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Article

Fire safety design of lithium-ion battery energy storage systems: A holistic and integrated approach according to the Italian fire safety guidelines

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Abstract: Battery Energy Storage Systems (BESS) based on lithium-ion technologies are increasingly used to support the integration of renewable energy in buildings and critical facilities. At the same time, several recent fire and explosion incidents have shown that thermal runaway and gas generation can represent a major hazard for occupants, first responders and the environment if systems are not properly designed. This paper presents a design-oriented framework for the fire safety of lithium-ion BESS installations that is explicitly aligned with the Italian Fire Safety Code (Codice di Prevenzione Incendi, DM 3 August 2015) and with the national guidelines for BESS issued by the Italian National Fire Rescue and Service. The paper first summarizes the main mechanisms of thermal runaway initiation and propagation, with emphasis on gas generation, overpressure effects and cascade failures in containerized and room-scale installations. It then maps these phenomena onto the performance-based structure of the Italian Fire Safety Code and the three operational regions defined in the national BESS guidelines: Prevention, containment (protection) and management. For each region, specific design measures are discussed, including cell qualification and abuse testing, thermal management and environmental control, advanced battery management systems, off-gas detection, fire detection and suppression systems, explosion prevention and venting, water management and emergency planning. Rather than proposing new experimental data, this work synthesizes recent international research and standards (e.g. UL 9540/UL 9540A, NFPA 855, IEC 62619, IEC 62932) and shows how they can be consistently integrated into the Italian performance-based framework for different BESS configurations. Beyond providing a structured review of recent research and international standards, the paper proposes a practical design framework and a set of representative design criteria that support the harmonized application of the Italian Fire Safety Code, the national BESS guidelines and international standards to typical BESS installations. The objective is to provide practitioners and authorities with a transparent set of design criteria and examples methodologies that support safe deployment of lithium-ion BESS in buildings, without compromising energy efficiency and sustainability targets.

Keywords: lithium-ion batteries; battery energy storage systems; thermal runaway; fire safety design; Italian Fire Safety Code; performance-based design; explosion prevention

1. Introduction

The global transition toward renewable energy and carbon-neutral societies has accelerated the adoption of distributed renewable energy systems integrated into building infrastructure, which is also supported by the establishment of Renewable Energy Communities (RECs) [1–4]. According to recent data, buildings and construction account for approximately 40 % of energy-related CO_2 emissions in urban areas, making them critical targets for decarbonization strategies. The European

Union's Energy Performance of Buildings Directive establishes requirements for improving energy performance while ensuring compliance with accessibility, fire safety, seismic safety, and intended use considerations. This dual mandate, achieving sustainability goals while maintaining or enhancing fire safety, presents a complex engineering challenge, particularly regarding the integration of Battery Energy Storage Systems (BESS) into building envelopes and facility designs [1–4].

Sustainable buildings are increasingly becoming complex "systems of systems" incorporating innovative materials, alternative energy sources, advanced construction technologies, and new boundary conditions. Energy storage systems, photovoltaic installations, and building envelope technologies have emerged as key enablers of energy efficiency and grid stability [5–8]. However, this technological complexity introduces novel fire hazards that were not present in traditional building designs. Recent fire incidents in sustainable buildings, including the Torre del Moro fire in Milano (2023), the Grenfell Tower fire in London (2017), and multiple residential building fires associated with photovoltaic and energy storage installations, underscore the necessity for comprehensive, integrated fire safety strategies that evolve in parallel with building innovation [9–13].

Lithium-ion batteries show noteworthy energy density and efficiency characteristics, making them the preferred technology for large-scale stationary energy storage applications. However, the same properties that enable high performance also to introduce inherent fire safety risks through thermal runaway. Thermal runaway is characterized by an exponential increase in temperature at a rate exceeding thermal dissipation capacity, driven by exothermic decomposition reactions of battery internal components. This process can reach temperatures exceeding 1000 °C within minutes and releases flammable, potentially toxic gases [14–19]. The hazards associated with thermal runaway propagate beyond individual cells through cascading failure mechanisms. When a single cell experiences thermal runaway, it generates sufficient heat and ejecta (solids, liquids, and gases) to initiate thermal runaway in adjacent cells, propagating through entire modules and, potentially, across interconnected battery packs in large-scale installations. The gases generated during thermal runaway are flammable and can form explosive atmospheres, particularly problematic in confined spaces where accumulation occurs unchecked [20–22]. Recent analysis of large-scale energy storage system incidents reveals that some installations, despite compliance with contemporary standards including UL 9540 and UL 9540A thermal runaway propagation testing, have nevertheless experienced fire incidents and propagation. These cases highlight critical gaps between current testing methodologies and real-world performance scenarios, emphasizing the necessity for comprehensive, site-specific engineering analysis [23–25].

The concept of Sustainable and Fire-Resilient (SAFR) buildings integrates sustainability and fire resilience objectives into a unified design framework. SAFR buildings are characterized by achieving sustainability targets – including reduced energy use, reduced material consumption, increased renewable energy integration, and improved indoor environmental quality – while simultaneously meeting resilience targets for fire events. The achievement of these dual objectives requires innovative design solutions and pioneering approaches that transcend conventional prescriptive compliance pathways. A holistic and integrated approach to fire safety design of SAFR buildings is therefore essential [26,27].

The purpose of this paper is to interpret the Italian guidelines for BESS installations [28] within the structure of the Italian Fire Safety Code [29,30] and to outline a design framework for lithium-ion BESS installations. The focus is on practical design choices for prevention, protection and management that can be justified by means of existing international standards and recent research on thermal runaway mechanisms, gas generation and explosion hazards.

1.1. Motivation and scope of the paper

The rapid deployment of lithium-ion BESS in buildings and critical facilities has outpaced the development and harmonization of regulatory frameworks. In Italy, the introduction of the performance-based Fire Safety Code and the recent national guidelines for BESS provide powerful tools for designers, but their practical application to specific configurations such as indoor rooms and containerized outdoor systems remains challenging. At the same time, international standards and guidance documents – such as UL 9540/UL 9540A, NFPA 855, IEC 62619 and IEC 62932 – offer valuable test data and design recommendations that are not yet fully embedded in the national framework.

In this context, there is a need for a design-oriented synthesis that links the physical mechanisms of thermal runaway, gas generation and propagation with the structure of the Italian Fire Safety Code and the operational regions of the national BESS guidelines. Rather than proposing new experimental data, the present work aims to provide such a synthesis and to translate regulatory requirements into explicit design criteria and workflows that can be applied to real projects. The focus is on typical indoor, outdoor and containerized BESS configurations, with particular attention to how international standards and recent research can be consistently integrated into the Italian performance-based framework.

2. Thermal runaway mechanisms and fire hazard characterization

Thermal runaway in lithium-ion batteries can be initiated by different types of abuse, which are commonly grouped into thermal, electrical and mechanical mechanisms [31,32]. In all cases, the underlying process involves self-accelerating exothermic reactions inside the cell that increase the temperature faster than heat can be removed, eventually leading to venting, gas generation and, in many cases, fire or explosion [33,34].

Under thermal abuse, an external heat source raises the internal temperature of the cell above critical thresholds. The sensitivity to temperature depends strongly on cells chemistry and the State of Charge (SOC). For cells with Nickel-Manganese-Cobalt (NMC) or Nickel-Cobalt-Aluminum (NCA) cathodes, experiments show a marked increase in thermal runaway risk above approximately 80 °C, with decomposition reactions becoming progressively faster as temperature rises. Typical reaction sequences include electrolyte decomposition, separator softening and shrinkage, internal short-circuit formation, decomposition of the solid electrolyte interphase (SEI), oxygen release from the cathode and oxidation of the anode [35–37]. Once these reactions are fully developed, temperatures can exceed

1000 °C within minutes and large quantities of flammable gases are released [38–41].

Electrical abuse includes overcharge, over-discharge beyond recommended limits and external short circuits. Overcharge promotes lithium plating on the anode and can cause gas generation, pressure build-up and short internal circuits. If cell voltage is pushed well beyond its design window, rapid decomposition of electrode and electrolyte materials can occur, triggering thermal runaway The SOC strongly influences the severity of the event: at 100 % SOC, tests report higher total heat release, steeper temperature rises and more intense jet flames compared with partially charged cells. The onset of internal pressure rise also occurs earlier at high SOC, which can be exploited as an early-warning indicator [42].

Mechanical abuse mechanisms comprise penetration (e.g. nail penetration tests), crushing and impact. These actions can locally damage the separator and bring anode and cathode into direct contact, creating high current paths and intense resistive heating. At the same time, the normal transport pathways are disrupted, so the current is concentrated in a small region. This combination of localized heating and short-circuit conditions can rapidly drive the affected cell into thermal runaway even in the absence of external electrical abuse [33].

2.1. Gas generation during thermal runaway

A key feature of lithium-ion battery thermal runaway is the emission of a complex mixture of gases in relatively short times [43–45]. Measurements on commercial cells show that the main species are carbon dioxide (CO_2), carbon monoxide (CO), hydrogen (H_2) and light hydrocarbons such as methane (CH_4), with additional Volatile Organic Compounds (VOCs), hydrogen fluoride (HF) and phosphorus-containing gases such as phosphorus pentafluoride (PF_5). The relative composition depends on cell chemistry, SOC, temperature history and external boundary conditions [46]. Fourier-transform infrared (FT-IR) and other spectroscopic techniques indicate a characteristic temporal evolution of the off-gas composition [46,47]. In an initial phase, before visible signs of thermal runaway, the spectrum is dominated by VOCs and hydrocarbons associated with electrolyte evaporation. As the event progresses and oxidation of organic materials accelerates, CO_2 and CO concentrations increase sharply. In more advanced stages, HF and other decomposition products appear at higher levels, and phosphorus-containing species may be detected depending on the salt and additive formulation used in the electrolyte [48].

Hydrogen plays a particularly important role from a safety perspective. It has a very wide flammable range in air (approximately 4–74% by volume) and a low minimum ignition energy, which means that relatively small leaks in confined volumes can already produce ignitable mixtures [48,49]. In addition, lithium-ion batteries can release oxygen during thermal runaway through cathode decomposition, so combustion can be sustained even when ambient oxygen is partially depleted. In closed or poorly ventilated BESS enclosures, off-gases can therefore accumulate rapidly above the Lower Flammability Limit (LFL), especially if multiple cells or modules vent in a short time interval.

Computational fluid dynamics (CFD) studies illustrate the potential severity of such scenarios. For example, simulations for a 20-foot ISO container indicate that simultaneous thermal runaway of a few dozen cells can raise gas concentrations near the LFL within several seconds, leading to internal peak overpressures of several hundred kilopascals and external overpressures capable of causing serious injury at a few meters from the container if an ignition occurs [48]. These results underline the need to consider not only cell and module behavior, but also enclosure geometry, venting arrangements and ignition sources in the overall design.

2.2. Thermal runaway propagation

Once a single cell has entered thermal runaway, the main question for system design is whether the event will remain confined or propagate to adjacent cells, modules and cabinets. Propagation occurs through a combination of heat transfer and mechanical and electrical interactions and is therefore sensitive to both cell design and pack architecture [50,51]. From a thermal standpoint, heat can be transferred by conduction (through direct contact between cells, busbars or structural elements), convection (by movement of hot gases inside the enclosure) and radiation (from high-temperature surfaces and flames). The thermal resistance between neighboring cells is a key parameter: if cells are closely packed with minimal spacing and no effective thermal barriers, tests indicate that propagation to adjacent cells is very likely [46,50]. Increasing spacing and introducing materials with suitable thermal and fire-resistance properties can significantly slow down or even prevent cell-to-cell propagation under comparable abuse conditions [50,51].

Electrical coupling can also accelerate propagation. When one cell fails and its voltage collapses, parallel-connected cells that remain charged can drive high currents through the failed cell, adding Joule heating on top of the exothermic reactions already in progress [51]. If this additional heating is not limited by appropriate circuit design or protective devices, the affected cell may reach higher temperatures and eject more hot gas and particles, increasing the likelihood that neighboring cells will also fail [52].

Finally, the mechanical effects of gas venting are not negligible. Rapid gas generation produces pressure differentials that can eject hot, sometimes conductive, fragments of electrode, separator and current collector materials, as well as liquid electrolyte droplets, towards adjacent cells [50–53]. This ejecta can damage casings and separators, creating new short internal circuits in nearby cells. In densely packed modules, this mechanism can be an efficient trigger for cascade failures, particularly when combined with limited thermal separation and strong electrical coupling.

For these reasons, experimental and numerical studies of propagation at cell, module and rack level are essential inputs for BESS fire safety design and for the definition of proper separation distances, barriers, suppression strategies and venting concepts in line with applicable standards and guidelines.

3. Integrated fire safety design framework

The Italian Fire Safety Code [29,30] (Codice di Prevenzione Incendi, DM 3 August 2015 and subsequent amendments) adopts a performance-based approach that can be applied to a wide range of activities, including installations with lithium-ion BESS. Rather than prescribing detailed solutions for each technology, the IFC defines general safety objectives and a structured design process. Practitioners can either follow deemed-to-satisfy solutions or develop alternative, performance-based solutions, if they demonstrate an equivalent or higher level of safety. In its general form, the IFC requires the following steps [29,30]:

- Scope definition: identify the building or facility to be designed, its intended use, the presence of BESS and other relevant systems, and any special constraints (e.g. existing structures, heritage value).
- Safety objectives: select and document the specific fire safety objectives to be achieved, such as life safety for occupants, safety of fire-fighting teams, protection of property and continuity of critical services, and environmental protection.
- Fire risk and scenario assessment: analyze credible fire and explosion scenarios, considering the characteristics of BESS (thermal runaway, gas generation, overpressure), other fuels present, building configuration, occupancy and evacuation conditions, and external exposures.
- Fire safety strategy: select and combine prevention measures, active fire protection systems, passive fire protection measures, fire safety management and emergency response procedures into an overall strategy that addresses the identified scenarios and objectives.
- Verification: adopt either standardized, deemed-to-satisfy solutions where applicable or develop performance-based solutions supported by calculations, simulations and test data to show that the safety objectives are met.

Figure 1 illustrates the iterative, performance-based design methodology adopted in the Italian Fire Safety Code and used in this paper as the backbone of the proposed framework for BESS. On the left, the spiral diagram shows how the design process progresses from the initial project scope through the definition of fire safety objectives, fire risk assessment and fire strategy, towards a final design, with each iteration adding knowledge and refining the level of detail. On the right, the upper panel emphasizes that a single, coherent fire strategy is articulated through ten complementary fire safety measures, while the lower panel recalls the state-of-the-art fire safety engineering approach, in which scenarios, objectives, performance criteria and solutions are linked through quantitative analyses. Together, these elements highlight that BESS fire safety design is not a single-step calculation, but a structured, iterative process that integrates prescriptive measures and performance-based tools within the Italian regulatory context.

The national guidelines on lithium-ion BESS issued by the Italian National Fire Rescue and Service refine this general framework for the specific case of BESS installations [28]. They organize the fire safety strategy into three operational regions that interact with each other:

- Prevention region: measures aimed at reducing the probability (frequency of occurrence) of cell failure and thermal runaway initiation. This includes cell quality assurance and abuse testing, environmental and thermal control, battery management system (BMS) functions, off-gas and temperature monitoring, and appropriate electrical protection.
- Containment (protection) region: measures designed to limit the consequences of a failure that has already occurred, by avoiding or slowing

the propagation to adjacent cells, modules and rooms. Examples include non-propagating layouts, minimum separation distances, fire-resistant barriers, fire detection and suppression systems, and explosion prevention and venting concepts.

- Management region: organizational and procedural measures that ensure safe operation over the life of the installation and effective emergency response. This covers training and qualifications of personnel, maintenance and inspection, control of hazardous materials near the BESS, access for fire-fighters and clear emergency procedures.

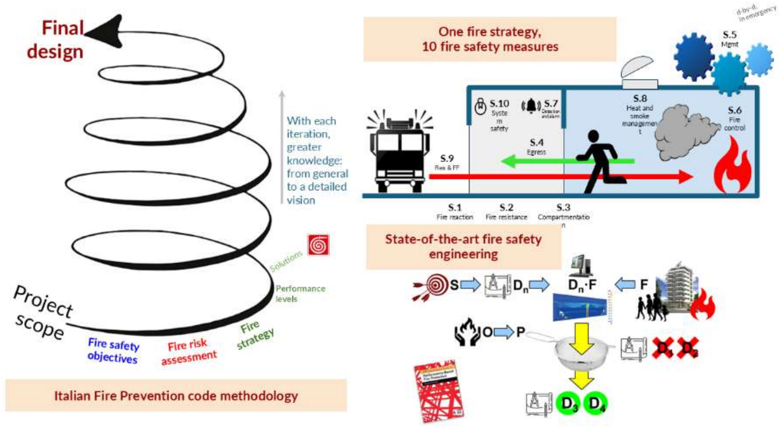

Figure 1. Iterative, performance-based fire safety design methodology of the Italian Fire Safety Code.

Within this structure, the Italian BESS guidelines define four main fire safety objectives that must be explicitly addressed in each design:

a) Prevention: Minimize the likelihood of accidental gas release, fire and explosion through appropriate design, installation and operation of cells, modules, enclosures and auxiliary systems.

b) Occupant safety: Ensure that occupants of the building can be evacuated or kept safe under credible incident scenarios, considering smoke and gas spread, heat release and structural effects.

c) Rescue team safety: Provide conditions that allow rescue teams, professional fire-fighters and other responders to intervene without being exposed to unacceptable levels of risk from thermal runaway, explosions or toxic gases.

d) Environmental and property protection: Limit damage to the BESS, to adjacent buildings and to the environment, including control of contaminated fire-fighting water and prevention of escalation to neighboring infrastructures.

For a given project, the integrated design task is therefore to show how the selected technical and organizational measures in the three regions (prevention, containment, management) collectively satisfy these four objectives, using the tools provided by the IFC. In simple cases, this may be achieved by combining the deemed-to-satisfy solutions suggested by the Code and by the BESS guidelines. In more complex or non-standard configurations (for example, high-energy BESS integrated in existing buildings or in proximity to sensitive receptors), performance-based analyses may be needed to justify design choices such as reduced separation distances, alternative suppression systems or specific venting layouts.

3.1. Representative design criteria and regulatory sources

To support the application of the design workflow in typical projects, it is useful to summarize key quantitative and qualitative criteria that recur in BESS fire safety design. These criteria link the physical hazards discussed in Section 2, the regulatory framework described above, and the practical design choices presented in the following sections.

Table 1 presents a set of representative design criteria for lithium-ion BESS installations, together with their main regulatory or standard sources and their implications for BESS design. The table includes, among others, criteria related to gas accumulation and fractions of the lower flammability limit (LFL), separation distances and compartmentation, qualification of cells and modules, fire detection and suppression performance, fire-fighter intervention conditions and operational safety and maintenance requirements. In the subsequent sections and design scenarios, these criteria are used to illustrate how the proposed framework can be applied to indoor, outdoor and containerized BESS configurations.

Taken together, **Figure 1** and **Table 1** constitute the practical backbone of the proposed framework. A practitioner starts by characterizing the project (BESS size, technology, location, occupancy) and selecting the applicable fire safety objectives. **Table 1** then provides a structured reference for identifying which criteria apply to each hazard aspect, which standards support them and what design implications follow. Where deemed-to-satisfy solutions are available and applicable, they can be adopted directly. Where the configuration is non-standard or prescriptive requirements cannot be met, the performance-based path described in Section 7 provides the verification workflow, with Section 8 illustrating how this path is walked in two representative cases.

Table 1. Representative design criteria and regulatory sources for lithium-ion BESS installations.

Hazard / design aspect	Design criterion	Main regulatory / standard source	Design implication for BESS
Gas accumulation and explosion risk in enclosed BESS rooms	Keep ventilation such that gas concentrations stay below 25% of the LFL or justify an equivalent safety level with performance-based analyses.	Italian BESS guidelines; ATEX framework for explosive atmospheres; conservative international practice based on fractions of the LFL.	Requires estimating gas release from thermal runaway scenarios and sizing continuous or demand-controlled ventilation, using simplified calculations or CFD where needed.
Separation between BESS and adjacent occupancies or property lines	Maintain the minimum separation distances required by the Italian BESS guidelines for indoor, island and containerized systems, or justify any reduction with PBD (Performance Based Design) analyses supported by large-scale tests and modelling.	Italian BESS guidelines; UL 9540/UL 9540A; NFPA 855.	Influences site layout for outdoor containers and room placement in buildings; may require iterative optimization of BESS rating, enclosure type and protective barriers.

Table 1. (*Continued*).

Hazard / design aspect	Design criterion	Main regulatory / standard source	Design implication for BESS
Fire and smoke spread between BESS rooms and other occupancies	Provide fire-resistant separations with ratings consistent with the Italian Fire Safety Code and activity, so that fire and smoke remain contained within the BESS room for a specified time.	Italian Fire Safety Code; national implementation standards.	Drives selection of construction materials, detailing of penetrations and door ratings, and may require upgrades in existing buildings when integrating BESS.
Thermal runaway initiation and propagation at cell/module level	Use cells and modules that pass abuse tests with limited gas release and no uncontrolled propagation under representative worst-case conditions.	IEC 62619; UL 9540A; Italian BESS guidelines on component qualification.	Affects technology selection, supplier qualification and allowable pack architectures, especially for indoor and containerized systems with limited ventilation and separation.
Fire detection and early warning	Provide automatic fire detection in BESS rooms and enclosures, integrated with off-gas and temperature monitoring where applicable, with alarm logic tuned for early intervention without excessive false alarms	Italian Fire Safety Code; EN 54 series; Italian BESS guidelines on monitoring.	Determines detector types and locations, integration of off-gas sensors with the fire alarm system and BMS, and escalation paths for alarms (local, remote, emergency services).
Fire control and suppression in BESS rooms and containers	Select water-based or hybrid suppression systems validated by representative tests or models, and design them to provide effective cooling and control of BESS fires under expected configurations.	Italian BESS guidelines; Italian Fire Safety Code provisions for fire protection systems; international guidance and test results for BESS suppression systems.	Influences the choice among sprinklers, water mist and hybrid systems; requires attention to water demand, water management, electrical isolation and potential re-ignition.
Fire-fighter safety and intervention conditions	Ensure that access, hydrants, equipment and pre-incident plans allow safe intervention distances and positions, considering possible delayed explosions and toxic gas release from BESS.	Italian BESS guidelines; Italian Fire Safety Code provisions for fire-fighter access and water supplies.	Affects site layout, access control, hydrant network design and the content of emergency plans shared with the fire service.
Operational safety and maintenance	Implement management and maintenance procedures that keep conditions and operating limits within predefined safe ranges and ensure periodic checks of detection, ventilation and suppression systems.	Management region of the Italian BESS guidelines; general fire safety management provisions of the Italian Fire Safety Code.	Requires alignment between design assumptions and operating procedures, including monitoring, maintenance schedules and training of personnel.

4. Prevention region: Proactive risk mitigation

In the framework of the Italian Fire Safety Code and the Italian BESS guidelines, the prevention region includes all measures that reduce the probability of cell failure and thermal runaway initiation [28,51,52]. For lithium-ion BESS, this begins at component level with rigorous cell and module qualification, and extends to thermal management, environmental controls, battery management systems and early-warning functions embedded in monitoring and protection schemes. A consistent prevention strategy relies on three elements:

- the selection and qualification of cells and components against appropriate abuse tests and standards;
- the control of operating conditions (temperature, SOC, current, environment) within safe limits;

- the early detection of abnormal behavior and the rapid removal of stressors before thermal runaway can develop.

4.1. Cell qualification and environmental/thermal controls

International standards define a set of mechanical, electrical and thermal abuse tests to characterize the behavior of lithium-ion cells and batteries under off-normal conditions [53–56]. For industrial and stationary applications, relevant examples include IEC 62619 for secondary lithium cells and batteries, IEC 62660-2 for cells used in electric vehicles, SAE J2464 and SAE J2929 for automotive abuse tests, UNECE R100.02 for traction battery safety and UL 2580 for batteries in motive and stationary auxiliary power applications. These documents specify test methods such as overcharge, over-discharge, external short-circuit, thermal exposure, crush, impact, vibration and drop, and define acceptance criteria in terms of venting, fire, explosion and leakage.

At BESS level, abuse test results provide a basis for selecting cell types and pack architectures suited to the intended operating conditions. Designs that have demonstrated limited gas release and no cell-to-cell propagation under representative worst-case abuse conditions are preferable, especially for indoor and containerized installations where ventilation and separation distances are constrained [57–60].

Control of the thermal environment is another key prevention measure. Maintaining cell temperatures within the recommended operating range reduces degradation and the probability of thermal runaway and can delay the onset of runaway even if a fault occurs. Depending on the installation, several techniques may be combined:

- air-based cooling using finned heat exchangers and forced or natural convection;
- liquid cooling with cold plates or jackets in direct contact with cells or modules;
- the use of phase-change materials and intumescent layers to buffer temperature peaks and slow heat transfer;
- adequate insulation and internal thermal barriers to avoid strong thermal coupling between adjacent cells and sensitive components.

The design of the thermal management system has to consider both normal operation and fault scenarios. Under normal loads, the system should prevent local hot spots and large temperature gradients within modules. Under abuse conditions, it should be robust enough not to fail catastrophically (e.g. loss of coolant, pump failure) in a way that would accelerate thermal runaway.

From a design standpoint, non-propagating layouts and increased spacing between cells and modules offer robust benefits, but they also introduce trade-offs. Larger separation distances can reduce energy density, increase enclosure size and complicate retrofits in existing rooms. In practice, designers must balance these constraints against the safety benefits, using available propagation test data and, where necessary, performance-based analyses to justify compact layouts.

4.2. Advanced battery management systems

Battery management systems (BMS) are central to prevention because they monitor key electrical and thermal parameters, enforce safe operating limits and can initiate protective actions when anomalies are detected. Modern BMS architectures for large stationary BESS typically include distributed sensing at cell or group-of-cells level, centralized or hierarchical control units and redundant communication paths to higher-level control and protection systems [61–63]. Typical monitored quantities are:

- voltage at cell and module level, to detect over- and under-voltage conditions or divergence between parallel strings;
- current at pack or string level, to identify over-current and short-circuit conditions;
- temperature at multiple locations within modules and enclosures, to detect hot spots and abnormal gradients;
- in some designs, internal pressure or strain signals, and electrochemical impedance spectroscopy (EIS) data to infer internal changes before they are visible in voltage or temperature.

Sampling rates in the order of hundreds to thousands of measurements per second for critical signals enable the detection of fast transients and very early stages of abnormal behaviors [63,64]. On top of these measurements, many systems now implement algorithms that estimate State of Charge (SOC), State of Health (SOH) and internal resistance, and in some cases use machine-learning models trained on historical data to identify patterns associated with incipient failures [65].

When abnormal conditions are confirmed, the BMS can take automatic protective actions such as [66,67]:

- opening contactors or solid-state switches to disconnect the BESS from the grid or from loads;
- limiting or stopping charge and discharge currents;
- initiating controlled load dumping or energy dissipation through dedicated resistive elements;
- triggering enhanced cooling modes or, where present, pre-cooling and thermal buffering strategies;
- sending alarms to higher-level control systems and operators for further action.

The effectiveness of these functions depends not only on the algorithms but also on their integration with protection devices, the speed and reliability of actuation and the clarity of alarm logic. For prevention purposes, the objective is to detect and mitigate anomalies while they are still reversible, well before thermal runaway thresholds are reached [63–67].

Advanced BMS and monitoring functions significantly improve early detection capabilities, yet they are not fail-safe. Diagnostic models are sensitive to sensor quality, calibration and data availability, and false alarms can erode operator confidence. Implementation therefore requires careful tuning, validation against real incident data where possible, and clear procedures for alarm escalation and response.

Furthermore, recent advances in machine learning and physics-informed modelling are opening new possibilities for the prevention region. Deep-learning ensemble methods and physics-informed Bayesian digital twins have been shown to enable precisely Remaining Useful Life (RUL) prediction and safety-constrained control in battery systems, including in robot-integrated manufacturing environments [68–70]. While the present paper focuses on fire safety design for stationary BESS rather than on manufacturing or prognostics, these approaches are directly relevant to the early-warning and BMS functions described above: integrating RUL-aware diagnostics into BESS monitoring systems could provide earlier and more reliable indications of cell degradation, reducing the probability of thermal runaway initiation.

4.3. Off-gas detection and early warning systems

Electrical and thermal measurements do not always provide the earliest indication of cell failure. Several studies have shown that small quantities of decomposition gases can be released from lithium-ion cells before significant temperature rise or voltage changes are observed [71,72]. For BESS in confined or semi-confined enclosures, dedicated off-gas detection can therefore be an effective early-warning layer complementing BMS functions. Different sensor technologies are available [45,73], each with specific advantages:

- Electrochemical sensors, typically targeted at CO, CO_2 or HF, offer good selectivity, low detection limits (down to ppb–ppm) and relatively low power consumption. They are suitable for distributed monitoring inside cabinets or containers;
- Spectrometric systems based on FT-IR or laser absorption spectroscopy can measure multiple gas species simultaneously and provide quantitative concentration information. They are more complex and costly but can give detailed insight into the evolution of gas composition during a failure event;
- Metal-oxide semiconductor (MOS) sensors are robust, relatively inexpensive and sensitive to a broad range of combustible gases and VOCs, making them suitable for general leak and off-gas detection in enclosures;
- Non-dispersive infrared (NDIR) sensors are commonly used for CO_2 and CO detection and have been successfully applied to battery venting experiments, with measured concentrations well above 30 000 ppm during thermal runaway.

To be effective as part of the prevention region, off-gas detection must be integrated into the overall control and alarm logic. This includes defining appropriate alarm thresholds, escalation steps and automatic responses, for example [64–67]:

- low-level alarms that prompt operator checks and, where appropriate, controlled reduction of load or SOC.
- higher-level alarms that trigger automatic BESS disconnection, activation of enhanced ventilation and notification of emergency services.
- coordination with thermal and electrical alarms to avoid conflicting actions and to provide operators with a consistent picture of the event.

5. Containment (protection) region: Active and passive fire protection

Even with robust prevention measures, failures cannot be completely excluded.

The containment (protection) region includes all measures intended to limit the consequences of a thermal runaway event that has already started, by slowing or preventing propagation, detecting the event in time, controlling fires and explosions, and protecting adjacent spaces and structures [28,74,75]. For BESS, this region covers fire detection and alarm systems, explosive-atmosphere risk assessment and management, fire control and suppression systems (including water-based and alternative agents), hydrants and manual equipment, and non-propagating layouts with appropriate spacing and barriers. Comprehensive fire detection and alarm systems complying with EN 54-1 and national fire codes provide the backbone of this region [76,77]. They typically consist of:

- automatic fire detectors installed in rooms, enclosures and other relevant spaces;
- control and indicating equipment (CIE) that receives and processes detector signals, manages alarm logic and provides outputs to local alarms and external systems;
- alarm devices for occupants and staff;
- emergency power supplies to maintain functionality during mains failures;
- manual call points in accessible locations to allow occupants or operators to raise an alarm.

For BESS installations, integration of dedicated off-gas and temperature monitoring (Section 4) into the fire detection and alarm system is particularly important, because thermal runaway can develop internally before significant smoke or open flames appear.

5.1. Explosive atmosphere risk assessment and management

Thermal runaway in BESS can generate large quantities of flammable gases in confined volumes, leading to the formation of explosive atmospheres. The quantitative criteria used in this framework are derived from a combination of sources. The 25 % LFL limit for ventilation design is a conservative engineering practice widely adopted in ATEX-based risk assessments and in international BESS guidance, reflecting the need to maintain a substantial safety margin below the ignition threshold even under conservative assumptions on gas release rates. Overpressure thresholds for explosion venting and structural design are based on recognized European and international standards for explosive atmospheres. Separation distances follow the prescriptive values of the Italian BESS guidelines, which in turn draw on large-scale test data including UL 9540A installation-level results. Suppression performance criteria are derived from representative full-scale tests and guidance documents referenced in Section 5.2. Where these criteria cannot be directly applied, Section 7 describes how equivalent safety can be demonstrated through performance-based analysis with explicitly stated objectives, scenarios and acceptance criteria.

The Italian Fire Safety Code and ATEX framework require a systematic assessment and control of this risk [28,78]. The main steps are:

a) Identification of emission sources: define where and under which conditions explosive atmospheres may form, including battery enclosures, cable ducts, ventilation ducts and adjacent technical spaces. Consider both normal operation (e.g. small leaks) and abnormal conditions such as thermal runaway or failure of ventilation systems [48,49,79];

b) Zone classification: classify hazardous areas according to the expected frequency and duration of explosive atmospheres (e.g. Zones 0, 1 and 2 as per ATEX), taking into account gas release rates, enclosure volumes and ventilation effectiveness [78];

c) Ignition source analysis: identify and evaluate potential ignition sources within classified zones, including electrical equipment, hot surfaces, mechanical sparks, electrostatic discharges and chemical reactions [79];

d) Risk characterization: combine the likelihood of explosive-atmosphere presence with the likelihood of effective ignition sources to determine the level of risk for each zone.

e) Protective measures: select and implement suitable measures such as gas-tight enclosures for cells and modules, continuous or demand-controlled ventilation, separation distances from ignition sources, equipment certified for use in hazardous areas and explosion venting where necessary.

The transient nature of off-gas release during thermal runaway — characterized by rapid, short-duration peaks rather than steady-state emissions — must be explicitly considered when sizing ventilation and assessing zone boundaries, as time-averaged approaches may underestimate peak concentrations. Similarly, external venting hazards must be addressed in the design: the discharge direction, momentum and temperature of vented gases and flames should be evaluated to ensure that venting panels do not create unacceptable hazards for adjacent occupants, structures or fire-fighters in the area outside the enclosure.

In many projects, full CFD simulations may not be feasible at preliminary design stage. In such cases, simplified engineering checks can still provide valuable insight and support conservative design decisions. A typical approach consists of:

(i) estimating credible gas release rates and durations for representative thermal runaway scenarios based on available test data;

(ii) calculating average gas concentrations in the enclosure for different ventilation rates and failure durations;

(iii) comparing the resulting values with conservative fractions of the LFL (for example 25 % of the LFL) to size normal and emergency ventilation or to define activation thresholds for demand-controlled ventilation. Although these calculations do not replace detailed simulations, they provide a transparent basis for initial design choices and for discussions with authorities when justifying ventilation capacities and explosion-prevention concepts.

Ventilation is often the primary protective measure. Continuous or automatically activated ventilation can keep gas concentration well below 25 % of the LFL under credible release scenarios, significantly reducing the probability of ignition. However, if a deflagration cannot be excluded, enclosures may need deflagration venting and explosion-resistant construction in accordance with recognized standards [28,45,78,79].

In practice, the design of ventilation and explosion protection systems is subject to practical limitations. Continuous high-capacity ventilation may not be feasible in all locations due to energy use, noise and architectural constraints, while large vent areas can conflict with structural or weather-tightness requirements. These constraints reinforce the need for site-specific analysis and transparent documentation of assumptions and residual risks, especially when standard prescriptive provisions cannot be fully met.

5.2. Fire control and suppression systems

Lithium-ion battery fires present challenges that differ from those of conventional hydrocarbon fires: cells can release their own oxidizing agent, re-ignition may occur after apparent extinction and gas generation can continue even during suppression [14,80–82]. Nevertheless, water-based suppression remains the primary and generally most effective option for BESS, provided that systems are correctly designed and integrated with the overall strategy. Water spray and sprinkler systems act mainly through [83–85]:

- cooling, by removing heat from cell surfaces and surrounding structures, lowering temperatures below those required to sustain combustion;
- heat absorption, thanks to the high specific heat and latent heat of vaporization of water;
- partial oxygen displacement near burning surfaces due to steam generation;
- reduction of radiative heat transfer through water droplets and steam clouds.

Experimental studies and guidance documents indicate that low-pressure water-mist systems can achieve similar or better cooling performance than traditional sprinklers with significantly lower water flow rates and reduced water damage, which is relevant for enclosed BESS where water management and environmental protection are concerns [83,84]. However, system design must be based on representative full-scale tests or validated models, as nozzle type, distribution, activation logic and enclosure geometry strongly influence effectiveness. Where water supply is limited or water damage is a major concern, hybrid systems that combine water mist with gaseous agents or local application systems may be considered. In all cases, practitioners must verify that suppression systems do not create unintended hazards [85] (e.g. electrical faults, structural overload from water accumulation, or exacerbation of gas mixing and dispersion).

Despite their advantages, water-based suppression systems present limitations that must be explicitly addressed in the design. Re-ignition after initial control remains a significant risk, as lithium-ion cells can continue to generate heat internally even after external cooling. Electrical hazards must be managed through reliable isolation procedures activated before or simultaneously with system discharge. Water demand can be substantial for large BESS installations, and the management of contaminated run-off – which may contain toxic compounds released during thermal runaway – requires appropriate containment and disposal measures, as addressed in Section 5.6.

5.3. Alternative suppression agents

Several alternative or complementary agents have been investigated for lithium-ion BESS fires [81,86]. They are generally used to support, not replace, water-based systems:

- Aqueous Vermiculite Dispersion (AVD) combines water with suspended vermiculite particles. The water component provides cooling, while vermiculite forms an insulating layer on cell surfaces that reduces heat transfer and limits re-ignition potential. Laboratory tests have shown effective suppression for certain cell formats and configurations, but large-scale performance in complex BESS layouts still requires further validation;
- Perfluorohexanone ($C_6F_{12}O$) and related fluorinated agents act mainly by interrupting combustion reactions and providing rapid evaporative cooling. They are clean agents that leave no residue and can be effective for incipient fires in enclosures. However, they do not stop thermal runaway itself and may require combination with cooling (e.g. water or liquid nitrogen) for robust control of fully developed cell fires;
- Liquid nitrogen is a cryogenic agent that can rapidly cool cells well below thermal runaway thresholds and displace oxygen locally. Experiments suggest that combined application of liquid nitrogen and water can reduce peak temperatures and re-ignition, but practical deployment at BESS scale is challenging due to storage, handling and safety constraints.

Given the current state of knowledge, alternative agents are best considered as part of targeted, locally applied systems (e.g. for specific enclosures or components), or as tools for fire-fighting teams, rather than as the sole primary suppression means for large BESS installations [81–86].

Water-based systems remain the reference solution for many BESS installations because of their robustness, availability and cooling capability, but they also have clear limitations. Re-ignition after initial control, the need to manage contaminated run-off and the requirement for reliable electrical isolation must be explicitly addressed in the design. Aerosol, inert gas and hybrid systems can complement water-based suppression in specific configurations, particularly for enclosed containers and sensitive equipment, yet they depend on enclosure tightness, may have limited cooling effect and often require more complex maintenance. These factors should be weighed case by case, rather than assuming a single technology can address all BESS fire scenarios.

5.4. Hydrant design and manual suppression

In addition to fixed suppression systems, the Italian BESS guidelines require that facilities be equipped with manual fire-fighting means suitable for lithium-ion battery fires [28,87]. This typically includes:

- external or internal fire hydrants designed, installed and maintained in accordance with the standard UNI 10779 or equivalent standards, positioned to allow safe and effective access for fire-fighters;
- portable fire extinguishers using agents appropriate for electrical and battery fires (e.g. water-based with suitable ratings, certain clean agents, or specialized battery extinguishers), located along access routes and near BESS rooms or containers, typically within 20 m travel distance.

Manual intervention on BESS fires must consider the potential for delayed explosions and the presence of toxic gases. Facilities should therefore provide clear guidance for fire-fighters on safe attack positions, minimum approach distances, preferred water application patterns and conditions under which defensive strategies (e.g. protection of exposures and controlled burn-out) are preferable to direct attack [28,85,86].

5.5. Non-propagation design and thermal barriers

The primary design objective of non-propagating layouts is to contain thermal runaway events within a single module, rack or container, preventing cascade failures across larger portions of the system [28,50–51]. This is achieved through a combination of spatial separation, fire-resistant barriers and limitation of electrical and thermal coupling. Key design principles include:

- Adequate spacing between modules, racks and containers to reduce conductive and radiative heat transfer. The Italian BESS guidelines provide minimum separation distances for typical configurations (e.g. container BESS and island BESS), which may be adjusted based on performance-based analyses using validated thermal models and test data;
- Fire-resistant partitions and enclosures (e.g. REI-rated walls and ceilings) that separate BESS rooms from other occupancies and from each other where multiple systems are present. These barriers should limit fire spread for a specified time, contain hot gases and support-controlled venting strategies;
- Internal thermal barriers within racks and cabinets, such as insulating panels, intumescent layers or structural elements with low thermal conductivity, to slow down cell-to-cell and module-to-module propagation. These measures should be selected and dimensioned based on experimental evidence of their behaviour under realistic abuse conditions [88];
- Limitation of electrical coupling that would otherwise sustain or aggravate propagation, for example by segmenting strings, designing appropriate protective devices and avoiding configurations where healthy modules can feed large currents into failed ones [51] (see Section 4.2).

Eventually, where prescriptive distances or barrier requirements are difficult to meet, performance-based approaches supported by large-scale tests (e.g. UL 9540A unit- and installation-level tests) and Computational Fluid Dynamics (CFD) or thermal simulations can be used to demonstrate that thermal runaway remains confined within defined boundaries and that temperatures and overpressures in adjacent areas remain within acceptable limits [50–51,89,90].

5.6. Water management systems

Water used for fire suppression or released from cooling systems can become contaminated with combustion products, electrolyte components and other hazardous substances. For BESS installations, water management is therefore an integral part of the containment region, with direct implications for environmental protection and facility integrity. An effective water management system should address at least the following aspects [28,80]:

- Collection: floors, curbs and drainage systems within BESS rooms or around outdoor containers should be designed to collect and channel fire-fighting water and any coolant discharge towards controlled collection points, avoiding uncontrolled spread to adjacent areas or public networks;
- Containment capacity: collection basins, sumps or retention tanks must be sized for credible worst-case scenarios, typically combining the design discharge of fixed suppression systems (e.g. sprinklers or water-mist) for the expected duration of operation with contributions from hydrants and possible cooling system leaks;
- Separation and treatment: where oils, fuels or other contaminants may be present, oil-water separators and, if necessary, additional treatment stages (e.g. filtration, neutralization) should be provided before any discharge to the environment or sewer system. Requirements depend on local environmental regulations and on the substances present in the facility;
- Controlled discharge: drainage from collection and treatment systems must be routed through controlled discharge points, with valves or other devices that allow operators to stop release in case of accidental contamination above acceptable limits;
- Monitoring and documentation: procedures should be placed to sample and, if required, analysis of collected water after significant incidents, and to document how contaminated water has been handled, treated and disposed of in compliance with applicable regulations.

In performance-based designs, the behaviors of suppression water, potential contamination pathways and interactions with structural elements (e.g. loads from water accumulation on floors or roofs) should be explicitly considered in the overall risk assessment and mitigation strategy [28].

6. Management region: Operational safety and emergency response

The management region comprises organizational, procedural and training measures that ensure safe operation of BESS over their life cycle and an effective response to incidents [28]. Even well-designed prevention and protection measures can be undermined by inadequate operation, maintenance or emergency planning. For this reason, the Italian BESS guidelines emphasize the role of competent personnel, documented procedures and coordination with emergency services. Key elements of the management region include:

- clear allocation of responsibilities for BESS operation, maintenance and safety;
- training and qualification of personnel;
- structured maintenance and inspection programs;
- continuous monitoring and logging of relevant system parameters;
- documented emergency procedures and pre-incident planning with responding agencies.

Implementation of containment and management measures in real projects often reveals gaps between ideal solutions and practical constraints. Existing buildings may lack space for additional compartments or vents, and operational procedures can diverge over time from the original design assumptions. For this reason, periodic review of BESS installations, including updates to risk assessments and emergency plans, is essential to ensure that the intended level of safety is maintained throughout the life of the system.

6.1. Maintenance provisions

A structured maintenance strategy is essential to preserve the performance of monitoring, protection and suppression systems and to detect early signs of degradation in BESS components [61–67]. Maintenance activities can be grouped into:

- Preventive maintenance: scheduled inspections, tests and component replacements based on manufacturers' recommendations, applicable standards and accumulated operational experience. This includes regular functional tests of fire detection and alarm systems, suppression systems, ventilation and gas detection, as well as checks of BMS functions and communication links;
- Corrective maintenance: prompt repair or replacement of components identified as defective during inspections or following alarms and faults. Clear criteria are needed to decide when the BESS or parts of it must be taken out of service until corrective actions are completed;
- Predictive maintenance: use of trended data (e.g. cell voltages, temperatures, impedance indicators, alarm statistics) to identify patterns that suggest degradation, enabling planned interventions before failures occur.

Continuous data logging of BESS operating parameters, alarms and maintenance activities supports [61–67]:

- verification that the system operates within its design envelope;
- identification of recurrent issues or weak points in the design;
- refinement of predictive models and early-warning criteria;
- traceability for incident investigations and reporting to authorities or insurers.

Maintenance requirements and intervals should be set out in a written plan, aligned with national fire codes, equipment standards and the specific recommendations of the BESS manufacturer and designer.

6.2. Emergency response plan

A documented emergency response plan specific to the BESS is a core requirement of the management region [28,80,89,90]. It should be integrated into the general emergency plan of the facility, but address in detail the hazards of lithium-ion systems (thermal runaway, gas release, potential explosions, re-ignition). At minimum, the plan should cover:

- Alarm recognition and classification: description of alarm types (e.g. BMS warnings, gas detection, fire detection) and corresponding severity levels, with clear criteria for escalation;
- Immediate operator actions: step-by-step procedures for operators on site and in remote control rooms, including verification steps, safe shutdown

actions, activation of additional ventilation or suppression functions and notification of internal and external stakeholders;

- System actions: list of automatic protective actions implemented by the BMS, fire detection and suppression systems, and how operators should interface with them during an incident (e.g. conditions to override automatic functions, if allowed);
- Communication with emergency services: pre-defined channels and contact points for rapid notification of the fire service and other responders, including the information to be provided (location and configuration of BESS, energy content, chemistry, presence of hazardous materials, status of isolation and suppression systems);
- Evacuation and access control: procedures for evacuation or shelter-in-place decisions for building occupants, and for controlling access to hazardous areas during and after the incident;
- Post-incident management: instructions for securing the site, monitoring for re-ignition or delayed gas release, handling of damaged equipment and contaminated water, and initiation of incident investigation.

Pre-incident coordination with emergency responders is strongly recommended. This may include site visits, sharing layout plans, information on BESS characteristics and expected hazards, and, where possible, arrangements to give responders access to real-time BMS and gas detection data during an incident. Regular drills involving both facility staff and emergency services help verify the practical effectiveness of the plan and identify areas for improvement.

7. Alternative design methodologies and performance-based approaches

The performance-based structure of the Italian Fire Safety Code is particularly suitable for the design of non-standard BESS installations that do not fit prescriptive solutions or where prescriptive distances and configurations are not practicable [28–30]. In these cases, quantitative analyses are required to demonstrate that safety objectives are still met. For BESS, performance-based design typically focuses on a limited number of critical scenarios [28,49]:

- single-cell or single-module thermal runaway with potential for cell-to-cell and module-to-module propagation;
- simultaneous failure of multiple cells in a container or room, leading to significant gas generation and possible explosion;
- fires involving cables, switchgear or other equipment in proximity to the BESS, with potential for external heating of the batteries and escalation.
- Depending on the scenario and objectives, different tools and methods can be used:
- zone and field models (CFD) to simulate gas dispersion, accumulation and explosion overpressures in containers, rooms and adjacent spaces;
- thermal models at cell, module and rack level to estimate temperatures, heat fluxes and propagation times during thermal runaway;

- evacuation models to verify that occupants can reach safe locations under smoke and heat conditions predicted by fire simulations;
- structural analysis to check that supporting structures and barriers can withstand predicted thermal and pressure loads.

The choice of models and input data must be consistent with the level of detail required and with available experimental evidence. Where possible, models should be calibrated or validated against full-scale tests or well-documented case studies. For BESS, results from standardized large-scale tests (e.g. UL 9540A unit, module and installation-level tests) can provide valuable boundary conditions and input data for performance-based analyses. A transparent performance-based design for BESS should:

- clearly define objectives and acceptance criteria (e.g. limits on overpressure, temperature in adjacent rooms, gas concentrations along escape routes, maximum structural deformation);
- document all key assumptions, including failure modes, ignition sources, ventilation conditions and intervention times;
- describe the models, input data and uncertainties, and justify their applicability to the specific installation;
- present results in a form that is understandable to authorities having jurisdiction and other stakeholders, including sensitivity analyses where appropriate.

For each selected scenario, the objectives and acceptance criteria should be stated explicitly. Typical examples include upper bounds on explosion overpressure in occupied or critical spaces, maximum allowable temperatures on structural elements and fire-resisting separations, limits on toxic and flammable gas concentrations along escape routes, and comparisons between available and required safe egress time (ASET/RSET). Making these criteria explicit is essential to ensure transparency and to enable consistent evaluation of alternative design options.

The choice of modelling approach depends on the type and complexity of the scenario. Gas accumulation and smoke movement may be analyzed using zone models for simple geometries or CFD tools for complex enclosures and venting arrangements, while thermal runaway and propagation can be represented through lumped-parameter or detailed thermal models at cell, module and rack level. Evacuation models and structural models are used to assess occupant safety and structural performance, respectively, and should be calibrated or benchmarked against test data or well-documented reference cases whenever possible.

Uncertainties and variability in input parameters are an integral part of performance-based design. Key sources of uncertainty include ignition timing and location, vent opening pressures and failure modes, ventilation conditions, intervention times and the severity of initiating events. These should be addressed through conservative assumptions, sensitivity analyses or, where appropriate, parametric studies that show how changes in the main parameters affect overpressures, temperatures, gas concentrations and evacuation conditions.

Finally, simulation results must be systematically translated into design decisions. For BESS installations, this typically means defining venting areas and locations, separation distances and barrier configurations, suppression system parameters and trigger conditions, and any required structural reinforcements or protections. Documenting these links between model outputs and design measures is crucial to demonstrate that the proposed solution meets the defined objectives and acceptance criteria and to facilitate review by authorities having jurisdiction.

Figure 2 illustrates a typical CFD-based workflow for performance-based analysis of fire and explosion scenarios in lithium-ion BESS installations.

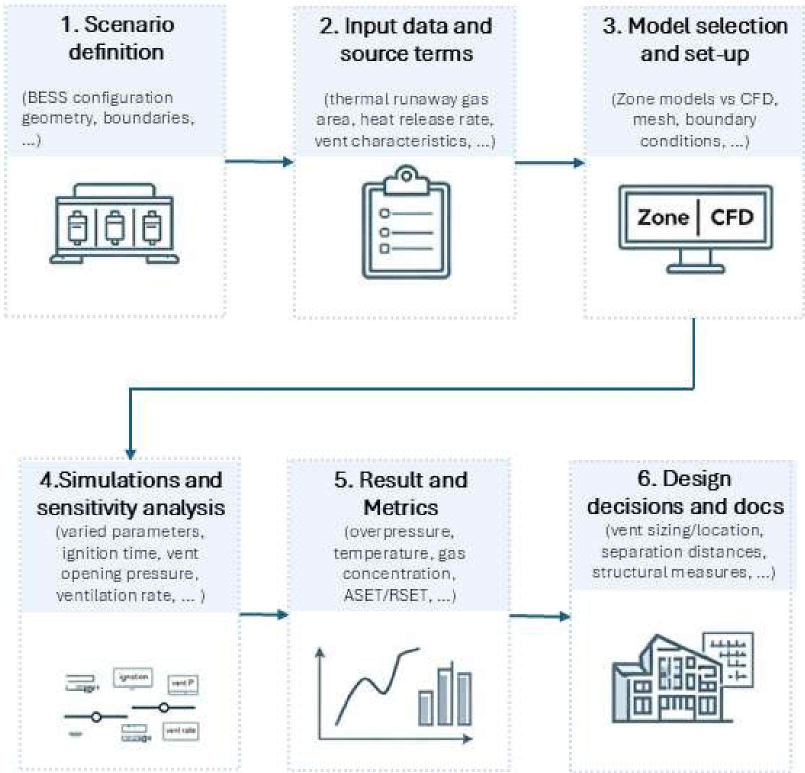

Figure 2. CFD-based workflow for performance-based fire and explosion analysis of lithium-ion BESS, from scenario definition to design decisions.

This approach allows designers to justify design choices such as reduced separation distances, alternative suppression concepts or specific venting solutions, while maintaining a consistent level of safety with respect to the Code's objectives.

8. Design scenarios for typical BESS configurations

To illustrate the practical application of the framework described, two representative design scenarios are presented. These scenarios are not based on a specific real installation but are constructed to be representative of common BESS configurations in Italy and comparable contexts. For each scenario, the design path is described step-by-step following the three operational regions of the Italian BESS guidelines: prevention, containment and management.

8.1. Scenario 1 – Indoor BESS room in an existing building

This scenario considers a lithium-ion BESS of approximately 500 kWh installed in a dedicated room within an existing mixed-use building. The main constraints are limited floor area, proximity to occupied spaces and restricted options for enlarging or modifying the structural envelope.

Prevention region: Cells and modules are selected based on abuse test results (IEC 62619, UL 9540A) demonstrating limited gas release and no uncontrolled propagation. The BMS is configured to maintain SOC within safe limits and to trigger early alarms on anomalous temperature or voltage trends. Normal ventilation is sized to keep gas concentrations below 25 % of the LFL under credible single-module thermal runaway, using the simplified engineering check described in Section 5.1.

Containment region: The BESS room is separated from adjacent occupancies by fire-resistant walls and a self-closing fire door with ratings consistent with the Italian Fire Safety Code and the activity category. Off-gas detection is integrated with the BMS and the building fire detection and alarm system. An automatic water-based suppression system is installed, with electrical isolation triggered before system activation.

Management region: An emergency plan is developed in coordination with the local fire service, identifying intervention distances and positions, hydrant locations and manual equipment. Periodic inspection and maintenance procedures cover ventilation, detection, suppression and BMS functions. A risk assessment review is planned every three years or after any significant modification to the BESS installation.

8.2. Scenario 2 – Outdoor containerized BESS near a sensitive site boundary

This scenario considers a 1 MWh lithium-ion BESS installed in a standard 20-ft container, located outdoors near the boundary of an industrial site adjacent to a sensitive receptor (e.g. a road or a public building).

Prevention region: Module layout within the container is designed to limit propagation, with spacing and thermal barriers validated by UL 9540A propagation tests. The BMS monitors SOC, temperature and insulation resistance, with remote alarm transmission to a control center.

Containment region: The container is equipped with explosion relief venting panels sized to limit peak overpressure to acceptable levels under credible deflagration scenarios (see Section 5.1). An automatic suppression system provides water-based cooling activated by combined smoke and off-gas detection. Separation distance from the site boundary is verified against the Italian BESS guidelines and, where reduced distances are justified by site constraints, a performance-based analysis is carried out using the approach described in Section 7.

Management region: Pre-incident information is shared with the local fire service, including container layout, BESS chemistry, estimated gas release quantities and recommended intervention positions. A site emergency plan identifies exclusion zones around the container in the event of an alarm or intervention

9. Harmonization with international standards

Lithium-ion BESS are regulated and guided by a growing set of international standards and technical documents. The Italian Fire Safety Code and the Italian BESS guidelines provide the overarching framework at national level, but consistent and effective designs require careful integration of these documents [28–30,74,89–91]. Key references include:

- UL 9540 and UL 9540A, which define safety requirements and test methods for energy storage systems and for the evaluation of thermal runaway propagation at cell, module, unit and installation level;
- NFPA 855, which provides detailed installation requirements for stationary energy storage systems, including location, spacing, fire protection and emergency response considerations;
- IEC 62619 and IEC 62932, which address safety requirements for industrial lithium-ion cells and batteries and flow-battery energy systems, respectively [92–95];
- FM Global Data Sheet 5–33 and similar documents, which offer insurer-oriented recommendations on BESS design, protection and risk management [96];
- relevant IEEE standards on stationary battery applications and personnel qualifications (e.g. IEEE 1657 and IEEE 1709) [97,98].

From the perspective of the Italian framework, these documents can be used in several ways:

- As sources of technical requirements for component and system safety (e.g. use of batteries certified to IEC 62619, systems listed to UL 9540, or designs aligned with NFPA 855 separation and fire protection criteria);
- As providers of test data and acceptance criteria (e.g. UL 9540A results used to support performance-based reductions of separation distances or to justify specific suppression and venting strategies);
- As references for detailed design of subsystems such as fire detection and alarm (NFPA 72 [75]), fixed water-based suppression (NFPA 13 [99], NFPA 15 [100]), and explosion protection measures.

Harmonization does not mean a simple accumulation of requirements, but a consistent choice of which provisions to apply and how they map onto the objectives and tools of the Italian Fire Safety Code. In practice, this implies:

- Identifying which international standards are most relevant to the specific BESS configuration and context (e.g. indoor vs outdoor, size, technology, presence of occupants);
- Checking for overlaps and potential conflicts between different documents (e.g. separation distances recommended by NFPA 855 vs those in Italian guidelines) and resolving them through performance-based justification where needed;
- Documenting how compliance with international standards contributes to meeting the four fire safety objectives defined by the Italian BESS guidelines (prevention, occupant safety, rescue team safety, environmental and property protection).

For authorities, practitioners and designers, a structured approach to harmonization can facilitate the approval process and support the safe deployment of BESS technologies while leveraging international experience and test data.

10. Conclusions and recommendations

This paper presents an integrated, design-oriented framework for the fire safety of lithium-ion BESS installations within the Italian performance-based regulatory context. The main engineering contributions of the work can be summarized as follows. First, a structured five-step design workflow has been proposed that links project characterization, hazard and scenario analysis, selection of prevention, containment and management measures, quantitative checks and performance-based analyses, and documentation and operational planning. Second, a set of representative design criteria and their regulatory sources have been made explicit through **Table 1**, providing practitioners with a transparent reference for applying the Italian BESS guidelines and Fire Safety Code in conjunction with key international standards such as UL 9540/UL 9540A, NFPA 855, IEC 62619 and IEC 62932. Third, two illustrative design scenarios – an indoor BESS room in an existing building and an outdoor containerized BESS near a sensitive site boundary – have been presented to show how the framework can be applied in practice. Fourth, the discussion of fire suppression options has been extended to provide a more balanced and critical treatment of water-based systems, aerosol, inert gas and hybrid technologies, including their respective limitations and implementation challenges.

The paper has inherent limitations that should be acknowledged. No new experimental data are presented, and the quantitative engineering checks included in the design scenarios are based on simplified assumptions intended to illustrate the methodology rather than to provide definitive design values. Some of the strategies discussed, particularly those related to advanced suppression systems and performance-based venting design, require further validation for emerging BESS configurations and chemistries beyond the lithium-ion technologies considered here.

Several directions for future research emerge from this work. Large-scale experiments on thermal runaway propagation and gas accumulation in representative BESS enclosures are needed to provide validated source terms for engineering calculations and CFD models. Improved models for new BESS configurations, including semi-outdoor and building-integrated installations, would extend the applicability of performance-based design approaches. The integration of advanced diagnostics, data-driven prediction and real-time monitoring into the design and operational framework represents a promising area for enhancing early detection and intervention capabilities. Finally, systematic analysis of real BESS incidents would provide valuable feedback for refining both design criteria and regulatory guidance.

From a regulatory perspective, the results of this work highlight the importance of continued harmonization between the Italian national framework and international standards. The performance-based structure of the Italian Fire Safety Code provides a suitable and flexible basis for addressing non-standard BESS configurations, but its effective application requires clearer guidance on acceptance criteria, scenario selection and the use of quantitative tools. Closer alignment with international standards and test protocols would reduce uncertainty for designers and authorities and would support the safe and efficient deployment of lithium-ion BESS in the built environment.

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