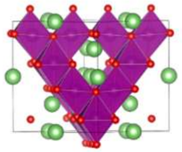


LFP

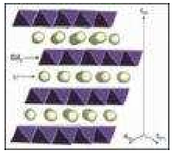
Most Stable

Other Li-ion Battery



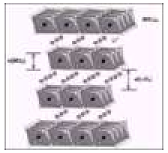
LMO

Stable



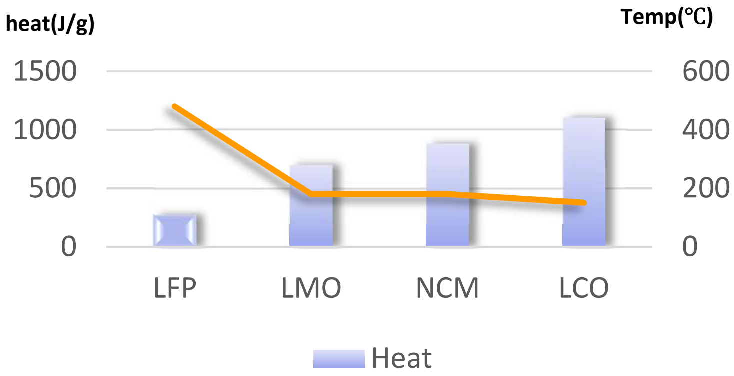
LCO

Less Stable



NCM

Less Stable

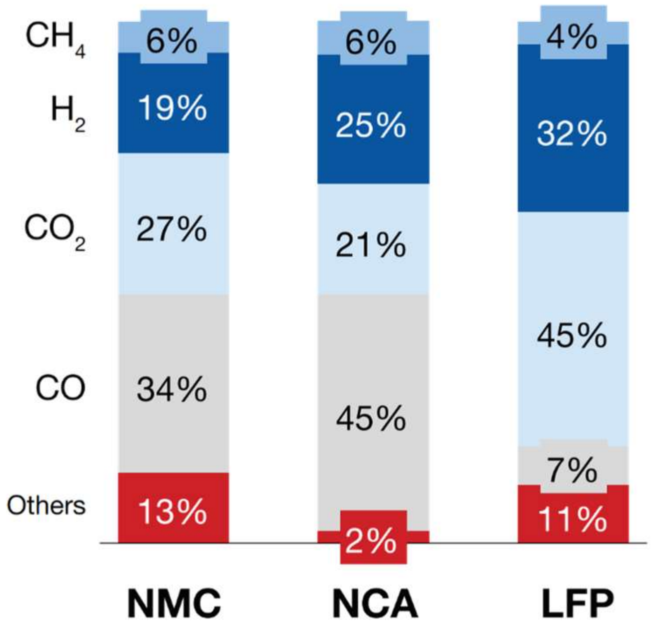


	Normal Charging		Over-charge, over-discharge, and over-temp cause Thermal Runaway (TR)	
LFP	$LiFePO_4$	Charging → $FePO_4$	TR Threshold (~250℃) →	$FePO_4$
LMO	$LiMn_2O_4$	Charging → $Li_xMn_2O_4$	TR Threshold (180℃) →	Mn_2O_3 + O_2 ↑
LCO	$LiCoO_2$	Charging → $Li_{0.5}CoO_2$	TR Threshold (150℃) →	$LiCoO_2$ + Co_3O_4 + O_2 ↑
NCM	$LiCo_{1/3}Ni_{1/3}Mn_{1/3}O_2$	Charging → $CoO_2 + NiO_2$	TR Threshold (180℃) →	NiO_x + Mn_3O_4 + O_2 ↑

Normal Charging

Over-charge, over-discharge, and over-temp cause Thermal Runaway (TR)

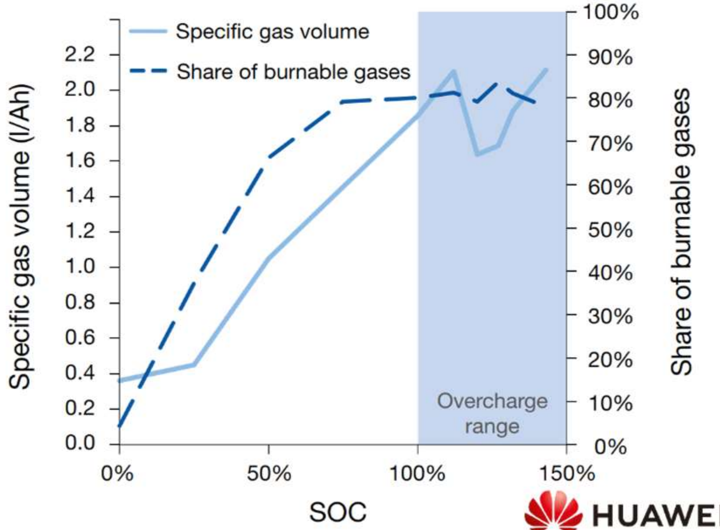
LFP Cell: More combustible gas



Volumetric compositions of the gas released in a termal event, listed by cell cathode chemistry

LFP produces significantly more hydrogen gas than other battery types and…

… gas volume increases linearly with SOC. A fully charged battery will produce significantly more combustible gas.



Cell Safety: 100+ Cell performance test and 5+ stricter core test items

100+ Cell Tests Standard

Safety test

External short circuit during high temperature	Vibrations	Thermal abuse
Overcharge	Squeezing	Drops
Forced discharge	Acupuncture	......

Cell performance test

Capacity	Circulating	Storage expansion force
Energy efficiency	Self-discharging	......
Lithium precipitation	Temp. rise	

White box test

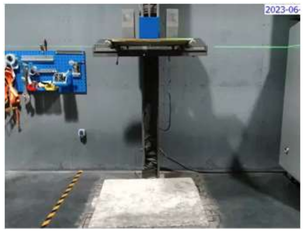
Appearance	Positive electrode	Isolation film size
Capacity	Negative pole	Isolation film thickness
Voltage	electrolyte	......

5+ Stricter test standards

Drops

No fire, no explosion, no liquid leakage during 1.0 m drop

Industry: No fire, no explosion



Acupuncture

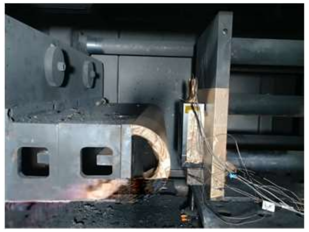
The needle penetrates through the cell without thermal runaway

Industry: No acupuncture test in standard

Crush

50kN, No fire, no explosion, no leakage, no smoke

Industry: 50kN, thermal runaway



Lithium precipitation

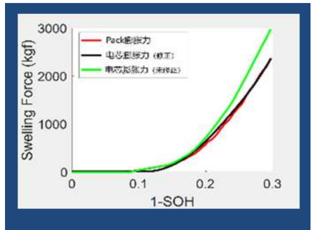
Lithium evolution does not occur during charging

Industry: Allow a certain range of lithium precipitation

Charge/Discharge

Simulation of the Real Working Conditions of Expansion Force during Pack Operation

Industry: Only consider cell operation process



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High-Strength Ceramic Separator Improves Battery Safety

Ceramic separators in lithium batteries usually use polypropylene (PP), polyethylene (PE), or multilayer composite separator as substrate. The surface of the separators is coated with a layer of Al_2O_3, SiO_2, $Mg(OH)_2$, or other inorganic ceramic particles with good heat resistance, which is tightly bonded with the substrate after special processes to improve heat resistance, heat shrinkage resistance, and puncture strength of the separators, and further improve battery safety.

- ✓ Improves the thermal stability of the separator to prevent large-scale contact between the positive and negative electrodes caused by separator shrinkage and prevent safety issues such as fire and explosion.
- ✓ Improves the puncture resistance capability to prevent short circuits caused by lithium dendrite formed after long-term cycles, reducing the risk of thermal runaway caused by internal short circuits.
- ✓ Neutralizes a small amount of hydrofluoric acid in the electrolyte to prevent volume swelling of a battery and ensure the charge, discharge, and cycle efficiency of lithium batteries.
- ✓ The porosity of the ceramic coating is greater than that of the separator, which enhances the liquid retention and infiltration of the separator and extends the cycle life of lithium batteries.

Separator	PE16	PE12 + 4 µm ceramic separator
Separator thickness (µm)	16	16
Melting point (°C)	138	147
Separator puncture temperature	147	154
Puncture strength	320	548

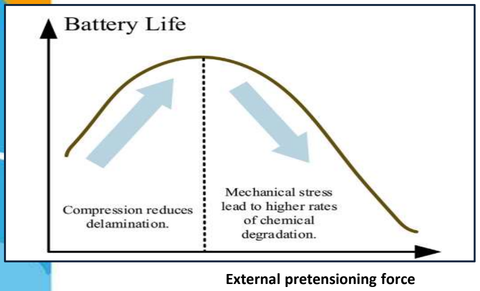
- ✓ The P12 separator has a 4 µm ceramic coating. The melting point is 9°C higher than that without the coating, and the puncture strength is high.
- ✓ When all separators have the same thickness, the performance indicators of the ones with ceramic coating are better.

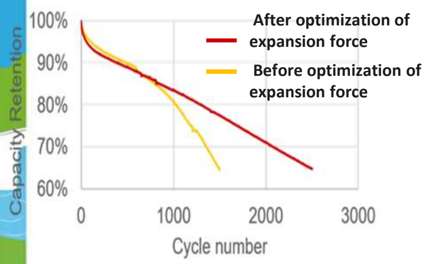
Figure 1 Comparison of the sizes of the pores on the damaged separator where an internal short circuit occurs at the 50% SOC

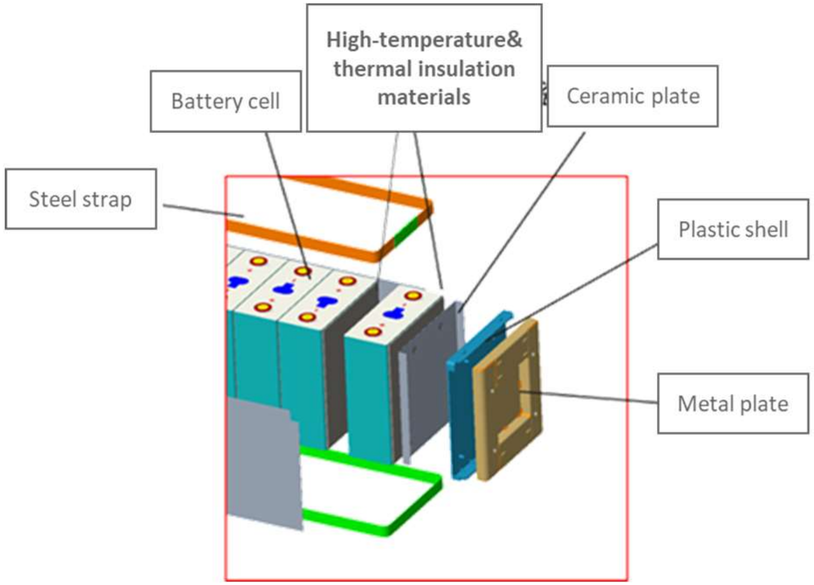
* Data reference: *The Effect of Battery Separator Properties on Thermal Ramp, Overcharge and Short Circuiting of Rechargeable Li-Ion Batteries*

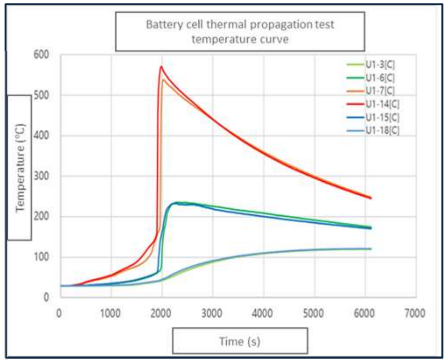
Cell level non-diffusion using high temperature insulation & heat resistant materials

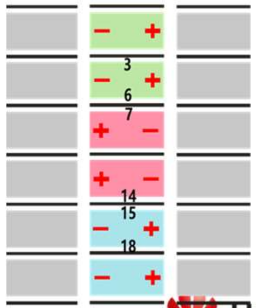
PACK-level thermal propagation protection involves placing suitable high-temperature insulation and thermal insulation materials between battery cells to prevent thermal runaway in one cell from affecting adjacent cells, which could lead to a thermal runaway chain reaction.





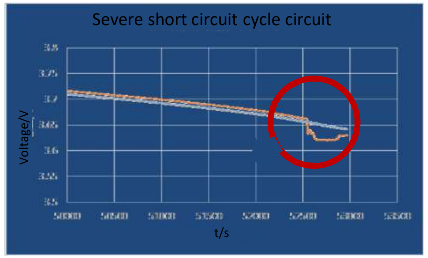






Cell-Level Intelligent Internal Short Circuit Detection

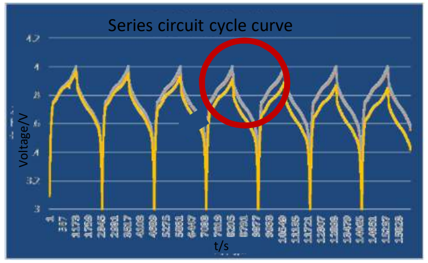
Smart Internal Short Circuit Detection



Instantaneous fluctuation of cell charge/discharge curve

Sudden Internal Short Circuit – Identification Algorithm

- 100% capture the fluctuation of the charge/discharge curve.
- Instantly identify & cut out packs with hazard for maintenance safety.

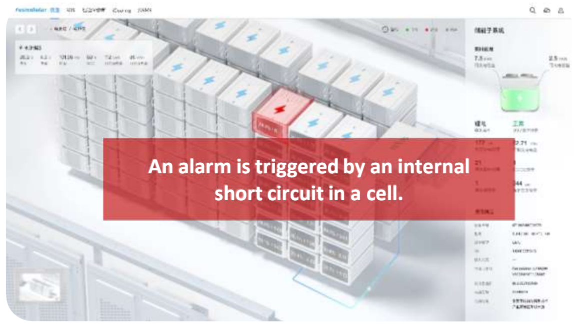


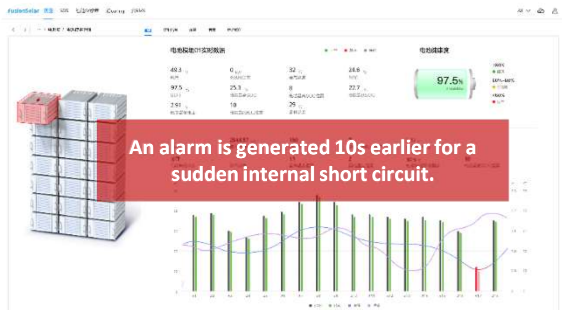
Chronic offset of cell charge and discharge curve

Derived Internal Short Circuit – AI Outliers Algorithm

- Accurately calculate internal resistance & capture the slight deviation in the curve caused by resistance change.
- Accurately locate and warn potential risks in advance

Cell-level internal short circuit alarm





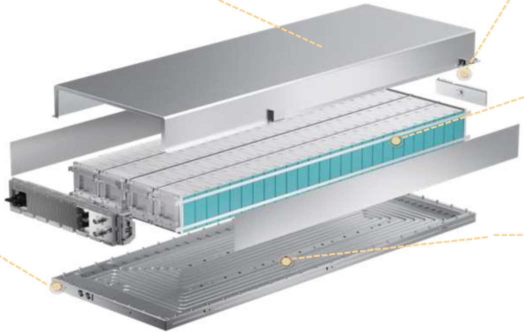
Pack-level Safety: thermal runaway non-diffusion

Iron Enclosure(tin plating)

Temperature resistance ~ 1538 ℃

Smart liquid cooling system

Rapid cooling of 20℃/min, suppression of abnormal rise of pack temperature



Positive-pressure oxygen blocking + directional smoke exhaust

Positive-pressure airtightness and professional pressure relief valve

Heat insulation between cells

Ultra high temperature thermal insulation material

High crosslinked insulating

Resisting electrolyte corrosion for 1000+ hours

Pack-level Safety-Seawater Immersion Test

verify the product safety under extreme seawater immersion conditions

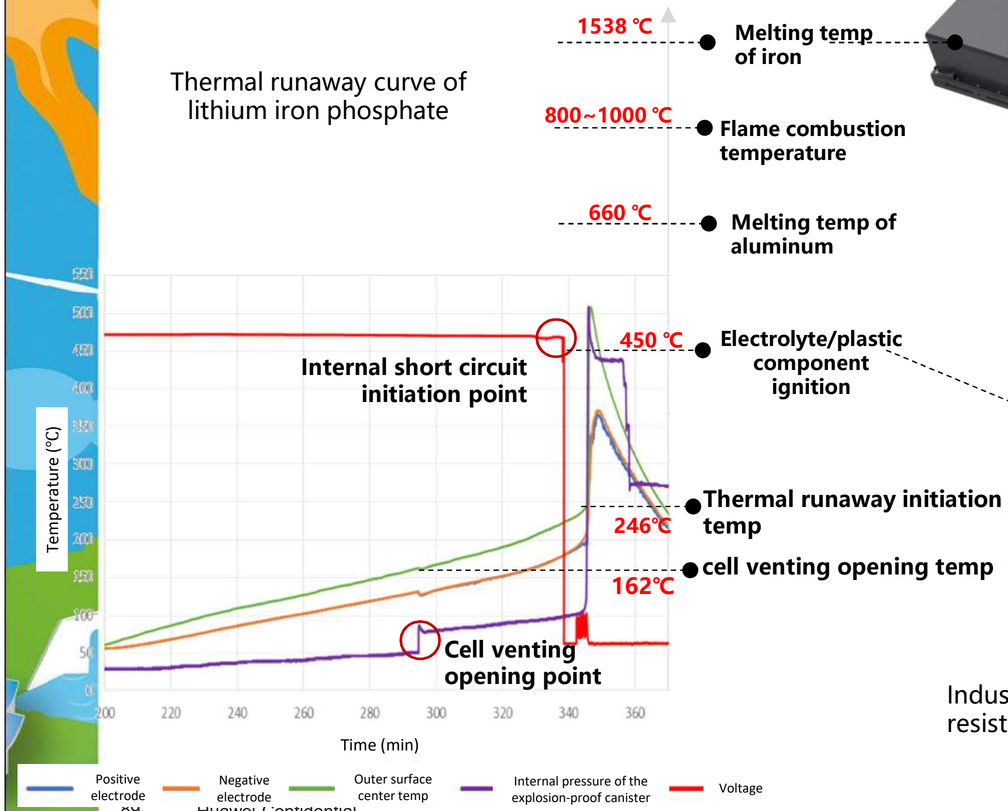
Directional Gas Exhaust Test

Industry's first "thermal runaway + active ignition" method, prevent the system from catching fire or exploding.

Pack Level Safety – Pack to pack non-diffusion

Máster ERMA

Thermal runaway curve of lithium iron phosphate



HW

Steel Shell

HW: Shell temp resistance: 1538°C

Cell ignition is contained within the PACK, with smoke and pressure vented directly

Industry

Flame-retardant plastic shell

Industry: Shell temp resistance: 450℃

Without a directed vent in the PACK, self-ignition of plastic shells can quickly spread to the container

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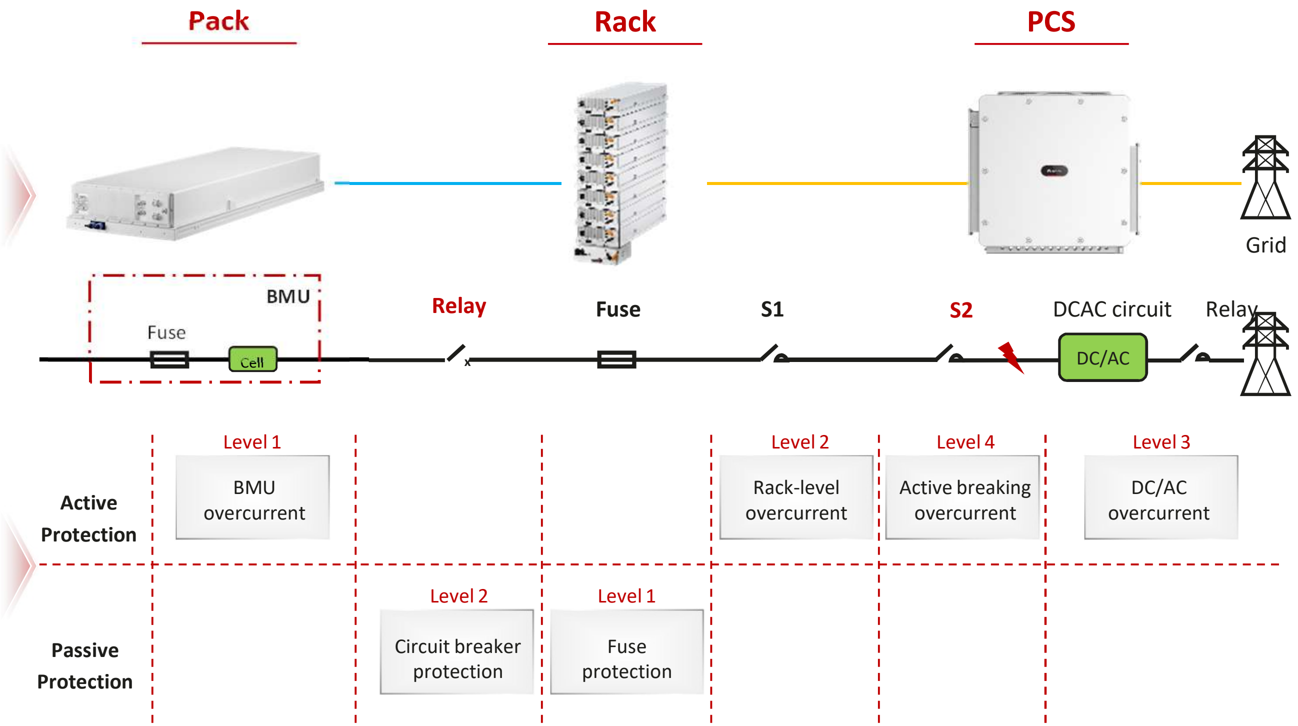
Proactive shutdown and passive isolation, implement comprehensive electrical protection for the ESS

Smart String ESS 2.0

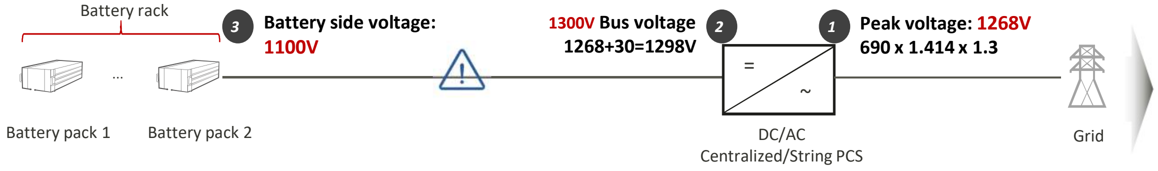
Fast breaking switch, fuse and circuit breaker protection on the DC side

- When the PCS is short-circuited, S1 acts first to protect the rack control box and battery rack.
- When the fault is expanded, the active and passive protections are combined, to ensures the full-range system safety.



The dual-stage architecture ensures safe operation and constant active power output during HVRT

Traditional Central/String Solution: PCS rated AC voltage of 690 V



During HVRT, 2 > 3

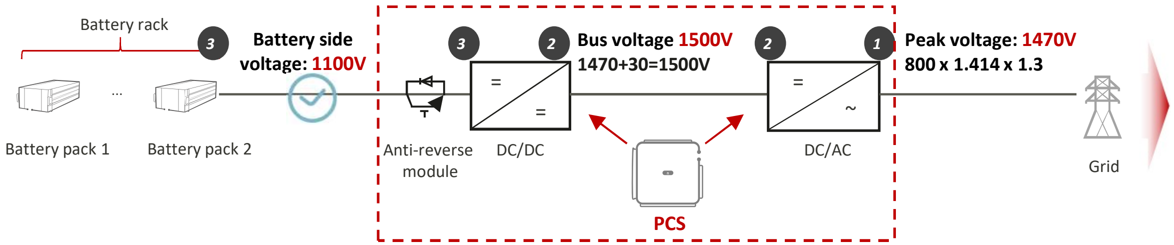
When the BESS SOC is ≤10%,

grid reverses the battery current,

causing battery thermal runaway and even fire.

Unable to maintain constant active output

Smart String ESS: DC/DC+DC/AC dual-stage architecture, PCS rated AC voltage 800 V



During HVRT, 2 > 3

Even if BESS SOC is ≤10%

No backfeed current enters the battery

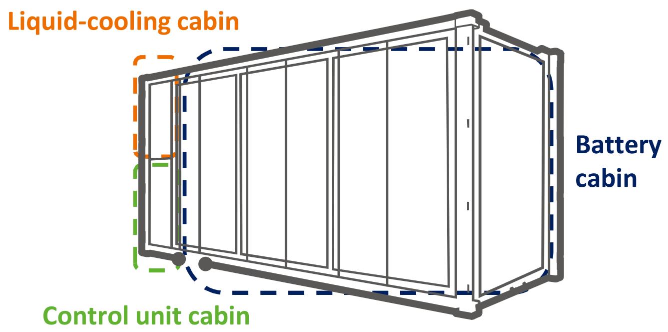
the BESS is absolutely safe

Ensure stable active output.

Structural Safety: Isolation of Different Compartments in the ESS Ensures High Reliability

Isolation design ensures high system safety

Separate the battery cabin, Liquid-cooling cabin and control unit cabin to ensure operation of the monitoring and fire suppression systems.



Structural safety, high protection and high reliability

The entire system meets the YD5083 standard (intensity 9) earthquake simulation tests

System protection degree IP55
Pack protection degree IP65

The anti-corrosion level of the container meets C5.
Neutral salt spray test duration reaches 720 hours.

Explosion Venting and water fire extinguishing test to ensure safety and effective fire extinguishing

Container-level safety
Explosion Venting Tests

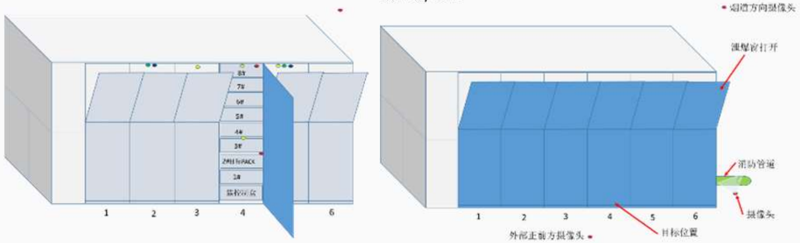
Explosion test simulation

Real Explosion Test of the System

- ✓ Explosion-discharge window opened
- ✓ The chassis deformation within the design range
- ✓ After the battery heat runs out of control, ignition and explosion do not cause shell disassembly and no matters fly out.

System-level safety
water fire extinguishing test

Water Fire Test Layout



System real water fire test (video acceleration 50 times)

21:32:59 light a fire → 21:38:05 Start spraying water → 21:44:06 Fire extinguished successfully

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120 Minute fire resistance for ESS container

The unexposed surface before the test

The exposed surface before the test

The unexposed surface of the sample
(after test duration of 120 minutes)

The exposed surface after the test

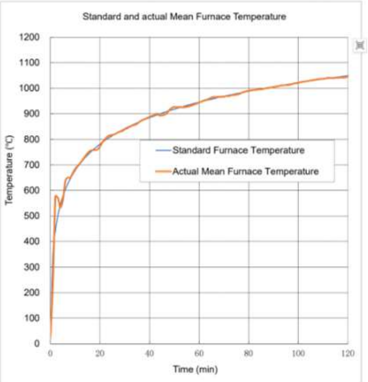


Figure 3 - Actual Mean Furnace Temperature/Time Curve and Standard Furnace Temperature/Time Curve

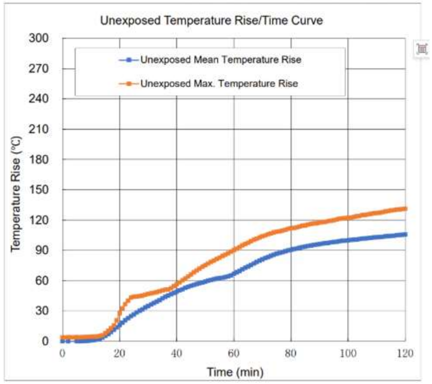
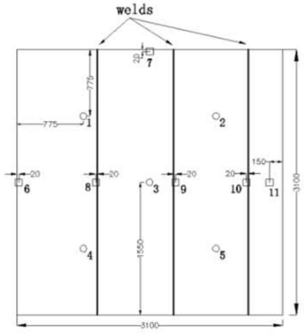


Figure 4 – Unexposed face temperature/time curve



○ Thermocouples for average temperature rise
□ Thermocouples for maximum temperature rise
No. 1, 2, 4, 5 in the center of each quarter for specimen
NO. 3 in the center of the specimen.

6. Conclusion

The sample was tested in accordance with EN 1363-1:2020 Fire resistance tests Part 1: General Requirements and EN 1364-1:2015 Fire resistance tests for non-loadbearing elements part 1: walls.

During the heating period of 120 minutes, the sample kept integrity and insulation. The mean temperature rise of unexposed surface was 105.6℃ and the maximum temperature rise was 131.1℃.

The performance of the sample was judged against the criteria for integrity and insulation as specified in chapter 6 of this report (Clause 11 of EN 1363-1:2020) and the sample satisfied the performance requirements for the following period:

Integrity	Insulation
120 minutes	120 minutes

EN 1364-1:2015 Standard

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Extreme Ignition Test of Huawei's Smart String & Grid Forming ESS

Start — 0 hour

Triggering 12 Cells into Thermal Runway, No Fire or Explosion after 4 Times Ignition Attempts — 1.5 hours

Triggering Another 4 Cells into Thermal Runway — 3 hours

No Fire or Explosion after 5&6 Times Ignition Attempts — 3.5 hours

Continuous Thermal Runway — 6.3 hours

Start Burning — 7 hours

End — 13 hours

Site Cleaning — The container structure is complete and can be hoisted

Huawei's Smart String & Grid Forming ESS Triumphs in Extreme Ignition Test

Puyang
LOCATION

February 9, 2025 - February 10, 2025
TIME

DNV

DNV and strategic customers witnessed the whole process on site.

Conclusion of Test

The success of this test underscores Huawei Digital Power's major breakthrough in system safety, delivering **comprehensive protection from the battery cell level to across the entire system**.
Through architectural innovation, the company has enhanced the safety protection mechanism of the ESS **from the container level (industry standard) to the pack level, effectively preventing thermal runaway spread**.

Highlights

1. **Real-World Verification** with 100% Mass-Produced Products
2. Triggering 12 Cells into Thermal Runway **Causes No Fire or Explosion after Multiple Ignition Attempts**
3. Ultimate Fire Resistance Capability Prevents Propagation under Maximum Oxygen Supply Combustion Scenario
4. **Slow Fault Progression** Provides Critical Time for Early Intervention to Avoid Serious Accidents

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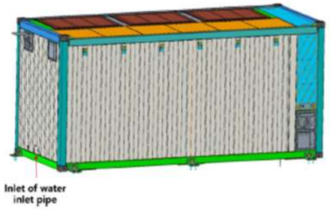
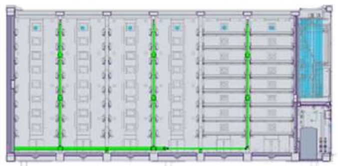
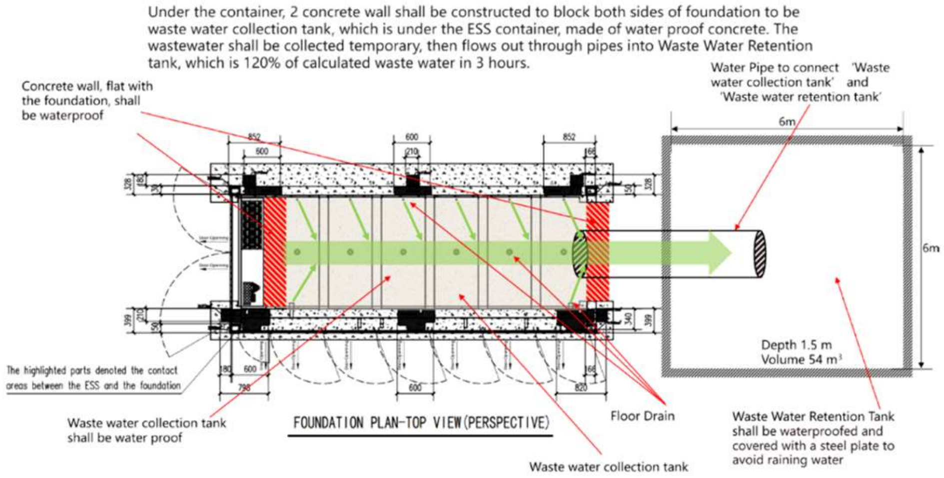
Environmental impact: Wastewater





Technical Specifications	Specification
Total Inlet Flow	244L/min
Water inlet pressure	⩾0.107MPa
Water inlet pipe diameter	DN50



Based on the water inlet 244L/min and the spraying time calculated as 3 hours, a total of **43.92m^3 of wastewater** will be produced. Wastewater will be discharged through floor drains.

3 What makes a BESS safe?

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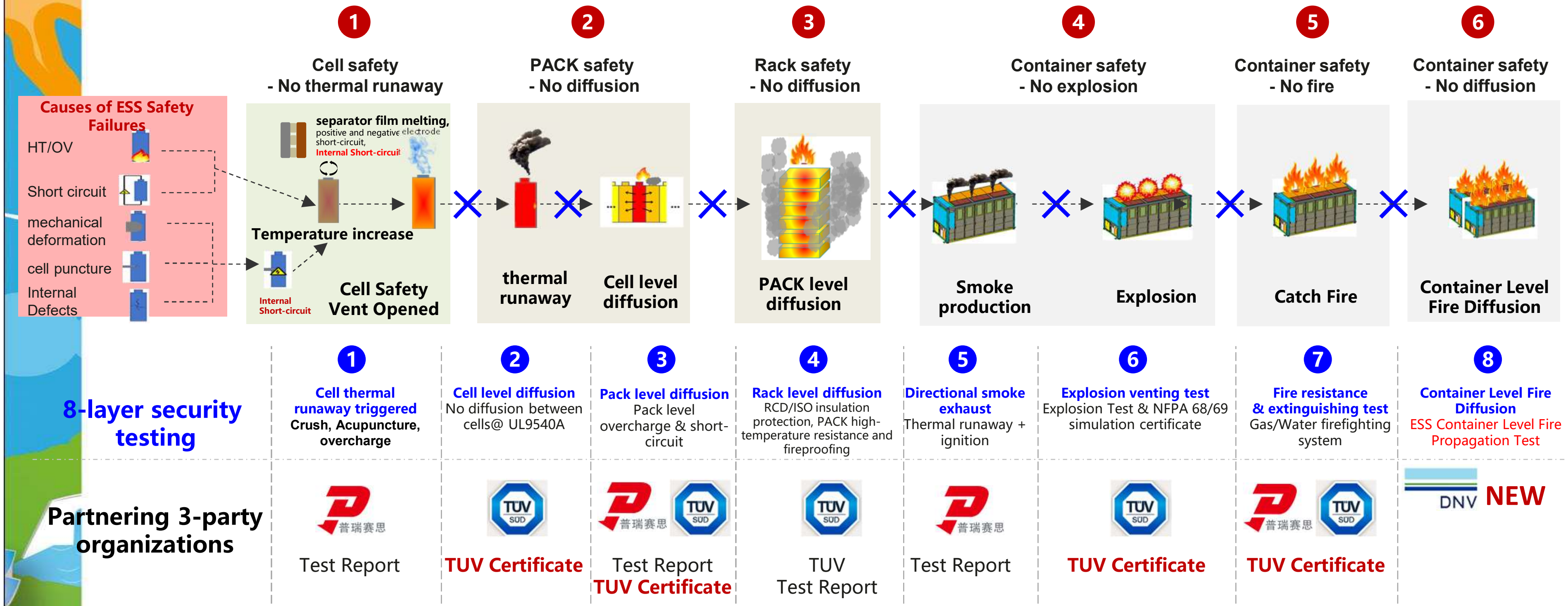
Safety Test Policy – Six Layer Fortress

Six-layer fortress technology, Ensure that energy storage products do not catch fire, explode, spread, or hurt people



Shenzhen Precise Testing Technology Co., Ltd. focusing on lithium batteries and their upstream and downstream
*TUV Authorized Lab
*CSA Certificate of Authorized Testing Lab

Thank you