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Review

Safety Aspects of Stationary Battery Energy Storage Systems

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Abstract: Stationary battery energy storage systems (BESS) have been developed for a variety of uses, facilitating the integration of renewables and the energy transition. Over the last decade, the installed base of BESSs has grown considerably, following an increasing trend in the number of BESS failure incidents. An in-depth analysis of these incidents provides valuable lessons for improving the safety of BESS. This paper discusses multiple safety layers at the cell, module, and rack levels to elucidate the mechanisms of battery thermal runaway and BESS failures. We further provide insights into different safety aspects of BESS, covering the system architecture, system consideration, safety standards, typical quality issues, failure statistics, and root causes. Various mitigation strategies are recommended and summarized. We highlight the importance of multi-disciplinary approaches in knowing, managing, and mitigating the risks associated with BESS. In general, this review paper serves as a guide for understanding the safety of BESS.

Keywords: BESS; safety; thermal runaway; system consideration; standards; quality issues; incidents; root causes; mitigation

1. Introduction

The implementation of intermittent, renewable electricity generation requires an increase in electricity storage. Battery energy storage systems (BESS) are a type of storage solution that stores electrical energy using batteries and other electrical devices. In recent years, with a total installed power of 50 GW on a utility scale [1], stationary BESS have become substantial contributors enabling renewable integration worldwide. The growth of this sector is further underlined by the fact that the European Commission has recently projected to install a total of 200 GW of BESS in the EU by 2030 [2]. In addition, there is a significant number of behind-the-meter installations, particularly in the commercial and industrial (C&I) sector. Along with the rapid growth of installed BESS capacity, a rise of safety concerns about the operational safety of these large installations can be observed. Here, we summarize various aspects and present mitigation strategies tailored to stationary BESS.

Although some residual risks always present with Li-io batteries, BESS can be made safe by applying design principles, safety measures, protection, and appropriate components. The overall safety of BESS is based on functional safety concepts and includes multiple layers of solutions for a variety of scenarios [3]. Figure 1 presents the typical safety hierarchy of a Li-ion BESS, covering the following levels:

- Cell: Selection of a cell chemistry and design best suited to the load profile and boundary conditions of the specific application. The cell design comprises basic mechanical protection, such as a vent disk and other protection elements against internal faults.
- Module: It has to fit the thermal and mechanical protection concept of the rack. The module also includes a layer of the battery management system (BMS), which ensures each battery cell stays within the safe operation window by collecting data such as current, cell voltage, and temperature.

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- Rack: Comprises a rack BMS, electrical protection devices (fuses and contactors) against external faults, as well as passive protection against mechanical threats and active protection against thermal ones.
- System: Comprises a system controller to coordinate the internal interplay of the components and serves as an interface to the "outside". In operation, environmental sensors continuously monitor for abnormal conditions around the BESS. Upon detecting any issues, they notify the temperature control unit for cooling/venting and the safety monitoring system. Additionally, a fire suppression system is essential to prevent the onset and spread of fires within the BESS.

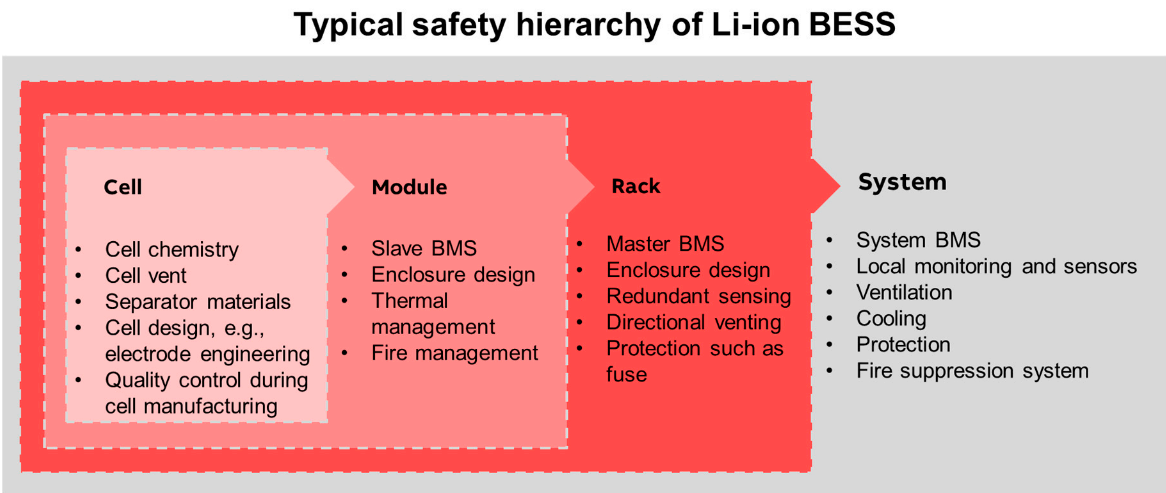

Figure 1. A typical safety hierarchy of BESS, adapted from [3].

The above-mentioned safety layers are interconnected and work in coordination to ensure the entire safety and efficiency of the BESS. In the following sections, each safety layer will be discussed in detail, providing an in-depth understanding of their functions, mechanisms, and interactions within the system. The detailed abbreviations and their definitions used in this work are listed in Abbreviation.

2. Safety Aspects on Cell Level

This section provides an overview of Li-ion battery cell chemistry, thermal runaway mechanisms, and safety considerations, focusing on the factors that affect thermal stability.

A Li-ion battery cell is composed of a cathode, an anode, a separator, and an electrolyte. Conventional Li-ion batteries contain a liquid electrolyte that is soaked in the pores of the separator and two electrodes. In the all-solid-state cell configuration, a solid electrolyte plays the role of both separator and electrolyte. Li-ion batteries have a family of different cell chemistries, depending on the selected cathode and anode materials. Figure 2 presents the mainstream Li-ion cell chemistries, their cell voltages (determined by the difference between the cathode and anode potentials vs. Li/Li^+), and practical capacities. Commercial Li-ion batteries commonly use cathodes such as lithium cobalt oxide (LCO), lithium iron phosphate (LFP), lithium nickel manganese cobalt oxide (NMC), lithium manganese oxide (LMO), and lithium nickel cobalt aluminum oxide (NCA) coupled with graphite or lithium titanate (LTO) anodes for both transportation and stationary energy storage applications.

Li-ion batteries are voltage and temperature-sensitive. Battery cells can store electrical energy as chemical energy operating safely under certain cell voltage windows and temperatures, as shown in Figure 3 [4]. For example, the graphite-based Li-ion cells have a preferred operation condition with a voltage range of 2.5–4.3 V and a temperature range of −30 to 55 °C [5]. At low temperatures <−30 °C, the graphite-based cell has reduced performance, such as poor rate capability and safety concerns such as lithium plating. The joule heat is a normal part of battery operation and causes different temperature increases depending on the cell's internal resistance and applied charge/discharge currents [6]. The generated heat can be dissipated during normal operations. Typically, Li-ion batteries have cell capacity degradation over time due to both cycling and calendaring aging [7]. Non-energetic failures such as increased cell resistance, Li^+ ion loss, cell swelling, electrolyte leakage, and the consequent cell dry-out are the most common failure modes for batteries.

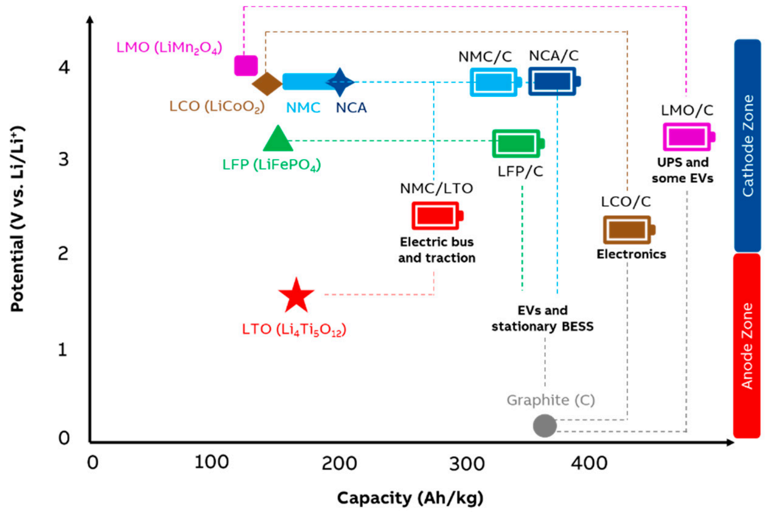

Figure 2. Different electrode materials and their capacities and working potentials (vs. Li/Li+). The combination of cathode and anode materials results in different types of Li-ion cell chemistries. EV: electric vehicle; UPS: uninterruptible power supply.

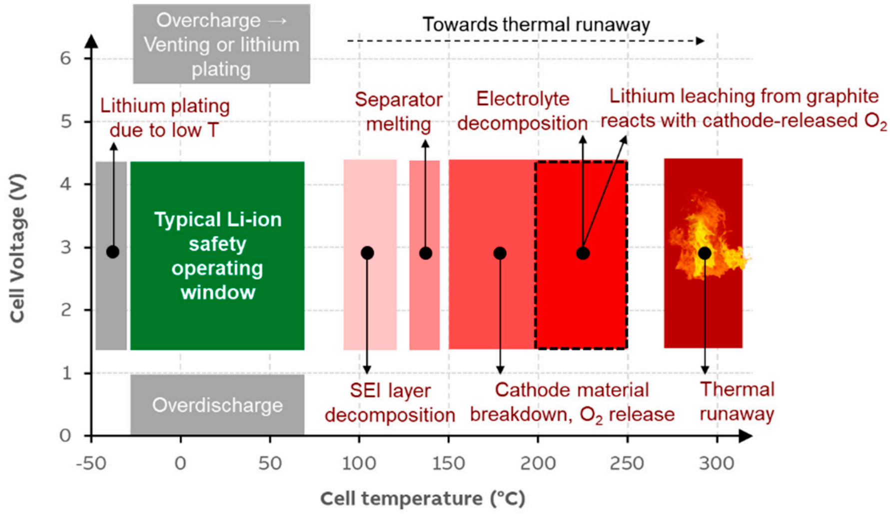

Figure 3. Li-ion safety operating window and the temperature-related processes of thermal runaway.

Non-energic failures show no thermal runaway but compromise the battery reliability [8]. However, off-nominal operating conditions can lead to continuous heat generation, gas release, and critical cell failures [9]. Figure 4 lists different abuse conditions, including thermal, electrical (overcharge, overdischarge, short circuit, etc.), and mechanical (nail penetration, crush, impact, etc.) abuses [10]. A series of exothermic chain reactions are triggered within the battery cell under those abusive circumstances, which usually lead to a sudden rise in the cell temperature. First, the solid electrolyte interphase (SEI) film on the anode starts to decompose at around 90 °C [8]. The polymer separator, such as polyethylene (PE), melts in the temperature range of 120–140 °C, which results in an internal short and self-heating [11]. The cathode active materials then decompose with the release of oxygen at temperatures ranging from 150–250 °C, depending on the chemistry [12]. The released oxygen may further trigger the electrolyte decomposition via oxidation. At elevated temperatures from 200 °C, lithium leached from the lithiated graphite anode begins to react with the cathode-released oxygen and/or the liquid electrolyte. When cell temperature reaches 250 °C, a large number of combustible gases (e.g., H_2, CH_4, and C_2H_4) evolve, substantially increasing the overall cell temperature and raising a high risk of thermal runaway [13]. Finally, the cell temperature increases in an uncontrolled manner, and the thermal runaway events occur when the heat generation rate is higher than the heat dissipation rate. In the worst scenario, the fire and explosion appear as the energic cell failures.

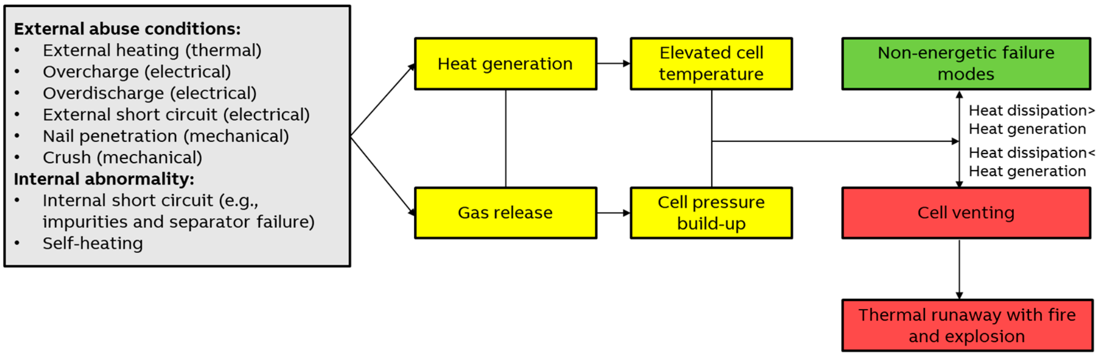

Figure 4. Causes and steps of battery cell failure.

The released energy during battery thermal runaway originates from three different sources including electrical energy, chemical energy, and combustion energy. Multiple parameters (e.g., cell chemistry, cell capacity, cell status, cell format, failure type, and analysis methods) are relevant to the amount of heat release. Figure 5 illustrates the key factors that affect the occurrence and extent of thermal runaway.

First, the employed cell chemistry directly impacts the severity of cell failure. Cells using high energy-type cathode materials are subject to more pronounced exothermic reactions. Different studies [14–18] have investigated the thermal reactivities of various cathode cell chemistries. Figure 5a compares the exothermic temperature and amount of released heat from the decomposition of different cathodes with electrolytes. The exothermic reactions of the LCO cathode have an onset temperature of about 150 °C [18]. In comparison, LFP and LMO cathodes have better thermal stability and higher exothermic onset temperature of approximately 200 °C [15,17]. Martha et al. [19] reported an average heat release of 290 $J/g_{electrode}$ from the reactions of LFP cathode (specific capacity of ~150 mAh/g) towards electrolyte (1 mol/L $LiPF_6$ in ethylene carbonate: dimethyl carbonate = 1:1). In the case of NCA cathode (specific capacity of ~200 mAh/g), a much higher heat release of 850 $J/g_{electrode}$ was reported by Wang et al. [20]. Despite the fact that the measured characteristics of thermal decomposition of cathode and electrolyte vary in different studies and test conditions, the general trend indicates that the thermal stability of common cathodes ranks as follows: LFP > LMO > NMC > NCA > LCO [14].

Cell capacity also affects the extent of battery thermal runaway [21]. The higher cell capacity translates to more stored electrical energy, resulting in larger heat release during thermal runaway. For example, a study determined the total thermal runaway heat release of a fully-charged 68 Ah LFP pouch cell reaching 6.7 MJ [22], which is a factor of 69 times higher than the fully-charged 1.3 Ah LFP 18650 cell [23].

The state of charge (SOC) of a battery cell is the ratio of the available capacity and the maximum possible charge that can be stored in a safe manner [24]. Battery SOC has a significant impact on thermal runaway behaviors. Both heat release and heat release power increase with higher SOC. Lamb et al. investigated the thermal runaway of a 16 Ah pouch-format LMO cell at different SOC [25]. Their test results shown in Figure 5b illustrate the self-heating peak power increases exponentially at high SOC, with a fast increase observed above 60% SOC. Such an exponential pattern is in line with the fast kinetics of decomposition reactions at high SOC. Wang et al. [26] reported that the SOC affects the thermal runaway propagation from one cell to another.

Another parameter of cell status, i.e., state of health (SOH), determines the loss of capacity during aging, leading to the decrease of the maximum storable energy within the cell. Doose et al. investigated the influence of SOC (30–100% SOC) and SOH (75–100% SOH) on the thermal runaway of a 5.5 Ah LCO-based pouch cell [27]. Their results showed a decrease in the extent of the thermal runaway reactions with decreasing SOC or lower SOH. Ouyang et al. compared the thermal runaway behaviors of 3.7 Ah NMC-based cylindrical cells with different SOHs, ref. [28] as shown in Figure 5c. Thermal runaway developed faster and earlier as the cell SOH decreased. The aged cell is prone to undergoing the thermal runaway at a lower temperature, while less mass loss was measured as a result of the faster evolution of thermal runaway. In the same study, the safety valves were shown to be effective in mitigating the risks and hazards of thermal runaway of cells under overheating conditions. Ren et al. further pointed out that not only the SOH but also the detailed ageing conditions have the influence on the severity of an occurring thermal runaway [29]. They identified the lithium plating as the main reason for the deterioration in thermal runaway characteristics, which was evidenced by the cell aged at low temperature showing an additional exothermic peak and lower thermal runaway onset temperatures in comparison to differently aged cells at the same SOH.

During thermal runaway and combustion, the organic electrolyte is one of the components that releases the most heat [30]. The amount of released oxygen from cathode materials such as NMC is not sufficient for the complete combustion of organic electrolytes. The cell vented electrolyte, materials, and flammable gases can further combust externally in air with a total energy release several times higher than the scenario without air access (as shown in Figure 5d) [31].

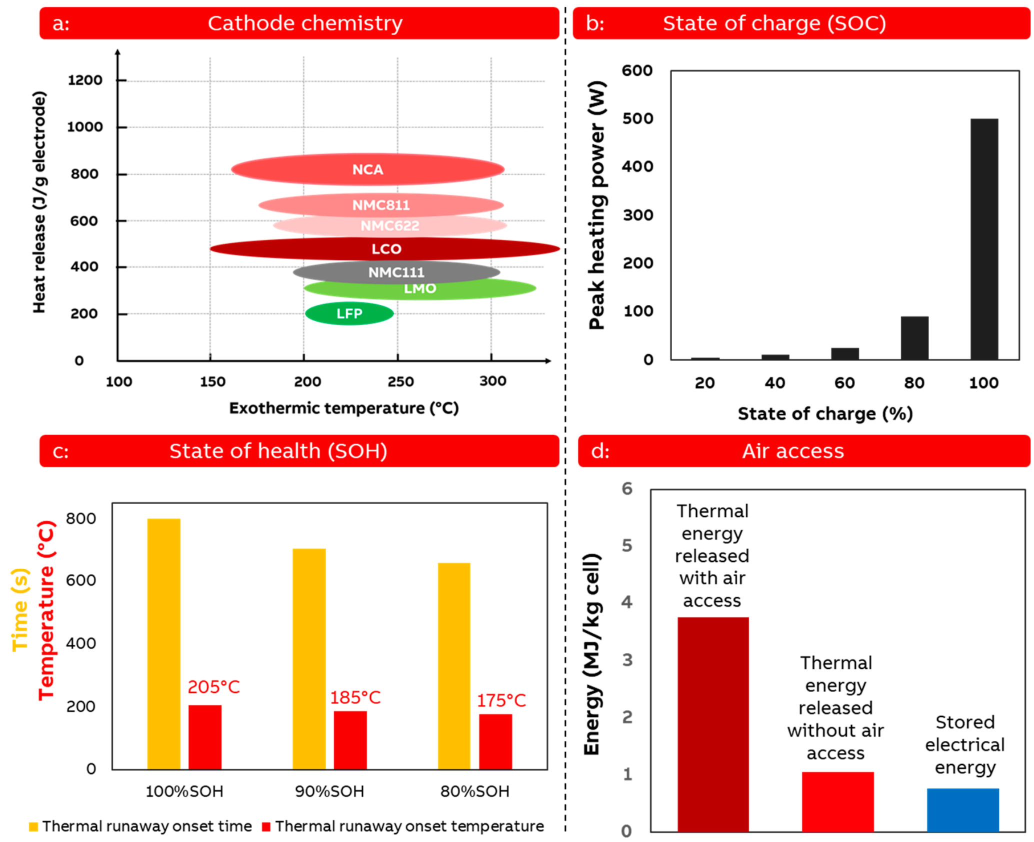

Figure 5. Key factors influencing the extent of battery thermal runaway with data taken from (**a**): [14], (**b**): [25], (**c**): [28], and (**d**): [31].

3. Safety Aspects on Module/Rack Level

Contrary to safety aspects on a cell level, safe battery modules and racks for state-of-the-art Li-ion cells must deal with hazards imposed by the cell itself. As discussed in the section above, hazards are generally imposed by heat generation and gas release. The main hazard arising from thermal runaway heat release is the inevitable temperature increase for neighboring cells and potential thermal runaway propagation. This fact is further aggravated by a general trend in module and rack design towards increased energy density and, therefore, typically narrower spacing between single-cell units [32]. Heat production and thermal runaway are typically accompanied by gas release originating from cell-internal decomposition reactions. The pressure increase and potential cell casing rupture oppose two main risks. First, highly flammable gases are ejected from the cell, forming either a fully ignited cell external flame with temperatures of 750–1000 °C or causing a fire and explosion hazard in the vicinity [22,33–35]. Second, the ejected gaseous emissions contain highly toxic compounds (e.g., HF and CO), causing environmental and human harm [36,37].

To mitigate cell-to-cell heat transfer, different thermal insulation strategies are followed between cells. A classical approach with thermally insulating materials has been conducted by Lee et al. [38]. They experimentally investigated different passive insulation materials like perforated stainless steel, intumescent solid, and ceramic fiber boards for insulation purposes in between cells. None of the actual could prevent thermal runaway propagation but could show a reduction in propagation speed by a factor of up to 17 with the ceramic fiber material. A numerical model proposed by Gong et al. [39] compared the influence of glass fiber, silicate fiber, and ceramic fiber in between cell insulation. In conclusion, glass fiber barriers outperformed silicate and ceramic materials. Using a similar insulation approach with silicate, ceramic, and glass fiber boards, Rui et al. [40] studied the synergistic effect of insulation combined with liquid cooling by experiments and numerical simulations. They concluded that only insulation materials in conjunction with liquid cooling suppress thermal runaway propagation in between cells significantly. Different fibrous and aerogel insulation materials were investigated by Liu et al. [41]. The study compared experimentally temperature traces of adjacent cells using ceramic fiber, glass fiber aerogel, ceramic fiber aerogel, pre-oxidized silk aerogels, and silicon dioxide aerogel insulation. The conclusion was that aerogels could further reduce adjacent cell temperature by at least 13% compared to fibrous insulation materials. Yu et al. [42] experimentally determined the insulation performance of an aerogel, polyimide foam, and mica tape composite insulation cotton in a dedicated setup. Polyimide insulation showed the best results for thermal runaway confinement, reducing total cell-to-cell heat transfer from 719 kJ to 390 kJ. Weng et al. [43] showed a novel insulating approach using an aluminum honeycomb structure. Under external heating, thermal runaway propagation within the cell array could be stopped, while without honeycomb, the thermal runaway propagated through the entire cell array.

Contrary to the passive insulation studies presented above, phase change materials have an active insulation function principle that allows latent heat storage and is also used for nominal operation cooling of battery packs [44–46]. Zhang et al. [47] combined phase change material based on paraffin, glass fiber, and pentaerythritol phosphate with active liquid cooling. They showed that under thermal runaway conditions, the hybrid system showed an effective heat transfer and dissipation to the cooling system while maintaining the material properties of the phase change material at high cell temperatures. As the flammability and structural rigidity of phase change materials are issues, Weng et al. [48] proposed an insulation system containing silica aerogel and flame-retardant phase change material. The study showed that structural rigidity and thermal insulation of the aerogel can be combined with a phase change functionality into a highly functional hybrid material for insulation purposes. An experimental study on the effectiveness of phase change material insulation is shown by Wilke et al. [49]. By triggering NMC-graphite cells into runaway via nail penetration, adjacent cell temperatures could be reduced from 189 °C (without insulation) to 109 °C (with a phase change composite material based on wax and graphite).

To mitigate the effects of fire and the highly flammable and toxic gaseous emissions produced during battery thermal runaway, the following strategies can be applied. Xu et al. [50] and Sun et al. [51] experimentally determined the effectiveness of water mist, CO_2, and HFC-227ea for extinguishing battery fires of NMC-graphite cells. Xu et al. concluded that only water mist was able to completely extinguish the fire, reducing the cell temperature by 133 °C compared to the reference without extinguishing fluid. Sun et al. confirm the best extinguishing performance for water mist while also seeing no thermal runaway propagation for that case. To suppress battery fires, Liu et al. [52] used dodecafluoro-2-methylpentan-3-one ($C_6F_{12}O$, Novec 1230) as a fire extinguishing agent, showing extinguishing times of 2–3 s and a reduced amount of smoke released. Figure 6 shows a typical setup for the performance assessment of extinguishing agents. The battery fire is triggered via a heater (red) attached to the battery cell. Once the cell is on fire, the fire suppressing agent is sprayed over the fire via a nozzle. By tracking the cell temperature, different extinguishing agents can be compered in terms of temperature reduction potential and ability to suppress reignition of the battery fire.

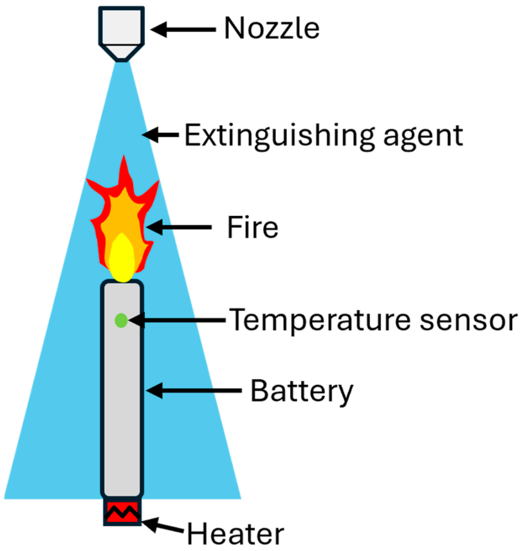

Figure 6. Typical setup for experimental performance assessment of extinguishing agents.

4. BESS Architecture

This section provides an overview of typical BESS architecture, including its main components, operational principles, and safety considerations.

Even though batteries have been integrated into storage systems with many architectural variants, there are often some similarities from a conceptual point of view [53–58]. In most cases, stationary battery systems contain a power electronic converter, protection components (breakers, etc.), and a transformer for the grid connection. Here, we describe a generalized architectural concept that helps to explain the safety-related aspects. Figure 7 presents the architecture of a typical BESS.

A BESS contains a battery part schematically shown as "battery racks" on the left side of Figure 7, and a "power converter", which is the converter itself combined with the protection devices, i.e., a low voltage (LV) DC switchgear and low voltage alternating current (AC) switchgear on each respective side of the converter (middle part of Figure 7). In addition, for systems connected to higher voltages, transformers are used to step up the voltage (in this example a medium voltage (MV)/LV transformer) and combined with a medium voltage switchgear to disconnect the BESS from the AC-network, if needed. In Figure 7, PCC stands for Point of Common Connection and is the final grid connection point.

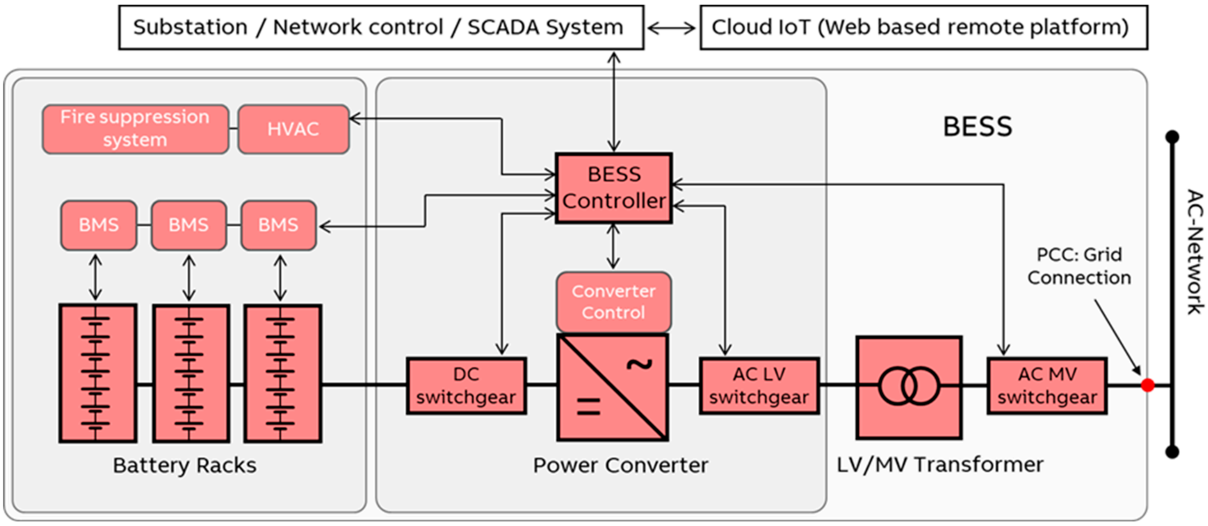

Figure 7. Architecture of a typical BESS in connection with the grid; see also [56,58] for more details.

The great advantage of battery systems is that they can be designed using a modular concept. Figure 8 shows such an example, where DC combiners connect battery racks in parallel (in this case, eight racks) to a power conversion system (PCS) and a MV/LV transformer to the power grid (in this case, a MVAC utility grid).

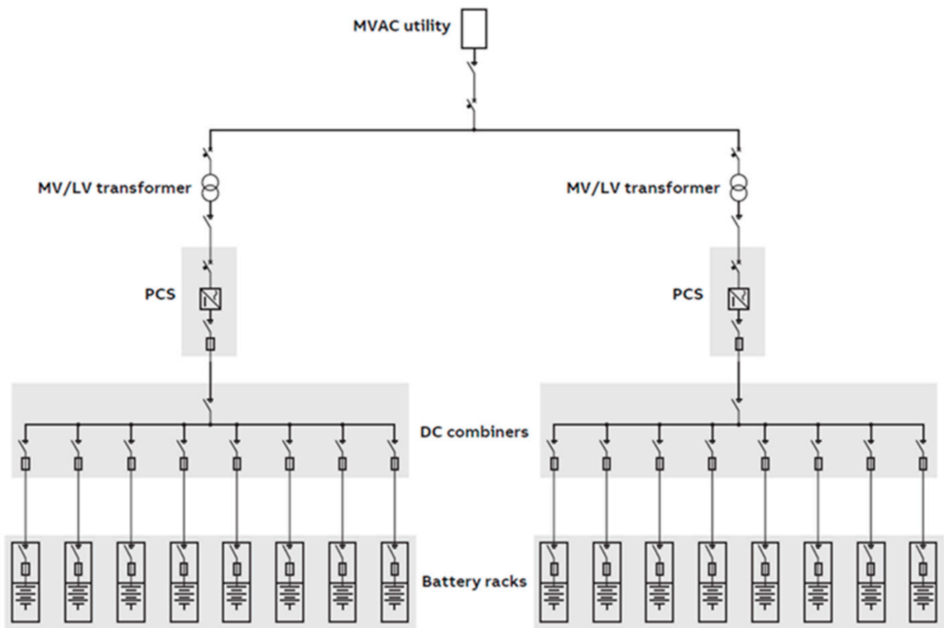

Figure 8. Single-line diagram of a 4 MW BESS with two sizing units, each including eight battery racks and one PCS and MV/LV transformer. The figure is taken from [53].

The design specification of the BESS in terms of power capability and energy content is often undertaken by so-called sizing units, which is the combination of several parallel racks and the corresponding PCS (there are two sizing units in Figure 8, as an example).

The energy content of a sizing unit can be increased by paralleling battery racks. However, the number of racks is restricted by the short circuit current that can be handled by the DC circuit breaker (see Figure 9). The power output of a sizing unit is increased with the size of the converter. However, the size of a single converter is restricted by the maximum AC current that can be handled by the LV AC breaker (see Figure 9). To be able to increase power beyond this limit, two converters can be connected in parallel, using several MV/LV transformers (two of them shown in Figure 8).

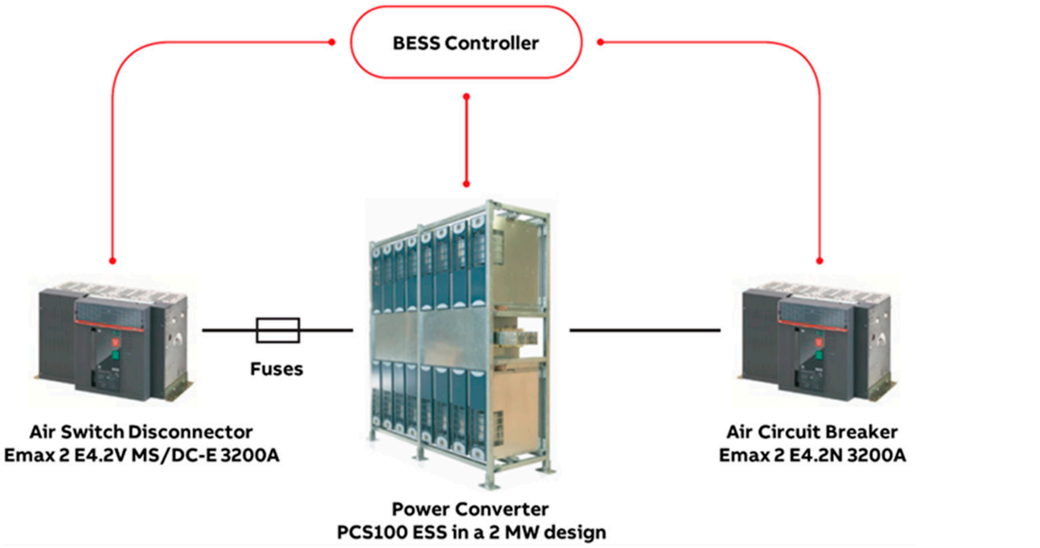

Figure 9. Power conversion system, including DC and AC protection devices. The figure is taken from [53].

To understand safety-relevant design aspects of battery systems, a detailed description of its architectural components is required.

4.1. Battery Racks

The battery racks are typically series-connected battery modules. Each module is a series and parallel configuration of single battery cells, providing a module voltage of typically between 20 and 100 V. The modules are typically connected in series, providing a typical rack voltage of 200–1500 V. Several battery racks are then typically parallel connected to achieve an overall nominal current of typically 100–1000 A.

Modules and racks are typically electrically interconnected with a BMS. The BMS plays a key role in battery safety, with the duty to ensure the stable operation of the battery and prevent abuse. It not only monitors the battery condition (voltage, current, temperature, and SOC, etc.) but also often performs cell balancing. Cell balancing is a process that involves monitoring the voltage of each battery cell to prevent overcharging and over-discharging. There are two main methods of cell balancing: passive and active [59]. In passive balancing, the energy of a cell with a higher SOC in comparison to the other cells is dissipated via a semiconductor switch and resistor combination. Active balancing redistributes charge from “high-energy cells” to “low-energy cells,” aiming to optimize energy use within the battery pack. This process extends system runtime and improves charging efficiency.

The BMS often comes in a multi-layer design: each module has a so-called slave BMS, typically a board that is directly mounted inside the module, measuring the voltage of each cell, the current through the cells/module, and the temperature distribution within the module. The data is transmitted to the rack BMS. This rack-level BMS communicates with slave BMS and can directly control one or more rack-integrated DC connectors or breakers. If racks are connected in parallel, a so-called combiner (see Figure 8) can be employed to couple the racks. The DC combiner also enables isolation and protection of the batteries from the rest of the system. It can include an additional fuse and breaker for each rack (depending on the rack protection design).

4.2. Power Conversion System (PCS)

The combination of different racks is connected to an LV DC switchgear to the power converter. In contrast to the nominal current (which is in the order of 100–1000 A, as mentioned above), the short circuit current resulting from the contribution of different racks can rise up to around 100 kA. Therefore, the LV DC breaker must have the breaker capacity accordingly. In addition to such a DC breaker, a fuse is usually employed. As shown in Figure 9, the PCS system is protected by a switch-disconnector combined with the PCS fuses. As an example, the air switch disconnector (breaker) in Figure 9 can withstand 100 kA for 1 s at 1500 V DC [53].

The power is converted by an AC/DC power conversion system. Such conversion is achieved by a bidirectional inverter, which enables the batteries to be charged or discharged. The converter size determines the power output of the BESS. Active power and reactive power are controlled at the same time. A variety of power electronic AC/DC converters for BESS are used in multiple applications. One example is the PCS100 module platform, as shown in Figure 9, or the PCS120, which is based on a 3-level converter module with 480–1100 V voltages and rated power of 250 kW. The modular systems can be scaled up to multi-MW designs.

The PCS has direct communication with the BESS controller to receive power setpoints from the overarching control. It is essential that the PCS is equipped with robust protection and switching mechanisms on both the AC and DC sides. Furthermore, the protective devices must be capable of communicating with the BESS control system in a manner similar to that of the converter.

On the AC side of the converter, an AC circuit-breaker is used to disconnect the converter from the transformer reliably if needed. As an example, an air circuit breaker in Figure 9 protects all applications up to 690 V [53].

4.3. Transformer, MV Switchgear and Grid Connection

The interface between the BESS installation and the grid is called the point of common connection (PCC), which is the reference point for the BESS in terms of voltage connection and specifications such as power and capacity. The voltage level at the PCC can be low-, medium- or high-voltage. A coupling transformer is typically used for connection at higher voltages. Depending on energy and power requirements, the transformer will often be a 2-winding or 3-winding version.

At the grid side of the transformer, a switchgear for that specific voltage is typically used. For example, an MV switchgear for secondary distribution is typically used if the BESS is connected to medium voltage. An example is a switchgear module designed for up to 40.5 kV, 630 A.

4.4. BESS Controller

The BESS controller integrates all components into a system so that it appears as a single unit towards the grid. It ensures that the grid code at the relevant PCC is met. One of its duties is to control the charging-discharging power by sending signals to the converter (illustrated by the arrow between the BESS controller and the converter control in Figure 7). The BESS controller receives all relevant data to supervise the system, especially the data of the BMS, which indicates the battery SOC, temperature, current, and voltages. The BESS controller is designed to trigger circuit breaker operations (open and close) and ensures overall protection by controlling the fire suppression system, Heating, ventilation, and air conditioning (HVAC), and sensors that detect any abnormal surrounding conditions of the BESS (flooding sensors, smoke sensors, gas sensors, etc.). Advanced BESS controllers allow smart integration into the grid. Examples are consideration of load or weather forecasts, time-varying energy prices, preserving given preferences of battery SOC, etc.

The BESS controller communicates with the highest control unit, the supervisory control and data acquisition (SCADA) system, installed at the utility site. On this level, the operator can define the BESS operation, which is often a pre-defined control logic for various applications such as peak shaving or frequency regulation. Once the battery controller receives the operation task from SCADA or an operator, it defines the power levels by sending out setpoints to the converter, as mentioned above.

4.5. HVAC, Fire Suppression System and Enclosure

The HVAC system consists of a precision air conditioner, air cooling ducts, and an automatic control system. These components work together to maintain optimal temperature and humidity levels for the batteries during charging and discharging.

The fire suppression system ensures the safety of the BESS, and is designed to limit the effects occurring during thermal runaway or other fire events.

Enclosures are typically equipped with doors to facilitate operation, maintenance, installation, and equipment replacement. They come in various sizes, such as indoor or outdoor cabinets and containers. Standard options include 10 ft, 20 ft, and 40 ft containers, with many designs being variations or modifications of standard ISO freight containers. Enclosures can also be tailored to meet the specific requirements and constraints of the application (see illustration in Figure 10).

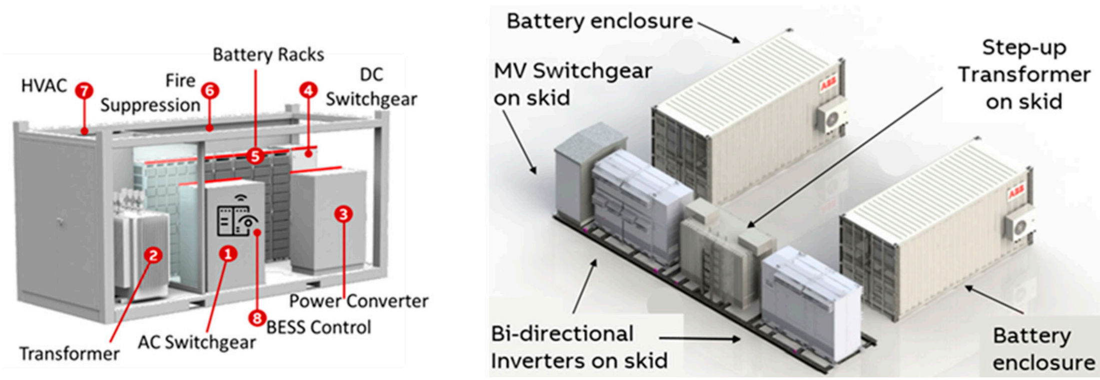

Figure 10. BESS design examples taken from [54]: For smaller systems, typically, container-integrated solutions are used, as shown on the left side of the figure. In this case, all of the above-mentioned components are integrated into one frame (cabinet or container). Several containers are often used for larger systems, and the batteries are placed in separate containers, with the rest of the equipment in its dedicated enclosure. The right side of the figure shows such an arrangement where a skid system concept is applied.

4.6. BESS System Considerations

As represented in Figure 11, a typical industrial system design must fulfill the applicable regulations and balance performance, reliability, and cost. Safety and reliability are obviously different concepts, but at the same time, they are related. For example, if a system has a very low reliability, it will fail often, and more potential safety issues are likely to occur.

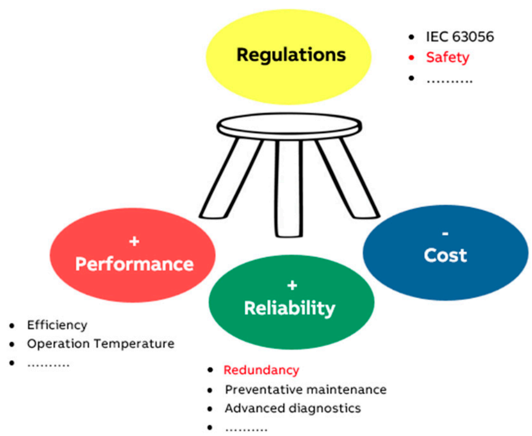

Figure 11. A typical industrial design has to fulfill the applicable regulations and balance performance, reliability, and cost.

No compromises can be made on safety, and not all failures have similar impacts on safety. Therefore, the “Stop Operation” has to be initiated if a given type of failure can put safety in jeopardy. On the other hand, a system can keep operating in degraded mode after a failure that has no impact on safety. This is called “limp mode” in modern automobiles and provides a contingency plan for vehicles to continue functioning, albeit at reduced performance, when vital systems or components experience failures.

To understand and classify all the potential failures and their effects, it is fundamental to carry out an FMEA (failure mode and effect analysis) of the complete system. The aspects to clarify for every single failure are: (1) Is the failure detectable? (2) What are the impacts on performance and safety? (3) Should a design change (detection, redundancy, etc.) be implemented?

Reliability refers to the likelihood that a product, system, or service will perform its intended function effectively over a specified period or within a defined environment without experiencing failure. To obtain a healthy design that reaches the desired reliability target, DFR (design for reliability) tools and methods shall be used.

The reliability of a system can be estimated using different techniques, including the use of specific software tools. One attractive technique is the calculation using the principle of the RBD (Reliability Block Diagram), which requires three steps. (1) Map the system in a reliability diagram. This is not a straightforward task, and a comprehensive analysis of the entire system must be conducted, taking into account all possible failure paths and the interactions between hardware, software, and protective mechanisms. The fundamental concept of the reliability diagram is that any non-redundant subsystem, which cannot be isolated in the event of a failure, should be treated as a series component within the system. (2) Assign MTBF (mean time between failures) and MTTR (mean time to repair) values for every subsystem. (3) Compute the MTBF of the configuration by applying specific equations to solve the reliability diagram [60].

Additional considerations include: (1) The MTBF of a given component or subsystem reflects the aging due to physical or chemical degradation. Design errors/weaknesses are not included in the MTBF calculations. (2) Typical best practices include the use of standard design margins on components as a function of the stress factors (temperatures, currents, voltages, etc.). In general, increasing design margins will increase the reliability. (3) The software doesn’t age and is considered perfect. The MTBF does not include software.

The above considerations are intended to provide just a short insight into some aspects of system design related to reliability and safety. It is important to underline that similar considerations must be made when the complete system is not designed from scratch but by integrating different components. For example, a new type of Li-Ion battery and BMS need to be integrated into an existing BESS or UPS system. Items such as cost, delivery time, availability, warranty, and stock are typically discussed in detail together with basic electrical specifications. On top of this, it is also fundamental to address the following points: (1) Supplier and product maturity. (2) Suppliers are available to have detailed technical discussions and cooperate, e.g., in sharing FMEA, reliability data, quality and field issues data, and life information. (3) Supplier availability to implement and release firmware modifications. (4) Extensive tests of the battery and BMS system are conducted, covering the verification of the cell and module performance and the basic electrical tests of the complete battery rack (charge, discharge, operational limits, etc.). (5) Conduct extensive tests to check potential reliability/safety weaknesses and compare the outcome with the expected result from the FMEA. These tests can be carried out in collaboration with the supplier and typically need to generate specific failures on the system. Common failures to consider include ground faults, protection faults, communication faults between the various BMSs (typically module, rack, and system), and BMS processors freeze. The latter can typically happen due to cosmic radiation that may corrupt memory data.

After the new battery and BMS validation, the focus has to go to the complete system, and an expanded FMEA has to be carried out. Figure 12 shows the complete system with UPS, Li-ion battery, and BMS, together with potential disconnection means and communication between UPS and BMS. As discussed before, no compromises can be made on safety, and it is mandatory to guarantee that no single failure in the BMS or in the UPS could cause catastrophic events. So, if a specific failure can jeopardize safety, initiating a "stop operation" is mandatory. This implies that this specific failure has to be detectable. Various solutions can be used to improve the system's integrity after one single failure. These solutions may imply hardware and software modifications in the UPS and/or in the battery/BMS to add some redundancy. With reference to Figure 12, other simpler solutions include adding a disconnection device between the UPS and the battery rack and communication between the UPS controller and the BMS. This communication can typically be used to exchange information but also to implement a watchdog between the UPS and the BMS so that every subsystem knows if the other is "dead or alive" and can act in consequence. The purpose of all this is to continue operation in "limp mode" as long as the safety is not jeopardized. Of course, the system has to issue detailed warning and alarm signals describing failures and the subsequent operation mode.

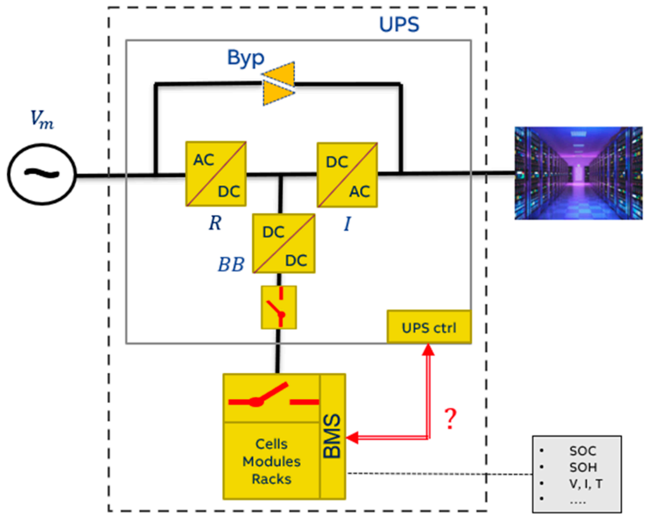

Figure 12. Complete system showing UPS, Li-ion battery, and BMS, together with potential disconnection means and communication between UPS and BMS.

In conclusion, similar to other industries, safety standards, and best practices are crucial and continuously evolving alongside the development of new technologies and products. This demands expertise and proficiency in system design, integration, controls, and operations.

5. Main Safety Standards and Codes

Many countries have implemented various regulations and legal mandates for BESS safety and provided guidelines to mitigate potential operational hazards [61]. The applicable safety standards and codes for BESS cover from the cell/module/rack level to the BESS installation level, as well as the key ones, are summarized in Table 1. There are four main types of safety standards, including the standards of the Underwriters Laboratory (UL), the International Electrotechnical Commission (IEC), the United Nations (UN), and the National Fire Protection Association (NFPA).

UL standards: The UL is a US-based organization that is fully authorized by the Occupational Safety and Health Administration (OSHA) to develop safety standards. Some of its standards are fundamental to BESS and are widely recognized in the sector [62]. UL 1973, UL 1642, and UL 9540A are often requested for battery-level safety. Unlike UL 9540A, both UL 1973 and UL1642 serve as direct certifications. UL 1973—Standard for Batteries for Use in Light Electric Rail (LER) Applications and Stationary Applications—ensures that the BESS is safe and reliable for use in practical conditions (e.g., for photovoltaic integration) [63]. UL 1642—Standard for Lithium Batteries—covers both non-rechargeable and rechargeable lithium batteries used as product power sources, aiming to reduce the safety risk [64].

Table 1. Key safety standards for a BESS from battery cell/module/rack level to the BESS installation level with data taken from [62].

<table>
<tr><th></th><th colspan="3">Key Standards for Battery Cells, Modules and Racks</th><th colspan="2">Key Standards for BESS and Their Installation</th></tr>
<tr><td>UL standards</td><td>UL 9540A test method
Testing the fire safety hazards associated with propagating thermal runaway within battery systems</td><td>UL 1973 certification
Batteries for use in stationary and motive auxiliary power applications</td><td>UL 1642 certification
Standard for safety of lithium batteries</td><td>UL 9540A test method
Testing the fire safety hazards associated with propagating thermal runaway within battery systems</td><td>UL 9540 certification
Standard for Energy Storage Systems (ESS)</td></tr>
<tr><td>IEC standards</td><td>IEC 62619 certification
Rechargeable lithium batteries for industry</td><td colspan="2">IEC 63056 certification
Requirements for rechargeable lithium batteries for BESS</td><td>IEC 62933-5-1 certification
Considerations for ESS</td><td>IEC 62933-5-2 certification
Requirements for BESS</td></tr>
<tr><td rowspan="3">UN/NFPA standards</td><td rowspan="3" colspan="3">UN38.3 certification
Transportation testing for lithium batteries</td><td>NFPA 855 certification
Installation of ESS</td><td>NFPA 13
Sprinkler system</td></tr>
<tr><td>NFPA 68
Deflagration venting</td><td>NFPA 69
Explosion prevention</td></tr>
<tr><td>NFPA 72
Alarm and signaling</td><td>NFPA 2010
Aerosol extinguishers</td></tr>
</table>

UL 9540A was developed by UL as a standard test method for evaluating thermal runaway fire propagation in BESS [65]. UL 9540A enables manufacturers to prove compliance with the new regulations. Tests based on UL 9540A can be performed at several levels of a BESS. UL 9540A also covers the BESS installation level safety. UL 9540A is referenced within UL 9540 [66]., i.e., the Standard for Energy Storage Systems and Equipment. UL 9540 is an overall compatibility and safety standard, which does not cover the individual component (e.g., batteries). UL 9540 offers a framework for ensuring the safe and reliable operation of BESS.

IEC standards: The standards-writing IEC is based in Switzerland and closely related to the International Standards Organization (ISO). The IEC 62619 standard (may accompanied by the IEC 63056 standard) specifies requirements and tests for the safe operation of Li-ion batteries used in industrial applications, including stationary applications [67]. On the BESS installation level, IEC 62933-5-1 [68] and IEC 62933-5-2 [69] specify the safety considerations (e.g., hazards identification, risk assessment, risk mitigation) and requirements (e.g., safety aspects for people and, where appropriate, safety matters related to the surroundings and living beings) for grid-integrated electrical energy storage systems, respectively.

UN standards: Another crucial aspect of battery safety is compliance with the transportation standard established by the UN, commonly known as UN38.3 [70]. This standard enables the testing and certification of batteries at various levels, from the cell to the module, thereby ensuring their safety during transportation.

NFPA standards: NFPA is a U.S.-based standards organization focused on fire prevention and mitigation. Various NFPA standards and codes address different safety aspects of BESS, such as fire prevention, suppression, and explosion prevention capabilities [62]. For example, NFPA 855 is a standard for the installation of BESS, which offers comprehensive criteria for fire protection and ensures that all installations are performed appropriately [71].

6. Typical Quality Issues of BESS

Battery systems are subject to factory quality audits, where the systems are inspected related to manufacturing issues. Specialized auditing firms conduct thorough assessments of storage systems to help mitigate operational risks associated with using the BESS for its intended purpose. One example is the advisory firm Clean Energy Associates (CEA). In a comprehensive report, CEA has described the findings of factory quality audits performed on over 30 GWh of BESS projects, with more than 1300 manufacturing quality issues identified [72]. The findings at each manufacturing stage were grouped into cell-level issues (30% of all cases), module manufacturing issues (23%), and system-level issues (48%). In other words, CEA determined that system-level issues were responsible for almost half of all defects identified in BESS systems. These quality issues are depicted in Figure 13.

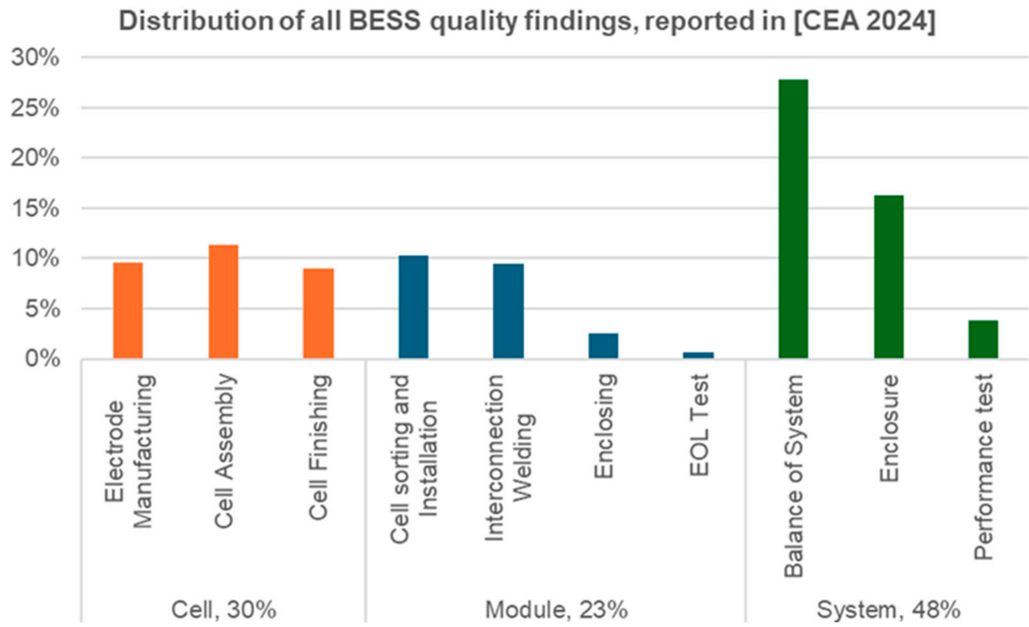

Figure 13. Manufacturing quality issues detected in factory quality audits on over 30 GWh of lithium-ion energy storage projects. Figure is taken from [72].

Of the issues identified, 26% of the BESS units inspected had quality problems related to the fire detection and suppression system, while 18% had defects in the thermal management system—both of which are crucial for functional safety. Failures in these systems can significantly increase the risk of fire.

A common finding in the audits was faulty actuators that did not respond to the command to release a fire-extinguishing agent. Such a non-responding release actuator could potentially allow fire to propagate. Other issues included non-responsive smoke and temperature sensors, which, if improperly wired, could prevent the smoke sensor from detecting smoke within the system. In addition, the auditors often found fire alarm abort buttons unresponsive. Failure to deactivate a false alarm could lead to unnecessary release of fire extinguishing agents or unwanted sprinkler-system activation, which could cause serious damage to energy storage equipment. Typical thermal management system-related defects were coolant leaks due to defective valves and loose pipe connections.

At a broader level, system-related issues primarily stemmed from two factors: first, the BESS integration process being largely manual and labor-intensive, and second, defects in upstream components that may have been overlooked during earlier quality checks [72].

7. Statistics of BESS Failure Incidents

As the BESS market rapidly expanded, more BESS failure incidents, including fires and explosions, were reported. Figure 14 lists the historically reported incidents of stationary BESS failures worldwide based on the public database [73]. Some incidents have been reviewed and analyzed in the literature [57,74–76]. The statistics broadly align with the BESS market growth. More than 10 BESS failure cases on average per year have been recorded since 2018. For example, about 15 BESS incidents were registered in 2023. Based on existing statistics, it is difficult to conclude the correlation between the incident frequency and the BESS size. However, the larger BESS is technically more prone to failures due to the increased number of connected components, e.g., more battery DC containers. Due to the growth of installed BESS size, more incidents were reported for larger systems (energy >50 MWh) in the past three years.

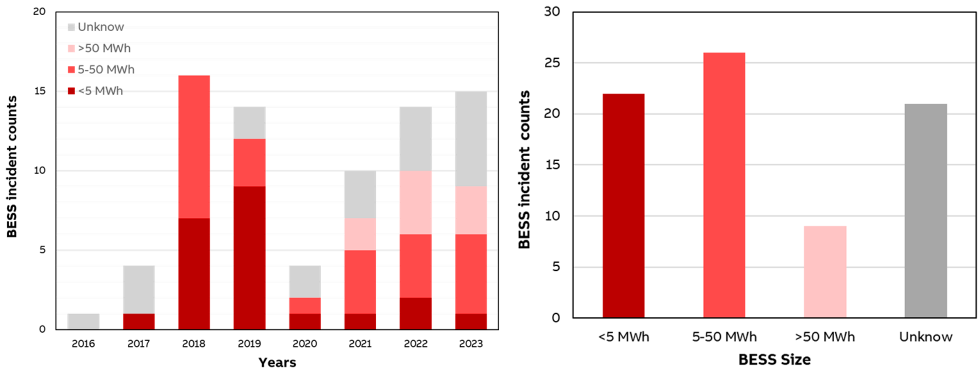

Figure 14. The analysis of BESS failure events based on the system energy with data taken from [73] since 2016.

Figure 15a shows the statistical analysis of BESS failure events and BESS system ages. 57% of the BESS failures occur within the first two years of their operation. Figure 15b shows that about 50% of BESSs were in operation when the accident happened, and 16% of BESS incidents have already appeared at the pre-commissioning and commissioning phases. Other Studies [77] also confirmed that poor commissioning practices are a significant contributor to unreliable safety and performance. Based on applications of BESS, almost half of the failures are connected to solar integration.

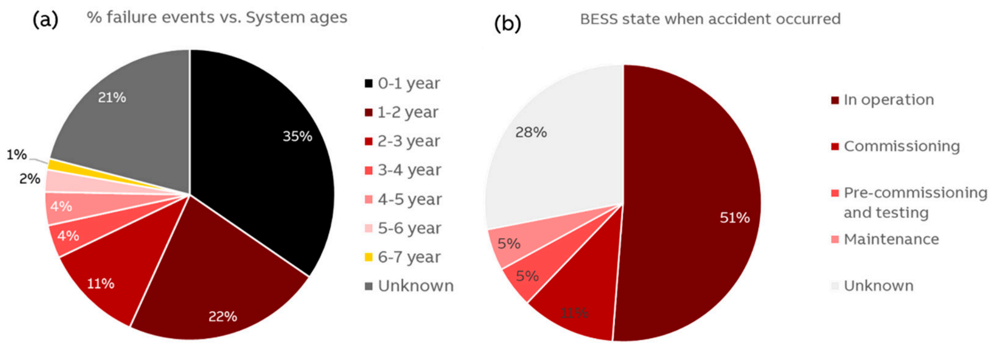

Figure 15. (**a**) The analysis of BESS failure events based on the system ages. (**b**) Statistics showing the state of BESS when the accident occurred. The data is taken from [73].

In cases of energetic failures in BESS systems, the "let it burn" approach was sometimes used to cope with fires and explosions, particularly when high-energy-density NMC batteries were involved [78]. However, it is at the cost of sacrificing at least one BESS container and continues the risk of propagation to the neighboring containers. Moreover, the combustion of a whole BESS container has adverse effects on the environment and human health (e.g., toxic smoke).

8. Root Causes and Mitigation Strategies

This section provides an overview of typical failure modes in BESS, examining root causes and proposing strategies for prevention, early detection, and hazard mitigation.

It is crucial to understand the typical BESS failure modes in the field. The past BESS incidents have provided learning materials to investigate the common root causes [57]. The failed elements can be batteries, controls (e.g., sensing, logic circuits, and communication systems) and other components (e.g., cabling, cooling systems, busbars, fire suppression systems). For example, a failure of a 300 MW/450 MWh grid-scale BESS was reported in

Victoria, Australia, 2021. A publicly released technical report identified the root causes of the incident [79]. The failure originated from a leak in the liquid cooling system, which led to electrical arcing within the battery modules. It generated substantial heat, triggering thermal runaway in the battery cells. EPRI's statistical analysis showed that controls and other components accounted for the majority of failed components, 46% and 43%, respectively [1].

The causes of BESS failures can be attributed to a multitude of factors, including those from cell selection to system integration [80]. The root causes involving battery cells include unsafe cell chemistry, cell manufacturing defects, poor cell balancing, and faults triggered by abuse conditions such as overcharge and external heating. Lacking thermal barriers between cells can possibly result in thermal propagation inside the battery module. The thermal propagation will continue if the cooling is insufficient. The BMS's failure to detect and react to an ongoing abnormality can lead to the continuation of catastrophic failures. The environment sensors (such as smoke sensors) and control systems provide the chance to intervene after the BMS failure.

The root causes of BESS fires have been identified as insufficient protection against electric shock, ineffective ventilation and fire suppression systems, and poor management of the operating environment [76]. Other issues during the installation, such as incorrect electrical installation, can also lead to system faults, resulting in BESS fires.

From the perspective of system integration and operation, it is challenging to integrate and operate BMS, energy management system (EMS), and power management system (PMS) together, and communication errors may occur among different systems [59]. Therefore, an integrated management system is recommended to coordinate the response to BESS incidents.

Based on the analysis of root causes and failure modes, different mitigation strategies and recommendations have been proposed to avoid the incidents and mitigate the hazards [57]. Close et al. suggested a holistic approach to improve BESS safety, which starts already from the BESS designing phase [57]. Conzen et al. proposed different prevention and mitigation measures for thermal runaway, e.g., the implementation of a mechanical exhaust ventilation system and deflagration vents [80]. Mylenbusch et al. gave recommendations to handle toxic gases and particulates that evolved during a BESS incident and highlighted the risk of reignition [81]. All components of the BESS must be designed, manufactured, and tested in accordance with the relevant safety standards and codes (see the corresponding section above). Each component has its place and functions to provide multi-layered protection to the BESS.

At the cell level, thermally stable materials and chemistries should be chosen for battery electrodes and electrolytes. Research efforts should be invested in developing next-generation batteries with improved safety, such as solid-state batteries. Different fail-safe designs, e.g., safety vents, thermal fuses, current interrupt device (CID), and positive temperature coefficient (PTC) protection, can be implemented. Enhancement of quality control and a fully automated process are recommended to reduce further defects during battery manufacturing [3].

At the module and rack level, battery thermal management should be carefully designed to regulate the temperature of the cells, thereby enhancing both their functionality and safety [82]. Forced air and liquid cooling systems are widely used in commercial BESS. Other technologies, such as phase change materials [83] and heat pipes [84], have been investigated for reinforced heat dissipation. In addition, the thermal insulation is critical to mitigate thermal propagation. Appropriate thermal barriers between cells and modules are necessary to prevent the spread of a cascading thermal runaway event.

The implementation of early detection and warning methods are important mitigation strategies to avoid battery fire and explosion. Today, setting thresholds for characteristic parameters (voltage, temperature, internal resistance, gas composition, smoke, etc.) is the main warning method for BESS. In some cases (e.g., the smoke is detected), the irreversible chain reaction of thermal runaway may have been triggered and unstoppable. New technologies such as electrochemistry-based, big data analysis, and artificial intelligence methods have been developed to identify much earlier abnormal alarms and take safety measures before thermal runaway occurs [85,86]. The purpose is to predict any type of malfunctioning at a system, subsystem, or component level resulting from environmental conditions, operating conditions, human errors, defects, etc. The first important brick for this is the prediction of the remaining life of consumables (batteries, AC and DC capacitors, fans, etc.) as well as their abnormal degradation. It is also very promising to use both a physics-based approach for real-time algorithms inside the BESS controller and a big data approach for algorithms in the cloud operating on global fleet data in different geographic and operating conditions.

On the BESS system level, the overall risk assessment and hazard mitigation analysis should be performed on each specific project. The ventilation and fire suppression systems should be regularly inspected and tested to ensure they effectively remove flammable off-gases and prevent the spread of fire. Other considerations, such as onsite water supplies, suitable environmental protection (e.g., sites in flood zones), BESS container layout, and access arrangements, are also recommended.

Last but not least, a pre-incident planning and post-incident recovery plan should be implemented. Pre-incident planning should include an emergency response plan that ensures the facility staff and local community can evacuate safely while also helping the local fire department determine the appropriate firefighting response. It is recommended that training be provided to emergency responders and relevant stakeholders before and during project commissioning. The post-incident recovery plan should address the decommissioning issues, including system de-energization, possible battery re-ignition, and the removal and disposal of hazardous battery waste [87].

9. Conclusions

BESS represents an essential solution in the modern energy infrastructure, offering supreme flexibility and resilience in the transition towards a sustainable energy future. However, as the deployment of BESS accelerates worldwide, ensuring their safety and reliability becomes a critical issue. This paper offers a comprehensive overview of the key safety aspects, considerations, standards, statistical analysis of failure incidents, root causes, and mitigation strategies for BESS safety.

Understanding the safety aspects, starting from the cell level to the full system, is recommended, as Li-ion cells require specific operational conditions to function safely. Operating beyond specifications can result in performance degradation and serious safety risks, e.g., thermal runaway. Safety measures include selecting suitable cell chemistries, employing thermal insulations between cells and modules, and facilitating heat dissipation inside the module/rack. Furthermore, fire suppression strategies, e.g., using water mist and specialized extinguishing agents, are critical to handling the flammable and toxic emissions from battery fires.

No compromises can be made on safety, and not all failures have similar impacts on safety. The system has to be designed to initiate "limp mode" or "stop" operation after any failure, together with the appropriate warnings and alarms. Reliability analysis, DFR, and FMEA are key to the design of a new BESS system, even if it is just the integration of existing subsystems (battery rack, BMS, PCS, etc.). This necessitates a high level of expertise and proficiency in system design, integration, controls, operations, and testing.

The number of reported BESS failure incidents aligns with the BESS market growth, indicating the necessity for proactive risk mitigation measures. Root causes of failures span from cell defects to integration and operational challenges. Implementing fail-safe designs, early detection systems, and thorough quality control processes are crucial steps toward preventing BESS failures and enhancing system reliability.

To conclude, BESS safety relies on various layers and components, requiring a synergistic approach that integrates material science, electrochemistry, modeling, power electronics, thermal management, protection, sensing, and fire suppression technologies. Ongoing research and development efforts focused on next-generation battery technologies, advanced thermal management solutions, and early warning systems offer promising opportunities for further improving BESS safety. For example, novel battery chemistries such as all-solid-state, sodium-ion, and niobium-based batteries are at the forefront of commercial R&D activities. These alternatives have the potential to offer improved thermal stability, reduced fire risk, and lower environmental impact compared to conventional Li-ion technologies. Together, these technological advances will make BESS not only safer but also more resilient and efficient.

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Abbreviations

Abbreviation	**Definition**
BESS	battery energy storage systems
BMS	battery management system
C&I	commercial and industrial
CEA	Clean Energy Associates
CID	current interrupt device
DC	direct current
DFR	design for Reliability
EMS	energy management system
FMEA	failure mode and effect analysis
HVAC	heating, ventilation, and air conditioning
IEC	International Electrotechnical Commission
ISO	International Standards Organization
LCO	lithium cobalt oxide
LER	light electric rail
LFP	lithium iron phosphate
LMO	lithium manganese oxide
LTO	lithium titanate
LV	low voltage
MTBF	mean time between failures
MTTR	mean time to repair
MV	medium voltage
NCA	nickel cobalt aluminum oxide
NFPA	National Fire Protection Association
NMC	nickel manganese cobalt oxide
OSHA	Occupational Safety and Health Administration
PCC	point of common connection
PCS	power conversion system
PE	polyethylene
PMS	power management system
PTC	positive temperature coefficient
RBD	reliability block diagram
SCADA	supervisory control and data acquisition
SEI	solid electrolyte interphase
SOC	state of charge
SOH	state of health
UL	Underwriters Laboratory
UN	United Nations
UPS	uninterruptible power supply

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