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Safety Challenges and Mitigation Strategies in Grid-Scale Stationary Lithium-Ion Battery Energy Storage Systems

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ABSTRACT

To date, Battery Energy Storage Systems (BESS) has been deployed in large-scale applications primarily to store energy in the grid, facilitate renewable energy integration, and provide grid stabilization. The BESS deployment has outpaced the development of governance mechanisms that take into account safety and environmental impacts throughout the BESS lifecycle. This thesis addresses the hazards of BESS and mitigation strategies through the combined lenses of safety and sustainability. Safety and environmental outcomes are co-produced by design, operational, and regulatory decisions, but have been historically treated in isolation. Peer-reviewed studies, inquiry investigations, standards, and life cycle assessment (LCA) studies are synthesized qualitatively. The risks of thermal runaway, fire and explosion risks, electrical hazards, and chemical contamination have been discussed in conjunction with the stages in BESS lifecycle.

Thermal runaway events are life cycle environmental events and not just safety events. Emissions of hydrogen fluoride, heavy metals, and volatile organic compounds are experienced in battery fires. These emissions have often been outside the boundaries of LCA, and the resulting impacts on the environment have been underestimated. Production flaws lead to double jeopardy, increasing the loss of embodied carbon and instigating contamination at the incident phase. Present regulations are not able to account for these issues adequately. One of the most important decisions in the lifecycle is the choice of battery chemistry. This decision influences the thermal stability, material demand, emissions, and recyclability of the battery. Lithium iron phosphate (LFP) is beneficial compared to nickel-rich chemistries (NMC/NCA) if used in stationary applications.

The analysis of mitigation techniques shows that there is no one-size-fits-all technology available that can address the range of hazards. Risk reduction through integrated safety design has been proven to be very effective. Trade-offs are inherent in the risk suppression methods. Toxic by-products and polluted run-offs are some of the associated trade-offs. Avoiding the build-up of gas and delay in ignition in batteries is key, since these two factors lead to severe incidents. There is very little guidance available in assessing the environment in post-incident phases. The safety standards NFPA 855, UL 9540A, and IEC 62933 have been analysed to investigate how fire safety standards can guide environmental assessment in the post-incident phase. Fire safety standards have very strong provisions on fire safety, whereas very weak accountability on the lifecycle of the batteries. A six-layered system of governance is suggested, which includes LCA disclosure, chemically sensitive procurement, post-incident analysis, and recycling mechanisms based on deployment rates.

Keywords: Battery energy storage system (BESS), lithium-ion battery, thermal runaway, life cycle assessment (LCA), fire risk, environmental impact, end-of-life (EoL), policy framework, renewable energy.

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Abbreviations

AC	Alternating Current
BESS	Battery Energy Storage System(s)
BMS	Battery Management System
CO	Carbon Monoxide
CO_2	Carbon Dioxide
DC	Direct Current
EOL	End-of-Life
ESS	Energy Storage System(s)
EV	Electric Vehicle(s)
GWP	Global Warming Potential
HCN	Hydrogen Cyanide
HF	Hydrogen Fluoride
HFC	Hydrofluorocarbon
HFC-227ea	Heptafluoropropane (gaseous fire suppression agent)
HVAC	Heating, Ventilation, and Air Conditioning
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LFP	Lithium Iron Phosphate
$LiPF_6$	Lithium Hexafluorophosphate
NCA	Nickel Cobalt Aluminum (Oxide)
NFPA	National Fire Protection Association
NMC	Nickel Manganese Cobalt (Oxide)

PCM	Phase Change Material
PCS	Power Conversion System
PF_5	Phosphorus Pentafluoride
POF_3	Phosphoryl Fluoride
SEI	Solid Electrolyte Interphase
SoC	State of Charge
SoH	State of Health
TMS	Thermal Management System
UL	Underwriters Laboratories
VOC(s)	Volatile Organic Compound(s)

1 Introduction

1.1 Background and Motivation for Energy Storage in Modern Power Systems

The structure of electrical power systems is undergoing a significant and irreversible evolution. Traditionally, the power grid remained stable due to dispatchable generation, which adjusted its output according to real-time demand. The electrical power system was balanced using central scheduling of thermal power and hydroelectric plants. But, as variable renewable energy (VRE), such as solar photovoltaic and wind power, becomes the main source of power generation in many countries (Song et al., 2024), the traditional mechanism of balancing the electrical power system is no longer feasible. The reduction of synchronous generators causes instability in the frequency range of the power system.

Batteries have taken up the challenge to address this structural deficit. Battery energy storage systems (BESS) have temporalized the relationship between consumption and production, enabling the desired level of renewable source penetration that would otherwise destabilize the grid(Behabtu et al., 2020). In addition to temporal shifting, large-scale batteries provide direct services to the grid such as frequency regulation, voltage support, spinning reserve, and peak load management, all of which become increasingly important as inertia decreases with the commissioning of fewer synchronous generators. The emerging safety, environmental, and governance challenges associated with the immense and rapid proliferation of these batteries have not been matched with research on how to address them.

The motivation for this thesis arises from a gap in this understanding. The current body of research largely separates BESS safety and environmental sustainability concerns. The safety literature investigates failure scenarios and safety controls, while the sustainability literature investigates BESS carbon footprint and material flows. In short, the literature appears to address two sides of the coin. But, this separation is indefensible. Chemistry choices that reduce thermal runaway risk also affect recyclability and dependence on critical materials. Manufacturing processes that lead to safer cells incur environmental costs that need to be amortized across the lifetime of the cells. Also, thermal events cause irreparable harm to the embodied environmental value of the manufactured cells and cause emissions of toxic species that pose both immediate safety and long-term ecological risks. This thesis, therefore, is motivated not only by the vast deployment potential of BESS but also by the structural inadequacy of the current framework addressing the safety and environmental aspects of BESS independently.

To the best of our knowledge, emissions of toxic gases during thermal runaway, including kilogram-scale hydrogen fluoride emissions, are unaccounted for in life cycle assessment. This thesis argues that this gap should be structurally addressed for the sake of responsible governance of BESS, an argument that is developed further in Chapter 3.

The lifecycle view of safety in grid-scale BESS shows that safety is an aspect of sustainability other than engineering safety. Safety failure (thermal runaway, fire, and explosion) will have subsequent repercussions on the cycle life, material efficiency, and environmental impact of the system. Therefore, this study considers safety not only from a technical perspective but also from other aspects that affect the sustainability of BESS throughout its lifecycle.

1.2 Growth of Renewable Energy Integration and the Role of Grid-Scale BESS

Integrating large-scale renewable energy fundamentally alters the operation of power systems and is not feasible without flexible energy storage. The output from variable renewable energy (VRE), mainly wind and solar, is non-matching with the demand and is non-controllable. At a low penetration level, the variability in generation can be accommodated by the flexible operation of conventional power plants. But, at a high penetration level, mismatches between generation and demand may cause system instability issues such as frequency and voltage variations and unnecessary curtailment of renewable energy (Zhao et al., 2023).

The intermittency of renewable resources can be seen at different time scales (sub-second, second, daily, and seasonal) and has a nonlinear effect depending on the level of penetration. Thermal units cannot accommodate the fast and large variations in renewable energy output due to ramp rate and minimum power output constraints. This is the main reason for the deployment of grid-scale battery energy storage systems that can absorb and inject power in the order of milliseconds (El-Bidairi et al., 2020; Hasan et al., 2024).

Note that the relationship between renewable energy and BESS is not that of complement, but that of being structural or enabling. Relatedly, massive amounts of renewable energy capacity without storage will require a massive amount of backup generation, mainly fossil fuel based, defeating the purpose of shutting down fossil fuel plants. Another risk of having large amounts of renewables penetrating the grid without storage is great fluctuations in frequency, impacting the stability of the electric power grid. Chapter 2 of this thesis discusses that the enabling role of BESS in renewables use is an enabling role in the sustainable or green use of energy production. This means that the enabling argument for the deployment of BESS cannot be treated in isolation in the sustainability argument for energy production. There are environmental and safety issues in the use of batteries that need to be addressed if BESS is to be deployed at large scale.

1.3 Increasing Deployment of Lithium-Ion BESS Worldwide

Owing to their exceptional round-trip efficiency of 90–95%, scalability, modularity, and a 90% reduction in cost per kilowatt-hour between 2010 and 2023, lithium-ion batteries have become the preferred chemistry for large-scale electrical energy storage(Koech et al., 2024) .The global installed capacity of lithium-ion battery electrical energy storage systems has increased from almost zero a decade ago to a multiple-gigawatt-hour scale, experiencing a compound annual growth rate greater than 20% through 2030 (Elliot et al., 2025). Large-scale lithium-ion battery energy storage systems have also been connected to national grids in multiple continents, providing frequency control, peak load, voltage regulation, and emergency standby power for the national grid at a scale of megawatts to hundreds of megawatts.

This boom is significant for environmental reasons on both sides, an interplay not well articulated in the literature: while BESS help grid integration of renewable energy and other decarburization measures in electricity generation, lithium-ion batteries rely on the supply of materials, which has intense environmental and social impacts. Christensen et al. (2021) elaborate on the tensions in sourcing lithium, cobalt, nickel, manganese, copper, aluminum, and graphite for lithium-ion batteries. Manufacturing has been found to be the most significant contributor to the life cycle greenhouse gas emissions of a battery. Le Varlet et al. (2020) estimate life cycle greenhouse gas emissions to be between 40–100 kg carbon dioxide equivalent per kilowatt-hour for the most common lithium-ion chemistries for grid-scale storage, with highly significant differences depending on the electricity grid used for manufacturing, cell chemistry, and assumptions regarding the end-of-life treatment of batteries. Jaradat & Khatib, (2025) extend this literature and confirm that there is indeed an environmental gain in using BESS to support renewable integration, but note that this depends crucially on the use and degradation of the system and the governance of its end-of-life.

Chapter 2 of this thesis illustrates, using comparative chemistry analysis, that the choice of cathode chemistry for the battery cell (NMC, LFP, or NCA) is an irreversible decision for the battery lifecycle that sets its maximum environmental performance. NMC and NCA have higher energy density but involve cobalt and nickel supply chains that have significant environmental and social challenges; LFP avoids these supply chains but requires a higher cell mass for the same installed kWh and provides better thermal characteristics. This thesis posits that the shortcoming left open by these frameworks is that they fail to comprehend these trade-offs as mutually determined outcomes, not the simultaneous results of identical design decisions.

In addition, the potential magnitude of a failure's impact is not linear with the size of the installed capacity. What is a relatively benign fault at a small scale can cause a kg-scale emission of toxic gases, thermal runaway across the entire facility, and permanent loss to recyclable battery materials at the grid scale. Hence, exploring and regulating these risks for grid-scale deployment is not an option but a necessity as the history of incidents discussed in Chapter 7 shows us time and again.

1.4 Safety Concerns Associated with Large-Scale Lithium-Ion Energy Storage

The advantages of Li-ion technology for grid-scale storage, including high energy density, fast electrochemical response, and durability for repeated cycles, give rise to unique safety issues that, while not necessarily more severe at larger scale, become more significant as a result of scaling. High energy density means a higher amount of stored chemical energy that could be released rapidly in energetic failure events. Electrochemical activity that enables high charging and discharging rates makes the cells susceptible to runaway thermal reactions due to a variety of abnormal conditions that are unavoidably realized while a grid-scale system is in service(W. He et al., 2024) .

The ultimate mode of failure with lithium-ion cells is thermal runaway. This occurs when heat within the cell exceeds that which can be dissipated, and temperature increases lead to a chain of uncontrollable chemical reactions, such as solid electrolyte interphase (SEI) decomposition, separator melting, release of lattice oxygen in the cathode, and other exothermic reactions, that rapidly propel the temperature to hundreds of degrees Celsius within a short span of time. Thermal runaway generates hydrofluoric acid fluorine-based gases that are highly toxic at low concentrations as well as other flammable and toxic gases. As shown in Chapter 3, quantities of these gases released per incident at the grid scale risk scale to be at the kilogram scale, including fluorine-based gases (hydrogen fluoride), carbon monoxide, hydrogen cyanide, and volatile organic compounds. Hydrogen fluoride yields were reported by Larsson et al. (2017) between 20 and 200 mg per Wh of the nominal capacity of the battery, and recent efforts provide finer characterization of these emissions with meta-analysis over charge and discharge chemistry types. These emissions pose an immediate occupational safety risk to workers and bystanders and are the environmental impacts of the BESS to be accounted for at the combustion (use) phase of the battery, which is currently not part of the implicit or explicit boundaries of the life cycle assessment (LCA) of battery systems.

At the system level, the risk from the battery event is significantly amplified. Within closely arranged battery racks and in containerized configurations, the thermal failure of one cell may lead to destruction of several cells, modules, racks, and then spread between containers through conduction, radiation, common gas space, and flaming debris. This amplification from a cell event to potential facility level event has been studied in full-scale tests (McKinnon et al., 2022) and analytically modeled Karmakar et al. (2024). The consequence of these events is the complete loss of the installed battery system, days of firefighting, and contamination of the site by the fire-suppression water interacting with dissolved metals in cells, electrolyte, or HF products from acid decomposition. The containerized ensemble of battery packs allowing the economic deployment of grid-scale BESS also creates the confined volume for the accumulation of flammable gases that once ignited after a delay can lead to deflagrations with consequences exceeding those of the initial thermal runaway, as repeatedly observed in the incident history in Chapter 7.

It is important to emphasize that safety of large-scale BESS is not solely a matter of reliability of individual components. As discussed in the preceding sections (and in Chapters 4 and 5 of this thesis), the system-theoretic safety analysis found by Rosewater & Williams, (2015) emphasizes the importance of interactions between electrochemical, thermal, control, or installation dimensions, and operational practice in the emergence of safety, in contrast to standards that focus on components. This same difference between the focus of standards on individual components and the actual practice of installation in the field is highlighted in the analysis of standards as part of the regulatory analysis and recommendations in Chapter 6 and in the preceding case studies of incidents in Chapter 7, as further motivation for new approaches to standards and labeling.

1.5 Overview of Major BESS Safety Incidents (2017–2025)

Between 2017 and 2025, a series of real-world incidents occurred that provided powerful evidence that the failure mechanisms described in Section 1.4 were not hypothetical; they happened repeatedly in various countries and continents, affecting employees, entire buildings, neighborhoods, or ecosystems. These incidents are reviewed in this dissertation primarily in Chapter 7. They establish three critical patterns. First, the most destructive effects of BESS incidents are due to the accumulation of hazardous gases and their delayed ignition, not the thermal events themselves (fire or explosion); this evolution profoundly transforms BESS incidents into environmental contamination events. Second, standard-compliant BESS installations did not prevent catastrophic failure. Third, none of these incidents was followed by a formal assessment of the environmental and lifecycle impacts of the BESS. As noted in the discussion on containerized systems in Chapter 7, the McMicken BESS event was an example of a delayed ignition caused by accumulated gas.

There were three near-simultaneous incidents in 2021. One was the Victorian Big Battery fire in Geelong, Australia, involving two Tesla Mega pack units at the 300 MWh facility (the unit size used in UL 9540A testing, unlike other battery types) that started due to leaking coolant during commissioning; the fire spread due to wind at a rate not tested according to the parameters set forth in that standard, and then suppression water was used, with unknown effects on environmental contamination(Blum, n.d.; Matich, n.d.).The second was the explosion and fire at the Jimei Dahongmen site in Beijing that released contaminants from debris and was not tested for release of toxic contaminants to the atmosphere in the applicable standards. The third was the fire at Carnegie Road in Liverpool that had the delayed ignition characteristics discussed in earlier incidents. A significantly different set of fires to consider for an analytical comparison is the string of fires, over 23 incidents, in South Korea from large scale ESS systems between 2017 and 2019. These are significant for analyzing the recurring nature after interim measures, which in Chapter 7 are discussed as being indicative of the systematic nature of design risk that impacts the environment over the life cycle with cumulative effects that are not discussed in the literature. A separate incident in California at Moss Landing was instructive to show issues with software integration and equipment failure, demonstrating that the hazard for grid-scale storage is not just in the electrochemical components but also in the control equipment.

All of these examples illustrate how BESS failures follow patterns, how they entail life cycle events with environmental outcomes that the existing regulatory framework established for safety-related incidents is ill-equipped to address (malodorous toxic fumes, depletion of consumable materials, disposal of damaged batteries into waste streams, and potentially uncontrolled environmental exposure from fire suppression runoff), and how the analysis of safety incidents and environmental life cycle accountability present a gap with serious and growing (relative to deployment capacity) implications. This set of observations lays the foundation for the critical claims of regulators in Chapter 6 and the proposed governance approach for battery life cycles in Chapter 8.

1.6 Research Objectives and Research Questions

The existing literature predominantly addresses safety and environmental sustainability as separate issues, with limited consideration of their interplay in grid-scale BESS. This thesis is inspired by the fact that the safety and environmental aspects of grid-scale BESS deployment are intrinsically connected to each other but separated research communities, standards, and regulations. The main objective of this research is to fill in the gaps by providing an integrated and lifecycle-oriented approach to analyzing the safety issues that arise over the lifetime of the BESS, failure and accident mechanisms, safety mitigation strategies, and safety standards and regulations with regards to effects on the environment and lifecycle sustainability.

Central research questions are as follows:

(1) What is the safety issues associated with grid-scale lithium-ion Battery Energy Storage Systems (BESS), and what is their interplay with the critical material supply chain and battery manufacturing, the use phase, and end-of-life, including recovery after incidents?

2) What is the influence of failure mechanism interactions and electrochemical, thermal, electrical, and operational cascading effects on the risk profile of large-scale systems, and how can cascading failures affect the life cycle environmental impacts and sustainability?

(3) What mitigations are in place across the BESS safety architecture (cell, module, BMS, thermal management, installation, etc.), and how effective are they? Where are the evidence and governance gaps related to the current mitigations?

(4) How can the aspects of lifecycle assessment and environmental impact be incorporated into certification or operational standards, or incident reporting to improve safety governance?

These questions are designed thematically to explore the problem (question 1 and 2, technical and empirical analysis in Chapters 2, 3, and 7), assessment of current response (question 3, Chapters 4 and 5), and translation into governance implications (question 4, Chapters 6 and 8). They jointly provide a more holistic analytical basis than previous reviews considering technical safety or environmental performance (often strongly focused on one or the other). This thesis addresses the resulting gap by treating safety and environmental performance as co-designed, co-implemented, and co-determined outcomes of operational, design, and governance choices.

1.7 Scope and Limitations of the Study

It should also be noted that this dissertation is specifically concerned with stationary lithium-ion battery energy storage systems (BESS) of grid scale connected to the electrical grid. Mobile battery applications, such as those found in electric vehicles, are excluded from this work as they have different regulatory requirements, mechanical injury profiles, and operating conditions that warrant specific treatment. Other battery chemistries such as solid-state and sodium-ion cells are explored tangentially in the instances when they help explain a concept or serve as a comparison to the overall lifecycle impact but are not examined in detail due to their limited stationary grid-scale deployment.

This thesis covers the full system from cell chemistry, module design, containerized installations, to grid-connected systems, including failure mechanisms, propagation, detection, suppression technologies, regulation, and cases of incidents. Lifecycle and environmental aspects are explored in each chapter as these strands are not separate but are being argued in this thesis as safety and sustainability mutually condition each other. This can be found in comparative chemistry in Chapter 2, emissions characterization in Chapter 3, design assessment in Chapter 4, suppression agent evaluation in Chapter 5, regulatory critique in Chapter 6, and incident consequences in Chapter 7.

The conclusions of this study should be interpreted in light of three key restrictions. Firstly, the study relies on qualitative literature review and analysis, without any new experimental research or data collection. The validity of the findings thus depends on the quality and comprehensiveness of published data. Secondly, the reviewed life cycle assessment data may have different system boundaries, functional units, and electricity mixes, making the comparison imprecise. The life cycle assessment data comparisons should be considered carefully, with methodological differences highlighted where relevant. Thirdly, battery chemistry and production technologies are rapidly evolving, so the conclusions reflect recent technological and regulatory trends at the time of writing. This is particularly true for Chapter 6, which considers the EU Battery Regulation and other recent regulatory frameworks. To wrap up, the study has critically reviewed a broad spectrum of recent literature to synthesize various aspects of grid-scale lithium-ion battery safety and sustainability.

A final observation from the literature review relates to the relative lack of integration between safety and sustainability across the lifecycle. In other words, while there is research on the safety risks and environmental impact of batteries from BESS, they are somewhat disparate and do not explicitly examine the role of safety performance in achieving sustainability throughout the lifecycle of BESS. For instance, while adverse safety events such as thermal runaway at the cell level and battery management system failures at the system level are well understood to damage the environmental potential of batteries in BESS by reducing their lifetime, recovering materials, and causing environmental harm through toxic emissions, its conceptualization in the context of designing for and measuring sustainability was not found in the literature. This research addresses this gap in knowledge by exploring how safety, typically an external consideration to sustainability, factors into the lifecycle sustainability of grid-scale BESS.

1.8 Structure and organization of the Thesis

The thesis has been structured to gradually build up from the fundamental concepts to the technical and empirical analysis, to the regulatory critique and synthesis. Each chapter acts as an analytical contributor to an overall story, linking failure mechanisms, mitigation strategies, regulatory frameworks, and the lifecycle sustainability in an integrated and non-overlapping way. Table 1 provides an overview of the scope of each chapter and its respective contribution to the lifecycle and environmental analytical thread of the thesis.

Table 1. Thesis Structure and Chapter Contributions to the Lifecycle–Safety Analytical Framework

Chapter	**Title**	**Principal Focus**	**LCA / Environmental Contribution**
1	Introduction	Context, motivation, research objectives, and thesis structure	The thesis's central analytical approach regards safety as an integral part of the lifecycle.
2	Fundamentals of Grid-Scale BESS	Architecture, chemistry, applications, and operational principles	At the outset, issues tied to chemistry-related LCA trade-offs, manufacturing burden, and operational degradation as a pivotal environmental factor were introduced.
3	Safety Challenges	Thermal runaway, fire, explosion, electrical, and Chemical hazards	Incident emissions associated with the life cycle assessment (LCA) of the agents are also issues of concern. In addition to potential controversy over environmental impact for production and use of the suppression agents, there is the possibility of contamination during disposal or other end-of-life considerations.
4	Mitigation Strategies Design	Battery pack/Battery management system (BMS) system integration design, thermal management, overall system level integration.	Selection of chemistry, EOL recyclability, auxiliary energy use, passive material lifecycle costs.
5	Mitigation Detection, Suppression, and Safety Architecture	Means of detection, suppression systems, safety barriers	Linguistic contamination; training data policies; environmental responsibility after accidents
6	Safety Standards and Regulations	International standards and regional regulatory frameworks	Governance gaps in LCA disclosure, EOL management, and toxic emission characterization
7	Case Studies of Major Incidents	McMicken, South Korea, Victorian Big Battery, Beijing, Liverpool, Moss Landing	Environmental and broader lifecycle implications related to materials are present in the incidents discussed above.

8	Integrated Safety–Sustainability Framework	Synthesis and recommendations	Lifecycle-integrated safety governance model for industry and policymakers
9	Conclusion	Summary, limitations, and future research directions	Research contributions and lifecycle governance agenda for future work

LCA = life cycle assessment; EOL = end-of-life; BMS = battery management system.

Chapter 2 establishes the technical context of the grid-scale BESS architecture with the physical, chemical, and control layers, along with the impact that chemistry selection, operational application, and degradation have on the BESS lifecycle. Chapter 3 presents the primary safety hazards (thermal runaway, fire and explosion, electrical hazards, chemical contamination) from the perspective of the overarching safety and lifecycle impact, with the emissions, contamination, and destruction of materials each hazard type entails. Chapter 4 discusses the mitigation approaches at the cell and module, battery management, thermal management, and system design levels, including their safety efficacy and environmental costs and gaps. Chapter 5 covers the operational layer (detection and suppression technology, integrated safety approach) with the lack of coordination and onboard strategies and gaps in the post-incident environmental management and training data for advanced detection.

Chapter 6 examines international and regional regulations and standards, making a critical comparison highlighting the lifecycle and environmental management oversight in common across all major sets of regulations. Chapter 7 provides a narrative explanation of safety incident management in three sets of cases—McMicken, South Korea, and the Victorian Big Battery; and Beijing, Liverpool, and Moss Landing—centering on the environmental and lifecycle impacts that incident-driven safety management largely overlooks. Chapter 8 provides a summary of findings in Chapters 2 to 7 and an integrated safety–sustainability framework with recommendations for industry and regulators.

Chapter 9 provides a summary of the research contributions, limitations of the study, and the most important recommendations for future research.

The structure provides a logical flow from an understanding of the technical and lifecycle nature of individual failure mechanisms, to the current state of mitigation and governance, to the wider lifecycle and regulatory context of the needs of a responsible deployment of grid-scale BESS. The individual chapters progress the discussion, rather than cover the same ground, keeping a narrative thread of lifecycle and environmental aspects that link technical safety analysis to sustainability governance.

2 Fundamentals of Grid-Scale Lithium-Ion Battery Energy Storage Systems

2.1 Overview of Grid-Scale BESS Architecture

A grid-scale lithium-ion battery energy storage system (BESS) is a cyber-physical system comprised of chemical, thermal, mechanical, and control layers that are closely coupled. Unlike consumer battery applications, a grid-scale BESS contains tens of thousands of cells that are hierarchically organized, whose system-level characteristics should not be inferred solely from the characteristics of an individual cell (Fantham & Gladwin, 2020).The aforementioned characteristics form the contextual backdrop in understanding failure propagation, lifecycle environmental impacts, and the intersections of safety and sustainability.

The physical hierarchy is as follows: cells, modules, racks, containerized enclosures, and then site level. At the cell level, manufacturing differences in capacity, internal resistance, and self-discharge rate in tens of thousands of cells lead to electrochemical imbalance that would eventually, if not constantly monitored, result in safety-related issues (Fantham & Gladwin, 2020). This point is critical as it highlights the manufacturing quality perspective, i.e. the tighter the tolerances of the cells at the manufacturing stage, the lesser the risk during operation, but with potentially more energy-intensive manufacturing processes. The energy cost of increased uniformity at the manufacturing stage against the benefits of reduced risk and increased life during the use stage is an interesting perspective that is seldom explored in the literature.

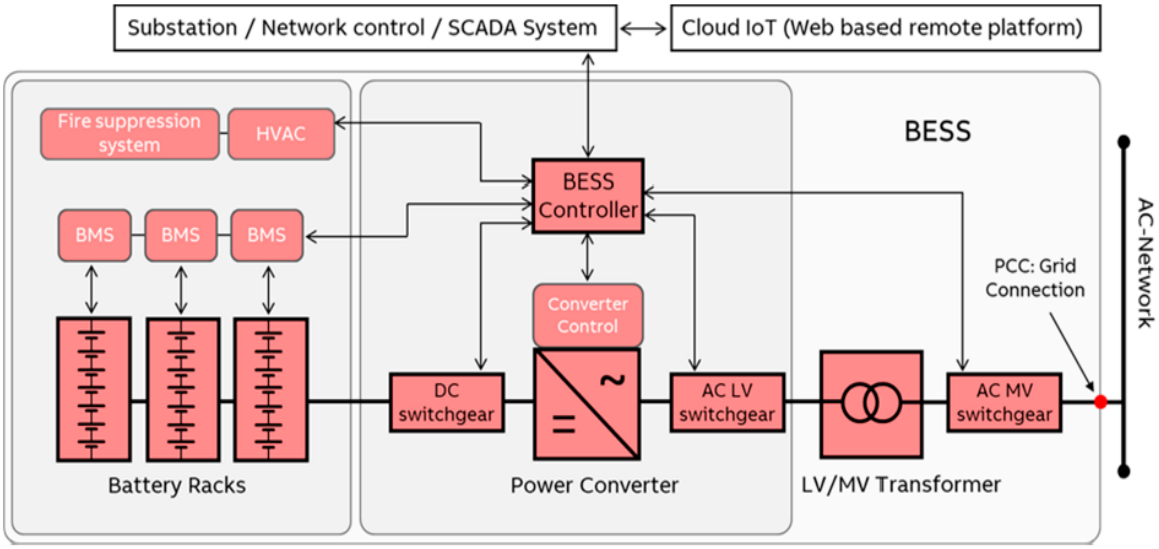

Figure 1: Architecture of a typical BESS in connection with the grid (W. He et al., 2024)

Protection circuitry, sensors, and thermal management are contained in modules at an accessible scale. Racks are the electrical unit of a grid-scale installation and share a common DC bus at high voltage. Faults are usually detected by protection schemes at the rack scale(McKinnon et al., 2022) ,but the arrangement of its constituent parts affects the airflow and heat distribution, which influences the propagation of faults, and is a design parameter that directly impacts the environment if it leads to premature degradation of the system life cycle.

The use of containerized enclosures is also a safety design approach that impacts the environment. The containment of space within the enclosure allows flammable and toxic gases to build up within the enclosed volume as a result of cell venting, adding the risk of explosion that would not typically be present if this was in the open air (Baird et al., 2020). But, this also provides a suppression and containment boundary in order to reduce the environmental impact. One of the key aspects to consider with respect to the choice of suppression agent is the balance between efficacy, in terms of controlling incipient fires, and atmospheric global warming potential, particularly for halocarbon agents, that is not always considered in the safety analysis but is an important environmental lifecycle choice.

BMS ensures the safety of the installation by always monitoring the voltage, current, temperature, and operating limits(Gabbar et al., 2021) .The BMS also estimates the battery's SoC and SoH, which are not directly measurable quantities(Şen et al., 2024) .Model-based algorithms are employed to estimate these quantities from measurable signals. The accuracy of these estimations deteriorates over time as battery cells age. Erroneous SoC estimations can have safety implications. Overestimation of SoC can cause overcharging, leading to unwanted electrochemical reactions. Underestimation of SoC can cause irreversible damage to the battery structure and electrodes. Aged battery cells produce an environmental impact by shortening the effective life of the battery as well as by reducing the amount of energy produced for every unit of embodied carbon in battery manufacturing (Christensen et al., 2021) .Fioravanti et al. (2020) propose that a majority of incidents on fielded battery cells are due to deterioration and inadequate monitoring for early detection rather than manufacturing defects. Rosewater et al. (2020) show that dangerous control actions can occur due to software bugs and communication errors even with individual hardware components functioning correctly. The above works argue that BMS is an integral construct for safety and sustainability, and existing practices do not adequately consider this.

Safety concerns can be directly related to temperature management. A temperature variation as small as 5 °C in the battery pack is sufficient to cause capacity degradation due to non-uniform aging and stress within the battery (Olabi et al., 2022). To manage the temperature inside the battery pack, many techniques can be used. The most used approaches are air cooling, liquid cooling, phase change material, or heat pipe. All these techniques have advantages and disadvantages concerning the working temperature and maintenance of the battery pack. For example, liquid cooling can be more effective in heat transfer and temperature distribution, but it can increase the complexity and maintenance of the system. Phase change material can help absorb heat passively, but more studies are needed to understand its behavior in extreme abuse conditions(Calborean et al., 2025) .Choosing one of these techniques can have lifecycle impacts due to the effect on energy consumption, maintenance, and the environmental impact of the coolant over the system lifetime, which is rarely considered in comparisons for safety analysis.

The power conversion system (PCS), which connects the battery bank to the AC grid, is another potential source of ignition. Electrical faults in power electronics (insulation fault, switching fault, inverter fault) are reported as the causal factor for BESS accidents, and the high DC voltage at grid-scale increases the impact of the fault. Plus, the converter topology influences the conversion efficiency and the usable battery capacity, affecting both economic and environmental aspects of the entire life cycle (Liu et al., 2022; Stecca et al., 2020) .These four layers are interdependent; if one fails, it leads to failure in the others in various sequences depending on how well they are designed, coordinated, and maintained. The most relevant design decisions for the safety and sustainability of grid-scale BESS (Battery Energy Storage Systems) are made at the architectural level, where electrochemical, thermal, control, and power conversion aspects interact.

2.2 Lithium-Ion Battery Chemistry: Comparative Safety and Lifecycle Analysis

The lithium-ion battery chemistry has a significant influence on the safety and sustainability characteristics of a grid-scale BESS. While the benefits of lithium-ion batteries (high energy density, long cycle life, low self-discharge) are generally acknowledged, these performances can vary with different chemistries. Battery cathode materials are known to have varying thermal and degradation characteristics as well as different environmental impacts and recycling potentials(Kiemel et al., 2021).Hence, the choice of the chemistry should be considered based much broader considerations than the ones used to rank their performances. From a chemistry perspective, the safety properties (for example, thermal stability) influence the environmental performance throughout the lifecycle based on degradation rate, criticality of the material, and management of the product after use.

The three chemistries predominantly used for grid-scale applications are nickel manganese cobalt (NMC), lithium iron phosphate (LFP), and nickel cobalt aluminum (NCA). Koech et al. (2024) showed that NMC and NCA chemistries offer higher energy density, but they have higher thermal risk and critical material reliance; in contrast, Yu et al. (2023) showed that LFP has higher thermal resistance, a longer cycle life, and better abuse tolerance. Hence, for stationary grid-scale applications where space is not as constrained as in other applications, the prevalent use of LFP shows that cycle life and thermal safety are prioritized over energy density.

From a lifecycle viewpoint, LFP is not always the preferred chemistry. Le Varlet et al. (2020) concluded that use conditions, lifetime, and recycling scenario mainly govern environmental performance rather than chemistry selection, and Kiemel et al. (2021) showed that a material criticality assessment based on concentration in supply and geopolitical risk makes NCA the least robust and LFP the most robust option. LFP cells have lower energy density, which would require more massive cells per equivalent storage capacity, potentially increasing the manufacturing impact per kWh.

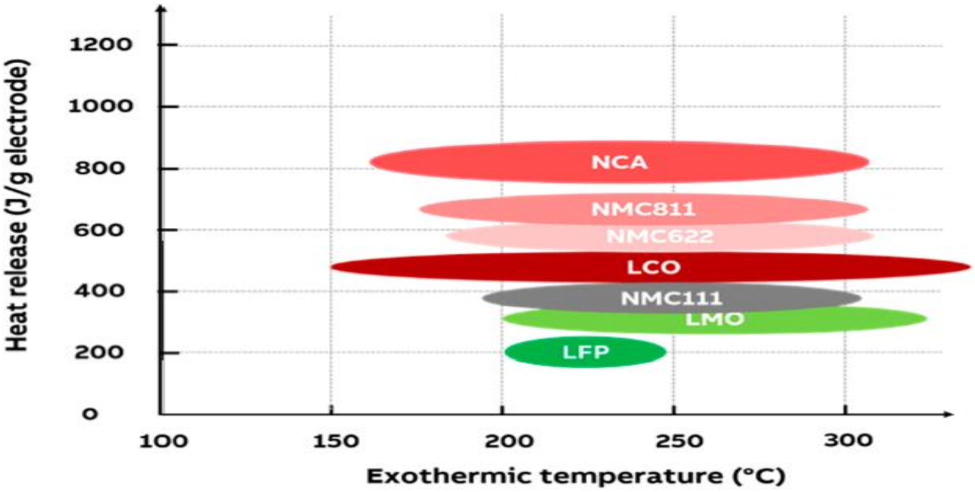

Figure 2: Exothermic onset temperature and heat release by cathode chemistry (W. He et al., 2024).

While safety and lifecycle perspectives from these two research fields LCA and safety studies are both pivotal, there is an absence of research that synthesizes these perspectives. For example, safety studies mostly focus on abuse tolerance and thermal runaway thresholds, while LCA studies focus on manufacturing emissions, resource use, and recycling efficiency. The chemistry comparison from Chapter 2 illustrated that these same susceptibility factors will also contribute to greater environmental impact. A higher susceptibility translates to more incidents, more dangerous discharges, and more challenging recycling, indicating that these consequences are closely correlated and cannot be independently optimized. A brief comparative summary of the three dominant chemistries is shown in Table 2 with regard to performance, safety, and lifecycle aspects combined, i.e., the selection criteria typically treated separately in the literature.

Parameter	**NMC**	**LFP**	**NCA**	**Safety Implication**	**LCA Implication**
Energy Density	High (150–220 Wh/kg)	Moderate (90–160 Wh/kg)	High (200–260 Wh/kg)	Higher density → narrower thermal safety margin	More kWh per kg → lower system-level burden
Thermal Stability	Moderate	High	Low–Moderate	Stability ↑ = runaway risk ↓	Stability extends service life → better GWP amortization
Cycle Life	1,000–2,000	3,000–6,000+	500–1,500	Longer life → fewer replacement incidents	More cycles → lower GWP per kWh delivered
Cobalt Dependency	High	None	High	Supply disruption risk; mining hazards	High extraction burden; geopolitical fragility
Nickel Dependency	High	None	Very High	Processing emissions and health risk	Energy-intensive refining; toxicity burden
Critical Material Risk	High	Low	Very High	Supply chain resilience	Material scarcity drives lifecycle cost

Thermal Runaway Risk	Moderate–High	Low	High	Direct incident probability	Fire emits HF, CO_2; soil/water contamination
LCA GWP (manufacturing)	High	Moderate	Highest	Embedded carbon payback period	Dominant lifecycle phase for all chemistries
Recyclability	Moderate	Improving	Moderate	End-of-life hazard and recovery	Closed-loop recovery reduces primary demand
Suitability for Grid-Scale	Limited	Preferred	Limited	Overall risk/benefit balance	LFP optimal when LCA + safety integrated

Table 2. Comparative overview of NMC, LFP, and NCA chemistries for grid-scale BESS: integrated safety and life-cycle assessment perspective. Sources: Kiemel et al. (2021); Koech et al. (2024); Le Varlet et al. (2020); Yu et al. (2023)

Ultimately, the synthesis for grid-scale systems cannot afford to be an a priori choice based on the chemistry' potential to offer the greatest lifecycle sustainability. The chemistry chosen for the sake of delivering more energy without significant consideration to further explore the thermal hazards to provide immediate cost more sustainable impacts may put future systems under scrutiny and doubt the systems sustainability. For stationary batteries connected to the grid, energy density should not be the most decisive property compared to thermal hazard, cycle life, sustainability of life cycle(Xie et al., 2020).

2.3 Applications of Grid-Scale BESS: Operational Profiles, Safety Risk, and Lifecycle Implications

Grid-scale BESS perform several key functions within the power system, including frequency regulation, peak shaving, and renewable energy integration. While these functions are well known, their safety and life cycle aspects are not. How the BESS is used (depth of discharge, cyclability, and assigned functions) affects its rate of degradation, thermal risk, and the resulting payback of the high embodied energy used in production(Zhao et al., 2023) .Hence, this section discusses the key functions one by one, highlighting them from a safety and sustainability perspective.

Frequency regulation is the most battery-intensive application. As more wind and solar replace synchronous generators, inertia will be lowered and the system frequency will change more rapidly following disturbances (Hasan et al., 2024) .BESS can respond by injecting or absorbing active power within milliseconds. In addition to providing primary frequency response, BESS can also provide synthetic inertia(El-Bidairi et al., 2020). Hasan et al. (2024) argue that BESS frequency regulation ability significantly supports grid stability, while Wang et al. (2022) illustrate that the same BESS frequency regulation ability directly incurs electrochemical cost as frequent partial cycling at high power rates accelerates battery degradation through lithium plating, stress on battery separator, and electrode fatigue. The electrochemical degradation mechanisms that contribute to battery failure also increase vulnerability to thermal runaway, implying a heretofore unreported relationship between frequency regulation demands and battery safety. Frequent battery use at high power rates not only decreases the period over which the manufacturing carbon is amortized but also leads to a decreasing thermal safety margin. Conventional life-cycle assessments do not report this interaction as the frequency regulation operational profile is not indigenized.

Peak shaving may induce a less severe cycling task but can generate a different lifecycle tension. The aim of peak shaving is to charge the BESS in off-peak hours and discharge it when there is a peak demand, thereby reducing the need for power infrastructure investment and deferring grid upgrades. While the economics are clear, both independently note that control strategies based solely on economic returns without considering the stress on battery cells can hasten the aging of the battery and increase the chance of fire incidents. These peak shaving batteries may need to be replaced much sooner than expected, so not only is there an economic loss, but there is also an inadvertent environmental impact due to increased production and eventual disposal a notion that is contrary to the ethos of sustainability mentioned above.

BESS are often cited as being deployed for the purpose of improving sustainability in terms of integrating renewable energy. Based on these findings, Behabtu et al. (2020) and Worku (2022) concluded that BESS promotes the penetration of renewable sources by disconnecting energy generation and use. Also, Atawi et al. (2022) showed that no single battery chemistry optimally overcomes the trade-off among power density, energy density, and dynamic response, and hybrid storage systems with different chemistries provide a better alternative. If a power system supports renewable generation and is otherwise working but it is driven to an early death due to aggressive usage, thermal management, or lifecycle management, then it cannot be considered as sustainable as it could be. The lifecycle value of a BESS to any renewable integration scenario is closely related to safety recommendations and operational strategy.

Table 3 provides a comparative synthesis of principal BESS applications, their operational cycling demands, associated degradation and safety risks, and their environmental burden profiles.

Application	**Cycling Demand**	**Degradation Risk**	**Environmental Burden**	**Safety–Sustainability Nexus**
Frequency Regulation	Very High (sub-second)	High	High	High – aggressive partial cycling accelerates degradation and thermal risk
Peak Shaving	Moderate (minutes–hours)	Low–Moderate	Moderate	Medium – optimizing the sizing is critical to avoid premature ageing.
Renewable Integration	Variable (hours)	Moderate	High	Medium – stochastic cycling; sustainability contingent on complete lifecycle management

Voltage Support	High (reactive, fast)	Moderate	Low	Low–Medium – predominantly reactive power; lower thermal impact
Black Start / Islanding	Moderate	High	High	If limited by the BMS, deep discharge events of a high battery increase the probability of runaway.

Table 3. Comparative analysis of grid-scale BESS applications: operational profiles, safety risk, and lifecycle environmental implications. Sources: Hasan et al. (2024); Rocha et al. (2022); Worku, (2022); Zhao et al. (2023).

An overall gap presented in all three application-specific categories is the lack of standardized approaches to quantifying the environmental cost of battery degradation over the lifecycle of the targeted application. While the existing technical standards and commercial frameworks consider the propulsion battery degradation as a factor that implements the revenue flows, a safety-LCA approach would explore how the degradation rate influences the incident probability as well as the environmental efficiency, both of which should be optimized together rather than separately.

2.4 Operational Principles of Large-Scale BESS: Multi-Objective Management and Lifecycle Consequences

The operational considerations of a large-scale BESS are not limited to simple charge and discharge logic. For power systems with reducing inertia and a high share of renewable energy, grid-scale BESS should be able to respond to multiple simultaneous timescales and always consider battery health to operate in a safe zone (Aryani et al., 2022). This has implications for both safety and sustainability of battery life that traditional operation does not consider.

The primary operational challenge at grid scales is tractability. Large-scale BESS are not managed optimally at a cell level, leaving localized states of charge and temperature stress levels unchecked (Farakhor et al., 2024). The gap between design intent and operational reality persists as hierarchical optimization methods progressively sacrifice optimality, each carrying direct lifecycle implications. Sub-optimal management at a cell level hastens unbalanced degradation, ultimately shortening the battery's service life and increasing the risk of localized overheating. Each shortening of the service life reduces the time to amortize the environmental costs of manufacturing, directly impacting subsequent deployment sustainability gains.

The intermittency of wind creates the need for flexible reserves that can quickly substitute for imbalances in generation and load in renewable-infused systems, further complicating the operation. While Chaudhary et al. (2021) highlight the importance of coordinated control strategies in energy management systems for micro grid stability, Ramos et al. (2022) identify lack of coordination in the control layers of storage and generation as a contributing factor in incidents. These authors highlight that the safety risk of grid-scale BESS is as much a control system challenge as it is an electrochemical one. Rosewater et al. (2020) elucidate these challenges through system-theoretic hazard analysis, showing that unsafe control actions can result from the interaction of components that are individually working as intended, which is not possible to capture with traditional reliability analysis.

All operations of the BESS are controlled by the BMS, monitoring SoC, depth of discharge, temperature, and SoH to ensure safe operating ranges and to maintain cycle life (Rouholamini et al., 2022) .Operation strategies that priorities short-term financial benefits over battery health and involve aggressive charging and discharging reduce the safety margin of battery temperature and induce faster degradation. Also, the environmental impact increases non-linearly with operational intensity — a BESS that is aggressively used and pushed to the boundary of its safe operating range may be optimized for life-cycle cost in the short term but causes more frequent replacement and extends environmental impact. Hence, from a safety and sustainable life-cycle perspective, operational management strategies cannot be decoupled — any such framework will fail to capture the complete picture.

2.5 Safety-Relevant Characteristics of Grid-Scale Installations: Environmental Dimensions

The safety risk characteristics of lithium-ion BESS at the grid scale are qualitatively different from smaller scales. Several features of large-scale BESS lead to risk scenarios that are not considered when analyzing risk at the cell or module level, and each of them comes with environmental implications associated with them.

They have a massive energy capacity; therefore, if only a small proportion of the total battery systems fail, they produce heat and gaseous products that cannot be contained within one enclosure. The tight packing of cells in containerized batteries shortens the heat transfer path between cells and enhances the propagation of thermal runaway, which becomes more difficult to suppress. Thermal runaway events are not just safety risks but environmental contamination events. Larsson et al. reported the release of poisonous fluoride gases during the combustion of lithium-ion batteries. Recent studies have reported the heat release and smoke gas emissions for the entire range of battery chemistries. The environmental aspects of these emissions are very different from the safety analyses primarily intended to protect the fire-fighting crew and the surrounding residents. The long-term consequences of atmospheric release of HF and other reactive gases, the soil and groundwater contamination from water runoff during fire suppression, and the persistence of cathode materials in the contaminated sites are lifecycle environmental burdens that current LCA methodologies do not incorporate due to these effects being considered low-probability tail events rather than a firmly expected consequence of battery aging.

The behavior of the control system also has impact. Rosewater et al. (2020) show evidence from system-theoretic hazard analysis of unsafe control actions arising from interactions between intended functioning components, which is safety and risk relevant.

Communication failures, software faults, and unanticipated discrepancies between BMS control logic and battery conditions have led to situations where the protective system appeared to work but did not operate as intended. Fioravanti et al. (2020) attribute most incidents in the field to wear, misuse, and lack of observation, as opposed to production faults, implying the need for safety testing and assurance that tracks the change in battery characteristics over time, rather than the use of design parameters based on the beginning-of-life test data. This has implications for the environment; safety testing and assurance that tracks the change in battery characteristics over time will extend the life of one unit, thus delaying the need for replacement and the associated risk to the environment as compared with a safety testing and assurance framework that is not.

Another example of the intersection between safety and risk to the environment is the handling of batteries when they reach end-of-life in installed systems. Hwang et al. (2025) showed that susceptibility to thermal runaway increases as batteries age from beginning-of-life to end-of-life, while Christensen et al. (2021) demonstrated that this evolution creates a compounding lifecycle risk management challenge throughout the electric vehicle and stationary storage value chain. The challenge for grid-scale BESS is that end-of-life conditions manifest individually and heterogeneously across tens of thousands of cells, and identifying individual cells or modules that are approaching potentially unsafe levels of degradation is a monitoring challenge. Systems that are not able to monitor for these conditions and identify them in advance create a risk of safety that is also a risk to the environment: the risk that end-of-life failure modes happen by accident instead of being planned for, causing the emissions, contamination, and loss of materials that are characteristic of thermal runaway events.

Taken together, the safety-related attributes of grid-scale systems highlight that there is a lack of an integrated analysis framework that considers safety risk, operational performance degradation, and lifecycle environmental impacts as they relate to harmony among system design and operational decisions. State-of-art analysis frameworks cover one or the other with technical credibility but not with extensive interactions, which ultimately matter for the safety and sustainability impacts of deployed grid-scale BESS.

3 Safety Challenges in Grid-Scale BESS — Environmental and Life-Cycle Dimensions

3.1 Thermal Runaway and Thermal Hazards

Thermal runaway is the primary safety concern for lithium-ion BESS and has the most direct life-cycle environmental impact. Thermal runaway is a self-propagating failure sequence where heat generated within the cell surpasses the heat dissipated by the cell, triggering a chain of exothermic decomposition reactions that progressively become more difficult to stop(Feng et al., 2018) .The main life-cycle risk of thermal runaway is that it wastes the embodied environmental impact of the cell (energy, emissions, and other environmental impacts associated with lithium extraction, cathode synthesis, cell manufacturing, and transportation) and causes additional environmental effects of the release of toxic gases and contamination.

3.1.1 Mechanisms, Triggering Factors, and Life-Cycle Linkages

They proposed a thermal runaway reaction mechanism: SEI decomposition between 80 and 120 °C first exposes the litigated anode with the electrolyte; the separator melts at a temperature higher than this, leading to an internal short circuit; the cathode lattice oxygen release at a temperature above ~200 °C leads to the acceleration of electrolyte oxidation in an uncontrolled terminal stage. Feng et al. (2018) also pointed out that the most frequently cited cause for internal short circuit as the trigger condition. Of particular concern is that internal short circuit can be caused by manufacturing defects that are not measurable from outside and might go unnoticed for a long time before causing thermal runaway; such latent defects include lithium dendrite formation, metallic particle contamination, and micro perforation of the separator.

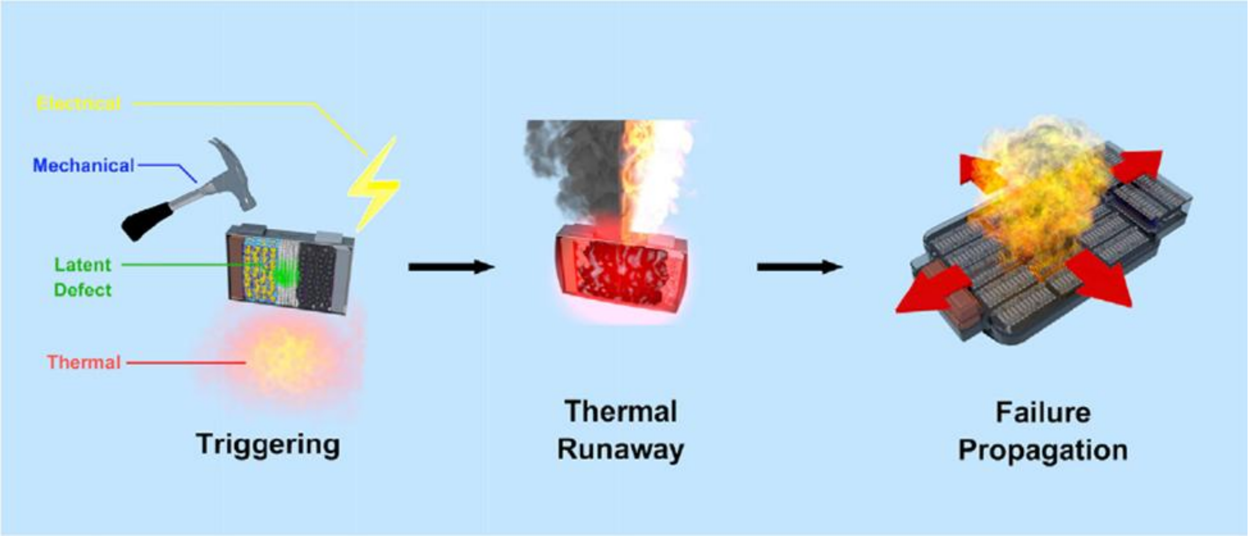

Figure 3: Typical thermal runaway failure sequence in lithium-ion BESS (Feng et al., 2020).

Philosophically similar to Feng et al., Galushkin et al. (2018) study thermal runaway initiation in a thermochemical perspective and conclude that high state of charge and the battery's cycling history both independently contribute to lowering the temperature at which exothermic reactions of electrolyte with cathode happen. While Feng et al. classify triggering events based on external conditions such as mechanical, electrical, or thermal, Galushkin et al. argue that the battery's current and prior usage (operating) history is equally important in predicting its vulnerability; this distinction has important ramifications for safety management at all stages of the battery life cycle.

This life-cycle dimension is rarely discussed. Consider that the faulty cell bears the full manufacturing emissions equivalent to 60–100 kg of CO2 per 1 kWh of storage capacity for NMC chemistries(Le Varlet et al., 2020) but does not provide any service before incurring the toxic emissions from failure. Liao et al. (2020) observe that the maximum temperature in thermal abuse triggered at high SOC is above 850 °C compared to significantly lower maximum temperatures at lower SOC values. Hence, grid-scale battery packs that remain at high SOC for immediate dispatch to the grid will likely incur more severe outcomes.

3.1.2 Propagation and Chemistry-Dependent Environmental Emissions

Propagation from the cell to the system level represents the safety risk in the grid. Wilke et al. (2017) identify temperatures in individual cells of close to 700 °C in open-air runaway, and even higher in confined accumulation scenarios. Propagation by conduction, convection, and radiation is demonstrated by Karmakar et al. (2024), where the thermal runaway of one cell generates enough heat to initiate a neighboring cell. Extending this analysis, McKinnon et al. (2022) ,based on full-scale UL 9540A tests carried out in a 6.06 m ISO container, show that propagation can generate flammable concentrations of gases which can create an explosion hazard, making it a coupled thermo-chemical, fluid dynamic phenomenon as opposed to being an individual cell phenomenon.

The toxic emission characteristics of these events are critical from an environmental and human health standpoint. Key toxic emissions were identified by Rappsilber et al. (2023) in their meta-analysis of available literature as being hydrogen fluoride (HF), carbon monoxide (CO), hydrogen cyanide (HCN), and volatile organic compounds (including benzene).Larsson et al. (2017) quantified emission yields of HF as 20–200 mg per Wh of nominal capacity, identifying fluorinated electrolyte salts (mainly LiPF6) as the main culprits. Extrapolating to a grid-scale battery pack, this equates to a discharge of several kilograms per incident. Larsson et al. (2017) argue that the toxic risks from emissions can supersede the risk from intense fire itself, a claim that while broadly true according to Rappsilber et al. (2023), is strongly dependent on cell chemistry and SOC. For example, the inherently higher nickel content in NMC cathode materials yields harsher emission results compared to LFP cells, a comparison that highlights the connection between cell chemistry selection and environmental/public health risk, which is currently absent from battery incident databases.

Thermal runaway events can also contribute to environmental effects beyond direct safety risks. Byproducts of combustion such as HF, HCN, and heavy metals from cathodes can seep into the soil and contaminate water runoff. Austin Zhang (2025) reported the results of comparative lab study into the effects of lithium and nickel—chemicals released from battery waste—on seed germination. Increasing concentrations resulted in seed growth suppression and eventually complete crop failure. Currently, there are no international standards that require environmental testing as part of the investigation following an incident involving a BESS. This gap in the regulation can have a compounding effect as installations increase.

3.2 Fire and Explosion Risks

3.2.1 Flammable Gas Generation and Deflagration Hazards

One of the most concerning escalation mechanisms in failing grid-scale BESS is the generation of flammable gases, which carries with it environmental hazards beyond that of fire alone. Rappsilber et al. (2023) quantified that total gas volumes vary between 3–48 mmol/Wh depending on chemistry, SOC, and the cell format, while Mylenbusch et al. (2023) proved that within this mixture, hydrogen is disproportionately dangerous due to its wide flammability envelope and very low ignition energy, a finding also emphasized by Baird et al. (2020) who showed that hydrogen and carbon monoxide levels rise with SOC, while carbon dioxide declines, making high SOC both the most useful and most explosively dangerous state of charge. Making the most-useful state of the battery from an operating perspective (higher SOC to deliver on-demand power to the grid) the most dangerously flammable.

Another problematic aspect of the delayed ignition is the potential for unintentional ignition during this period. Rappsilber et al., (2023) observed that even after flames were suppressed, gas continued to flow for hours, creating a risk of explosion after the initial fire that is not normally considered. An identified risk of explosion associated with enclosed BESS is the buildup of gases leading to delayed ignition, which has been the cause of several explosions in the past (refer to Chapter 7). McKinnon et al. (2022) showed that the flammable gas concentration reaches an explosive level prior to ignition, whereas Baird et al. (2020) showed that the ensuing deflagration, although subsonic, produces enough overpressure to cause the container walls to burst and spread the fire to adjacent containers, thereby escalating a cell incident to a site incident.

3.2.2 Fire Suppression: Comparative Effectiveness and Environmental Trade-offs

The challenges in extinguishing lithium-ion batteries have been summarized as a mismatch between traditional fire suppression methods and the battery chemistry, which provides an internal source of heat through decomposition. Xu et al. (2020) conducted a comparative analysis of CO_2 and halogenated fire extinguishing agents such as HFC-227ea and water-based products. They found that CO_2 and halocarbons effectively suppress visible flames but do not provide sufficient cooling to prevent re-ignition because decomposition inside the cell continues independently of whether the flame is sustained on the outside of the cell or not. Water mist has a superior ability to absorb heat ("cooling effect") but can be dangerous if used on energized batteries, while Majeed et al. (2024) point out that the cathode releases oxygen at higher temperatures, which can negate the efforts to prevent ignition by applying free or bound oxygen in the environment. This is one of the key reasons why inert gas may not be fully effective. Once a lithium-ion battery fire has been suppressed, there is still a risk that it may re-ignite.

Another important aspect of choosing the suppression agent is how it impacts the environment. While HFC-227ea is highly effective at suppressing flames, its global warming potential is tens of thousands of times more than CO_2, and that is rarely considered in the design of safety protection systems for BESS, as mentioned by Fei et al. (2026) in their review article. Water-based suppression systems do not have this issue but will result in contaminated water runoff that may contain dissolved battery chemicals leaching into the soil or drainage systems. To the best of the author’s knowledge, there is no existing comparative analysis or life-cycle analysis study assessing the environmental impact of different suppression systems, and this is worth further investigation.

3.3 Electrical Hazards

Electrical hazards in grid-scale BESS are just as important — if not more so — than thermal runaway, as they are the causes of thermal runaway. They also have life-cycle dimensions that standard electrical safety procedures fail to acknowledge.

One of the most significant electrical abuses is the overcharging of a battery. Zhang et al. (2021) showed that moderate overcharge irreversibly damages the structure of the cathode, accelerating subsequent degradation in NMC chemistries, while Hwang et al. (2025) showed that it is true for the entire life of the battery, where electrochemical abuse accelerates degradation and the risk of thermal runaway increases non-linearly as the battery ages from BOL to EOL.

Internal short circuits pose a different detection challenge. Guo et al. (2026) highlight that the same aged cells with detected internal defects exhibit indistinguishable behavior from healthy cells, meaning the defects will remain undetected by regular monitoring methods until the cell temperature starts to increase. This is not a shortcoming of existing methods that can be improved through research but a critical flaw in assuming the BMS monitoring and control hardware is enough to protect the battery pack. Edwards & Dobson (2025) emphasize this further from a high-voltage DC systems perspective, explaining that the battery modules remain energized after the battery pack is isolated from the grid, posing a potentially lethal hazard to service personnel and first responders.

The most severe and environmentally damaging manifestation of high voltage DC hazard is arc flash. Cabello et al. (2025) modeled the behavior of DC arcs in high-power systems and showed that these arcs do not self-extinguish at current zero, thus sustaining for a longer duration compared to AC arcs and resulting in an incident energy 2-3 orders of magnitude higher than the typically used formula for arc energy estimation. The environmental impacts of these arcs in terms of vaporized metallic contaminants and potentially chronic organic pollutants released due to insulation burning are currently not defined in the standard incident reports, which in the future will have a greater impact with increasing installed BESS capacity.

3.4 Chemical and Environmental Hazards

3.4.1 Toxic Gas Emissions and Life-Cycle Emission Accounting

The toxic gas risk presented by BESS thermal runaway events is surprisingly significant compared to the volumes of material in BESS cells and is yet to be fully considered in the context of the environmental life cycle. Larsson et al. (2017) highlight hydrofluoric acid (HF), phosphorus pentafluoride (PF5), and phosphoryl fluoride (POF3) as the most hazardous species, produced from LiPF6 thermal decomposition. They develop quantitative parameters for the release of HF in the range of 20 to 200 mg per Wh (milli-gram per Watt-hour), equivalent to multiple-kilogram releases at grid scales. Rappsilber et al. (2023) build on this early work and meta-analyze other thermal decomposition studies to highlight additional chemical release species including CO, HCN, and benzene (among a large number of carcinogenic and VOC species). While the first study focused on the fluorine chemistry, the second explores how the state-of-charge (SOC) and different chemistries influence total emissions, both providing quantitative relative measures that can inform operational domain safety. But, neither of these studies are considered in a life-cycle emissions perspective, i.e., emissions from the combustion phase of the thermal event are considered in standard BESS systems LCA.

Another facet is occupational health. Mylenbusch et al. (2023) highlight that prior to any dispersion, HF, CO, HCN, and hydrogen chloride within BESS containers can reach fatal concentrations, making regular emergency response to these fires impossible. Deposition of fine particulates with nickel, cobalt, and manganese (by burning anode/cathode active material) contaminates personal protection equipment, which can lead to continuous exposure and decontamination efforts, creating a public health impact that is not accounted for in the cost implications of a BESS incident.

3.4.2 Electrolyte Leakage, Soil Contamination, and End-of-Life Environmental Risks

Electrolyte leakage commonly occurs in conjunction with other BESS failure modes. Jeevarajan et al. (2022) report that off-nominal operation contributes to electrolyte leakage in addition to venting, fire, and explosion risks. At the grid-scale, leakage from minor per-cell spills can result in large volumes of organic carbonate solvents and lithium salts that spread to adjacent compartments and seep into structural and electronic components. Austin Zhang (2025) shows that lithium and nickel from spent batteries inhibit plant growth and seed germination at contaminant levels likely found in soil, with total crop death at higher concentrations - demonstrating the environmental hazards of contaminated BESS sites that are not currently part of incident consequence analyses.

The problem is aggravated by the end-of-life phase. Christensen et al. (2021) investigating risk management over the lifecycle of lithium-ion batteries, conclude that the environmental risk is amplified by the fact that end-of-life solutions for recycling cells are not yet developed, which could lead to discarded cells releasing electrode materials directly into the environment. NMC cells contain materials (cobalt, nickel) that are more critical for recycling than in LFP cells, which is preferred for safety reasons (lower risk of thermal release with LFP) but not for environmental reasons (NMC is more toxic if discarded into the environment).Le Varlet et al. (2020) ,comparing the life cycle environmental impacts of different cells in a stationary energy storage system, conclude that there is significant difference in the environmental impact, mainly related to end-of-life treatment, which needs to be further clarified.

Table 4. Failure Propagation Pathways in Containerized BESS and Environmental Consequences

Propagation Stage	Primary Mechanism	Environmental Consequence	Key Reference
Cell-level failure	Internal short circuit / overcharge	Embodied carbon loss; no service delivered	Feng et al. (2018); Zhang et al. (2021)

Cell-to-module	Conduction, radiation, convection	HF, CO, VOC gas generation begins	Karmakar et al. (2024); Larsson et al. (2017)
Module-to-rack	Hot gas movement; jet flame	Toxic plume formation; deflagration risk	Baird et al. (2020); McKinnon et al. (2022)
Rack-to-container	Gas accumulation; pressure build-up	Explosion; soil/water contamination	Mylenbusch et al. (2023)
Container-to-facility	Radiant heat; flaming debris	Multi-container loss; long-term site pollution	Lystianingrum et al. (2023)
Re-ignition (delayed)	Residual heat; trapped gas	Prolonged emission; responder exposure	Rappsilber et al. (2023); Wang et al. (2019)

Source: compiled from cited studies

3.5 Failure Mechanisms, Risk Propagation, and System-Level Dynamics

3.5.1 Failure Mode Patterns and the Early-Deployment Risk Window

Failure in grid-scale BESS can rarely be attributed to a sole cause, but rather multiple interactions among electrical, mechanical, design, and operational factors. Al-Mahmodi et al. (n.d.) report that 80 percent of BESS failures occurred within two years after deployment, with predominant contributing factors from this “early” window being integration issues, setup mistakes, and insufficient testing. Zalosh et al.(2021) verify that in incidents involving thermal runaway, root causes can interact, such as overcharging, ground faults, and cell voltage imbalance, and would not be anticipated in linear, single-cause analyses. The environmental implication of this "deployment" window for incidents is significant, for systems that fail have the entire environmental impact burden of manufacturing and installation with minimal use.

3.5.2 Operational History, Cascading Failure, and Re-ignition

After deployment, the operational history begins to impact the risk of failure. Galushkin et al. (2018) show that both SOC and cycling history independently reduce the thermal runaway threshold, with experiments confirming a nonlinear progression toward thermal instability. Grid-scale systems designed for frequent regulation services (deep and rapid cycling) will age faster than storage systems designed for buffering applications, leading to a heterogeneous risk profile within the same system that a unified protection approach cannot fully capture.

In containerized systems, cascading failure is the worst-case scenario. Mylenbusch et al. (2023) note that the modular, high-density configuration that makes grid-scale BESS economically feasible is a system design that enables cascading propagation, i.e., thermal radiation, flaming, and the pressure wave of explosion propagating from one container to many others. They further observe that with millions of cells in a single grid-scale BESS, a statistically rare single-cell failure is a near-certain event for the entire installation over its lifespan, emphasizing safety designers consider arresting propagation as the primary objective. Wang et al. (2019) identify re-ignition as an ongoing risk, wherein the internal decomposition progresses regardless of surface flame being quenched by way of self-sustaining sequential reactions in SEI, electrolyte, and electrode active materials.

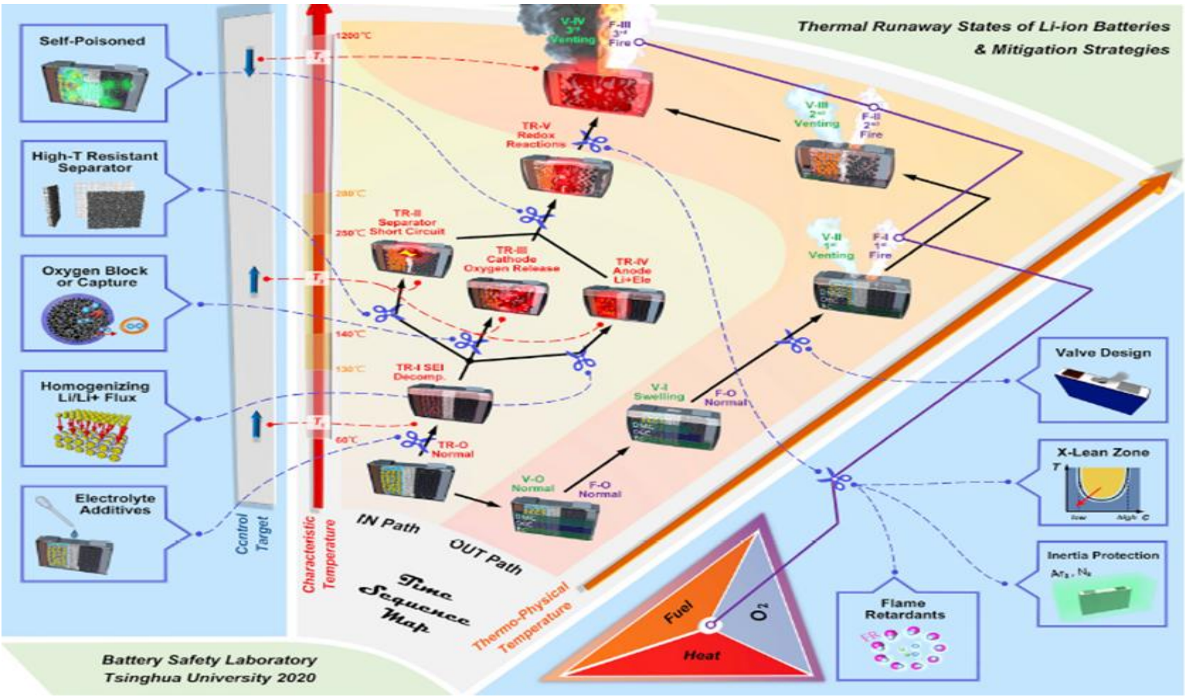

Figure 4: Thermal runaway timeline: internal reactions and external venting/fire pathways (Feng et al., 2020).

For a grid-scale BESS, this means that the compromised system can continue to be reactive for hours to days, a surveillance and response burden largely absent in most operational protocols.

3.5.3 Gaps in the Literature and Regulatory Frameworks

In summary, the body of work cited in sections 3.1–3.5 reveals three related literature and regulatory review gaps. First, the life-cycle accounting of the environmental impacts of BESS safety incidents is lacking in two respects. The first is the life-cycle assessment system boundaries of the now understood to be hazardous life-cycle phase of battery combustion (and related release of HF, heavy metals, and VOCs) are not considered within the system boundaries of the life-cycle assessment. And second, the environmental impacts of BESS safety incidents are not currently required and assessed within the standard reporting and investigative procedure and practice for those incidents, despite recent studies that can provide a foundation for understanding those environmental consequences (Austin Zhang, 2025; Larsson et al., 2017; Rappsilber et al., 2023). Second, the comparative environmental performance of different battery chemistry options as it relates to thermal safety and toxicological environmental impacts during end-of-life are treated as separate stand-alone topics within the literature. Aspects of comparative environmental performance between battery chemistry options can be found in Christensen et al. (2021) and Le Varlet et al. (2020). Third, the selection criteria for suppression system design do not currently account for environmental impacts. The trade-offs between HFC-based fire suppression agents, which have a high global warming potential, water-based suppression systems, which create contaminated runoff, and inert gas-based suppression systems, where there's a risk of re-ignition, have not been subject to comparative life-cycle assessment.

3.6 Summary

In this chapter, the key safety risks in grid-scale Li-ion BESS — thermal runaway, fire and explosion, electrical risks, and chemical contamination — are discussed from a holistic safety and life cycle perspective. It is apparent that these safety risks have environmental impacts beyond the incident itself: embodied carbon from manufacturing is lost with premature failures; toxic fumes and plume from fires are unaccounted for in the life cycle assessments; contamination of the environment with electrolyte and electrode materials have well-studied impacts; and there is an environmental risk tradeoff in the choice of fire suppression agents, which is unaccounted for. Chapter 3 further advocates for the concept of co-determination, with an essential empirical extension. It highlights that thermal runaways are safety events that are simultaneously lifecycle environmental events, entailing direct emissions, environmental contamination, and irrecoverable lost materials. These effects are outside the scope of traditional LCA methodologies. Mitigation strategies are discussed in Chapter 4.

4 Mitigation Strategies Design, Prevention, and Life-Cycle Integration

This chapter will discuss the main mitigation methods applied to safety issues presented in Chapter 3 (thermal runaway, fire and explosion, electrical hazards, and chemical contamination) at different levels of the BESS architecture: cell and module, management system, thermal control, system and installation level. We bring here a critical analysis of life-cycle environmental aspects and a literature review on evidence of real-case incident outcomes. The literature review here highlights a continuous disparity between design intent versus demonstrated performance, which is wider than what the regulatory landscape considers.

4.1 Cell- and Module-Level Design Strategies

4.1.1 Battery Chemistry Selection: Safety and Life-Cycle Trade-offs

The choice of chemistry is by far the most critical design decision in constructing a grid-scale BESS, influencing its thermal and environmental safety as well as the recycling at the end of its life. The three primary cathode chemistries used in commercial lithium-ion batteries—lithium iron phosphate (LFP), nickel manganese cobalt oxide (NMC), and nickel cobalt aluminum oxide (NCA)—carry different balances of these attributes, and considering this choice as a technical optimization overlooks life-cycle implications.

As stated in Chapter 2, LFP provides greater parity to NMC and NCA in terms of thermal stability, raw material independence, carbon production to manufacture, and end-of-life recycling. For the purpose of mitigation, an inherent lower likelihood of thermal runaway being initiated provides no other safety impact in battery risk than the most significant impact. The supporting evidence for this statement is provided in Chapter 2. The life-cycle aspect reinforces some of these findings, yet adds further possibilities. Jaradat & Khatib (2025) report in their review of the literature on life cycle assessment (LCA) that across the lifetime of the batteries, LFP has a lower global warming potential per kWh delivered than

NMC, mainly because of lower manufacturing emissions and a longer cycle life. A more rigorous analysis of LCA differences across battery chemistries for stationary storage applications is presented in Le Varlet et al. (2020) .They too find that LFP is the preferred chemistry but they point out that most of the difference is due to end of life treatment of the batteries – a point that procurement agencies need to assess more carefully. As discussed in Chapter 2, cost-per-kWh procurement metrics are not accounting for supply chain, safety, and end-of-life environmental costs documented by Christensen et al. (2021). The consequence with respect to mitigation strategy is immediate: chemistries chosen solely for cost of acquisition embeds a greater thermal risk and greater end-of-life complexity than if the full lifecycle costs were considered from the outset of the procurement process.

4.1.2 Electrolyte and Separator Design: Safety–Sustainability Tensions

Conventional liquid electrolytes — $LiPF_6$ dissolved in organic carbonate solvents — are both flammable and toxic. Rappsilber et al. (2023) demonstrate that fluorine-containing electrolyte components are the primary source of HF generation during thermal runaway, while organic carbonate solvents are volatile organic compounds that degrade air quality during thermal events and are toxic to aquatic ecosystems upon leakage. From a lifecycle perspective, $LiPF_6$ hydrolysis products present Eco toxicological risks whose severity is not reflected in current end-of-life handling standards.

Solid-state electrolytes are widely proposed as a transformative alternative, offering non-flammability and superior electrochemical stability. Yu et al. (2023) present a substantive case for solid-state batteries as the next-generation safety architecture, noting eliminated flammability hazards and improved thermal tolerance. However, they acknowledge manufacturing complexity, lower ambient-temperature ionic conductivity, and significant processing energy requirements as unresolved challenges. Critically, LCA data for solid-state cells at grid scale remain unavailable — a gap identified by Yu et al. that prevents the full environmental benefit of the transition from being quantified. Flame-retardant electrolyte additives represent a near-term compromise: phosphate-based formulations reduce flammability without requiring the manufacturing transition that solid-state electrolytes demand, though their long-term stability and the Eco toxicological profile of their degradation products in end-of-life battery streams constitute an uncharacterized environmental risk. The literature has not yet produced a comparative LCA of additive-modified versus solid-state versus conventional electrolytes at grid scale — a gap that impedes evidence-based selection.

4.1.3 Thermal Barriers, Module Spacing, and Mechanical Protection

At the module level, the design determines how a cell-level failure can propagate and become a failure at the system level. In a recent paper, Mylenbusch et al. (2023) investigate the three main propagation control mechanisms: the spacing between the cells, the use of thermal barriers, and the structural protection of the cells. They conclude that the combination of the three control mechanisms determines the difference between a minor incident and a failure cascade. The spacing controls the radioactive and conductive heat transfer between neighboring cells, where a small spacing leads to a thermal continuum, and a large spacing result in the introduction of a passive resistance. Mylenbusch et al. caution that the spacing is not an independent parameter, and the chemistry, the format, and the SOC must also be considered. Generic spacing requirements, as currently spelled out in standards, do not account for this.

Thermal barriers, implemented as ceramic insulation, phase change material (PCM) inserts, or intumescent panels, do not prevent thermal runaway events, but they increase the propagation time between two neighboring cells, providing a larger window for detection and intervention. In a recent review on PCM usage in battery packs, Calborean et al. (2025) concur with this observation and highlight the limitation that once the latent heat capacity of PCM is exhausted, additional thermal protection is not available. Wilke et al. (2017) validate experimentally that PCM composites placed between cells can effectively delay the onset of propagation and lower peak temperatures experienced by adjacent cells, though they observe that failure events at high SOC and high cell failure rates may exceed the capacity of PCM. Calborean et al. and Wilke et al. collectively highlight the merits and limitations of thermal barriers as passive mitigation measures.

Mechanical protection provides another method of prevention. According to Mylenbusch et al. (2023), mechanical deformation caused by vibration, shock, or impact can initiate internal short circuits, thus adding to the causal links that the safety literature establishes between physical integrity and thermal runaway. The environmental perspective of the module design specifications is lacking. The adopted materials for thermal barrier or structural components add to the overall embodied carbon of the manufacturing process and add complexity to the end of life process. There is a lack of data on the life cycle assessment of the thermal barrier materials, which are composites, used in grid-scale battery energy storage systems (BESS).

Table 5. Comparative Assessment of Cell- and Module-Level Mitigation Strategies

Strategy	**Primary Safety Benefit**	**Key Limitation**	**LCA/Environmental Consideration**	**Reference**
LFP chemistry	Higher thermal runaway onset; no cobalt	Lower energy density vs NMC/NCA	Lower GWP; simpler end-of-life	Chen et al. (2021); Le Varlet et al. (2020)
NMC/NCA (high-Ni)	Higher energy density; smaller footprint	Elevated thermal instability; cobalt sourcing	Higher GWP; complex recycling	Christensen et al. (2021); Tran et al. (2021)
Solid-state electrolyte	Non-flammable; HF elimination	Manufacturing complexity; no grid-scale LCA	LCA data absent; high processing energy	Yu et al. (2023)
Flame-retardant additives	Reduced flammability; near-term applicability	Degradation product Eco toxicity uncharacterized	End-of-life environmental risk unstudied	Rappsilber et al. (2023)
PCM thermal barriers	Propagation delay; detection window extended	Finite latent capacity; adds mass/volume	Embodied carbon of composite materials quantified	Calborean et al. (2025); Wilke et al. (2017)
Module spacing	Passive heat transfer resistance	Chemistry/SOC dependent; not standardized	Reduces packing density; affects land use	Mylenbusch et al. (2023)

Source: Compiled from cited studies. GWP = global warming potential; LCA = life-cycle assessment.

4.2 Battery Management Systems

Lastly, the BMS serves as the primary active safety layer in BESS of grid scales, providing monitoring and parameter estimation, triggering protection and control action, and fault diagnostics. The effectiveness of the BMS algorithms heavily depends on accurate sensing and underlying assumptions that are used in a model, as well as the reliable operation of sensor and hardware subjected to the evolving thermal and electrochemical stresses throughout the battery life cycle. A BMS that is functioning well at the beginning of life may offer substantially diminished protection as the cells age and the underlying assumptions diverge, which is an aspect that the literature addresses partially but has not been fully incorporated into the safety assessment.

4.2.1 Multi parameter Monitoring: Coupled Signals, Not Independent Metrics

Voltage, current, and temperature serve as intertwined indicators of the battery’s electrochemical and thermal status. As explained in Şen et al. (2024), the voltage deviation indicates the potential overcharge and dendrite growth, the current excess causes internal heating and structural damage, and the elevated temperature shows the combined thermal effects of both voltage and current; therefore, a BMS that monitors these signals in isolation cannot provide a complete status of the battery. In the same spirit, See et al. (2022) studied the functional safety of battery management systems used in large-scale battery packs and emphasized the need to monitor voltage at the cell level since the pack-level voltage and current measurement masks individual cell-level deviations that are critical for safety. Combining the arguments from Şen et al. and See et al., an ideal BMS should provide an integrated multipara metric monitoring of each individual cell as a bare minimum safety requirement. Commercial battery management systems implement this ideal monitoring at varying levels of efficacy.

There is no identified lifecycle aspect of monitoring reliability. Sensors will deteriorate over time due to drift, corrosion, or loss of calibration, contributing to measurement errors that may cloud the state estimation with the cell degradation. To date, there is no identified requirement to assess the sensors' performance across the lifetime of the grid-scale BESS installation, as suggested by Gabbar et al. (2021).

4.2.2 SoC and SoH Estimation: Accuracy, Degradation, and Safety Coupling

Safety-related functions of BMS, such as SoC and SoH estimation, are subject to irreducible errors that increase along with cell aging. Zhang et al. (2018) provide an elaborate review of various SoC estimation techniques, such as Coulomb counting, open-circuit voltage, Kalman filtering, and data-driven approaches, and conclude that no existing single technique can ensure the required accuracy of SoC estimation over the entire lifetime under different operating conditions, ambient temperatures, and battery models used for grid-scale energy storage systems. They also identify the principal source of errors in estimations is the variation in model parameters with aging. Models calibrated at the beginning of life may not accurately represent the battery models as the batteries age. Şen et al. (2024) ,investigating from a safety perspective, show that the SoC overestimation leads to overcharging conditions and SoC underestimation leads to over-discharge conditions, which are the initial conditions for the failure mechanisms explained in Chapter 3.

The SoH estimation presents further challenges. Peng et al. (2022) conducted a survey on capacity estimation techniques for BMS applications, where the authors denote the widely used 80% capacity for end-of-life (EoL) definition in a BMS environment as a loose guide at best for estimating thermal runaway risk. Citing Hwang et al. (2025), they argue that in the cells aging beyond this capacity number by conventional estimation methods, the risk of thermal runaway could increase substantially. The risk of thermal runaway in aging cells is not factored into the safety standards for the BMS, leading to a potential mismatch for long-term grid-scale battery applications.

4.2.3 Protection, Balancing, and Fault Diagnostics: Active Safety Layers

The above two functions protect the BMS against overcharge and over-discharge, which are the most basic safety functions of the BMS. Chen et al. (2021) remark that in grid-scale battery packs, the commonly used protection threshold voltage at the pack level inevitably masks individual cells reaching extreme upper or lower states prematurely. Rao et al. (2025) provide an extended discussion on fault diagnostics related to protection functions. They explain that model-based approaches provide accurate fault localization directly, assuming the development of an accurate physical model, whereas data-driven approaches identify deviations from normal operation without relying on the physical model, although they require significant training data for different fault types and cannot detect new faults that have not been trained. In both approaches, false-positive diagnosis can arise as the model-based diagnostics approach is considered inaccurate when the ageing of individual cells deviates from the original model assumptions and the data-driven diagnostics approach cannot be generalized to different ageing mechanisms.

Cell balancing links these monitoring and safeguarding functions to lifecycle performance. Rao et al. (2025) show that unbalanced populations of cells in a module generate differential stress that accelerates ageing in a specific locus, causing internal resistance variations and increasing the risk of hotspots — a lifecycle feature that has safety and environmental implications, for obvious reasons. Dynamic balancing algorithms that respond to prevailing conditions are a step-up compared to predetermined balancing intervals, reducing excessive charge-discharge cycles and better controlling differential stress. The shortfall is that the BMS fault analysis will not reveal the presence of latent internal faults such as microscopic perforations in the separator or cell anode dendrite formation, which Guo et al. (2026) show will develop undetected into a thermal cascade.

4.3 Thermal Management Systems

Thermal management poses safety risks, lifetime effects, and carries environmental impacts – and these are often treated independently. Hemavathi et al. (2026) conclude that heat generated from lithium-ion cells cannot be avoided, and if not appropriately managed, an inevitable buildups leads to self-catalyzing degradation and thermal runaway. Grid-scale battery management involves thousands of these cells, variable current draws, and tightly packed casing, which exacerbate the impact of thermal management decisions on the safety, lifetime, and environmental impacts of a battery's use and afterlife phases.

4.3.1 Air, Liquid, and Phase Change Cooling: Comparative Performance and Trade-offs

At the grid scale, air cooling is the least effective thermal management method. Hemavathi et al. (2026) explain that it is an inherent limitation of air cooling that the low heat transfer coefficient of air cooling is unable to handle the rate of heat generation at high-power grid-scale operation. An extensive review of thermal management systems by Zichen & Changqing (2021) clarifies that non-uniform airflow over large cell groups creates thermal gradients, which in turn create localized hotspots, ageing differences, and electrochemical imbalances that may increase the risk of long-term faults. This is the nature of air cooling at grid scale and not a remedial fault of installation.

Liquid cooling overcomes these issues with much higher heat transfer coefficients, permitting closer control of temperature and more even ageing. Hemavathi et al. (2026) acknowledge this thermal management performance but raise the risk factors often ignored in safety studies, namely, the risk of leakage of cooling fluid near high voltage DC terminals causing hazardous situations and the risk of pump, pipe, or seal malfunction leading to new failure modes not present when air cooling is used. Olabi et al. (2022), in a review of thermal management of batteries, emphasize that flow channel design could result in temperature non-uniformity issues similar to air cooling at a much higher cost and technical complexity. Plus, changes in coolant as it wears out become a source of chemical waste and ongoing maintenance cost over the life of the battery, factors often ignored in comparative studies of different thermal management methods (Zichen & Changqing, 2021).

Phase change material (PCM) offers a different approach by passively absorbing latent heat. Calborean et al. (2025) argue that PCM provides a safety window contribution by slowing the temperature rise in abnormal conditions to allow for an increased reaction time; it does not provide a sustained reduction in temperature. Wilke et al. (2017) experimentally verify that PCM provides a delay in propagation and reduces peak temperature in neighboring cells. Both papers note the significant disadvantage of PCM in that once its latent heat capacity is fully absorbed, it ceases to have any thermal protection value, even if the fault conditions persist. Calborean et al. also note that the low thermal conductivity of PCM restricts the heat absorption rate in the case of high-rate generation faults, such that high-state-of-charge, high-rate events may exceed this capacity before it is fully absorbed. The weight and volume penalty of PCM subsequently reduces packing density for installation and requires material selection considerations of flammability, chemical compatibility, and degradation, which the lifecycle environmental impact is yet to be fully quantified.

4.3.2 HVAC Integration, Gas Management, and Lifecycle Energy Cost

Enclosure HVAC is also targeted to extend the thermal management of all the cells within a battery pack and all modules within the battery pack at the battery enclosure level, primarily to maintain constant ambient temperature within different rack and container architectures, as well as to address the build-up of flammable and toxic gases in malfunctioning conditions. As explained by Mylenbusch et al. (2023), the latter cannot be considered an additional function: without automatic enclosure ventilation reacting to gas sensing that initiates well before reaching critical concentration levels, the enclosure ceases to be safe and serves as an active risk of explosion. To them, this is not an improved design, and it has been missing in multiple large-scale incidents to that account.

The design of HVAC systems based on optimizing conditions for normal and abnormal conditions is a largely undiscovered space. HVAC systems that are effective in providing the required airflow for the normal operation of BESS, may spread heat or flammable gases during a thermal runaway event if not designed and updated for abnormal conditions. Tailored HVAC systems that can alter their behavior from conditioning ambient air to shutting down or rerouting airflow in specific zones can be an extremely valuable design approach that, to date is not always mandated by relevant design codes and standards. Active cooling technologies consume auxiliary energy during the operational life of the battery system. While cooling a battery system can significantly increase its operational life by reducing thermal stress cycles that the battery undergoes, thereby creating higher returns from its manufacturing investment to the environment, it is critical to understand the auxiliary energy consumption of the active cooling system throughout the BESS lifecycle as part of the BESS design process, which largely remains unexplored at this time.

Table 6. Comparative Assessment of Thermal Management Approaches for Grid-Scale BESS

Approach	**Safety Contribution**	**Key Limitation**	**Lifecycle / Environmental Implication**	**Reference**
Air cooling	Low cost; simple; modular	Insufficient heat transfer at grid scale; hotspots	Low auxiliary energy; no coolant waste	Hemavathi et al.(2026); Zichen & Changqing (2021)
Liquid cooling	High heat transfer; uniform temperature	Leak risk; pump failure modes; high complexity	Coolant waste; periodic replacement; maintenance burden	Hemavathi et al. (2026); Olabi et al. (2022)
Phase change material	Passive; propagation delay; no moving parts	Finite capacity; low conductivity; adds mass	Embodied carbon of composite materials; flammability characterization needed	Calborean et al. (2025); Wilke et al. (2017)
HVAC + gas management	Ambient control; explosion prevention	Normal vs fault-mode conflict; adaptive design absent from standards	Auxiliary energy across operational life; maintenance overhead	Mylenbusch et al. (2023)

Source: Compiled from cited studies.

4.4 System-Level Design and Installation

Fundamentally flawed in the analysis of safety in BESS above is the assumption that collectively these well designed components would lead to a well-designed system. This is seen from incidents that this is not the case. The crucial decisions on safety design come at the stage of the spatial arrangement, enclosure geometry, ventilation design, materials, and installation practices that determine whether a localized problem will become a catastrophic systemic failure. It is here that there are also significant environmental and lifecycle impacts.

4.4.1 Container Design: Containment Asset and Explosion Liability

The containerized enclosure is an item of safety equipment but also an impeding factor in safety. As identified by Mylenbusch et al. (2023), it is a barrier that acts as a safety boundary but also a confined volume that can cause an otherwise innocuous thermal event to accelerate to an explosion due to the potential accumulation of flammable gases. The dual role of containerized enclosures—providing containment while enabling gas accumulation—has been observed in real incidents (see Chapter 7).

Currently, it is accepted that due diligence on thermal runaway initiation is unachievable and that enclosures should be designed to limit the effects of thermal runaway within one cell and prevent propagation to other cells by using fireproof materials and cell partitioning (Mylenbusch et al., 2023). In analyzing explosion incidents, Zalosh et al. (2021) argue that the enclosures should be designed to mitigate deflagration risk, not suffer it, which means that weakest points are purposely engineered in the structure (roof panel, vent panel, etc.) to release pressure away from personnel, as is standard in the explosion protection design of chemical plants and storage of combustible materials. This fundamental premise is yet to be incorporated into the guidance for BESS installations and this has contributed to tragic incidents on multiple occasions.

4.4.2 Layout, Ventilation, and Fire-Resistant Materials: Integrated Safety Design

The collection and dissipation of gases is impacted by spatial configuration and while ventilation strategies can augment safety, there is a direct connection between early spatial design decisions and the potential for safety issues, yet the design priorities focus on energy density optimization over safety. Zalosh et al. (2021) echo these points, highlighting layout decisions early in the design process impact safety downstream in ways that excess ventilation can never truly cover. Lystianingrum et al. (2023) ,in a review study of large-scale BESS accidents, pointed towards the accumulation of gases in tight spaces lacking adequate ventilation as the immediate cause of explosions in systems where the detection and suppression systems were seemingly in working order. This critical insight identifies that active safety systems cannot patch the passive spatial design issues in ways that put the paradigm of layered safety with active systems acting as fallbacks to insufficient design into question.

Regarding gas risk mitigation, the best approach might be active ventilation tied to gas sensors, in order to clear any potentially dangerous build-up of gas before it reaches ignition concentrations (rather than mitigating after the gas has reached ignition conditions). Mylenbusch et al. (2023) concur, while also noting, as per the HVAC above (section 4.3.2), that there is a contradiction in using normal mode ventilation as it can disperse thermal by-products. Close et al. (2024) provide similar guidance regarding passive material design, showing by way of incident reports that lack of suitable thermal barriers contributed to rapid thermal spread in the Arizona McMicken incident despite active systems in place.

An installation quality gap has also been identified by Close et al. (2024) as a situation unmet by standards. Poor installation practices, such as inadequate spacing, wiring, and ventilation, have been cited as factors that contributed to several BESS failures, producing effects that would not result from an ideal installation process. The gap between design and installation is a governance issue that chronic exposure exacerbates: An installation that meets design specifications during commissioning may later have safety-related deficiencies due to the ingress of humidity and thermal cycling that deteriorates insulation over time.

4.4.3 Standards Compliance and the Evidence of Its Insufficiency

The above-mentioned standards provide a useful guide in the design. But, as discussed in Chapter 6 on the regulatory analysis and corroborated by the incident analysis in Chapter 7, it is to be noted that compliance to the above-mentioned standards in itself does not ensure safety at a system level. The design implication to be derived here is that the standards should be considered as a threshold, and a scenario-based consequence analysis and cradle-to-grave environmental impact study should be sought in the evaluation of the design.

Taken together, these results point to a risk-based design approach where standards play a lower role in achieving system safety and where the impact of a range of scenarios, lessons learned from failures, and lifecycle environmental impact are used in the assessment of system design. System design is the critical interface in safety engineering and the lifecycle sustainability of the water system. System design attributes such as the layout, ventilation, choice of materials, and installation of the system can limit the impacts of failures to protect the salvage value of the system. Without the right system design, local failures can lead to significant negative environmental and economic impacts. The need to analyze system design within both safety and lifecycle perspectives, as opposed to simply meeting the requirements of standards, is not a lofty goal but one that is realistically supported through research data.

4.5 Summary and Critical Synthesis

This chapter reviewed design approaches to BESS safety from the four mitigation levels of cell and module, BMS, thermal management, and system installation, all within the context of safety and the BESS lifecycle. It highlighted three findings that cut across the four mitigation levels. First, each mitigation level includes lifecycle environmental repercussions not considered in design assessment. Selecting chemistry brings its own supply chain risks as well as end-of-life challenges for recycling. The more complex BMS design cannot close the gap in detecting latent internal defects. Thermal management approaches come with additional energy and maintenance costs. And the choices made at the system level for BESS design will impact how serious the environmental consequences will be when a failure event takes place. Second, the literature and evidence examined underline that the energy, environmental, and economic costs of active safety systems cannot substitute for the passively safe design of cells, modules, or systems—a critical finding regarding the layered safety approach of standards. Third, the literature reviewed for this chapter demonstrates, at four levels of mitigation, clear gaps between design approaches and performance. The standards and compliance approach to design does not address these gaps. Chapter 5 examines the regulatory and operational context for these design approaches and whether current regulation and standards are up to the task of designing for the scale and environmental risks of grid-scale BESS.

5 Mitigation Strategies — Detection, Suppression, and Integrated Safety Architecture

In this chapter, we discuss detection, suppression, and safety architecture as BESS safety management strategies and approaches in operation, which, in essence, translate the design safety features discussed in Chapter 4 into hazard identification, hazard consequence mitigation, and emergency response coordination. We critically examine these three aspects with respect to their environmental/lifecycle facets, chiefly that undetected hazards will burn and consume recyclable material; mismatched suppression agents produce toxic byproducts and contaminated runoff; and disjoined approach in devising safety features escalates locally resolvable malfunctions into facility-wide environmental and financial hazards. The literature on these aspects is voluminous but examined in silos, while their concerted assessment is critical to their net effectiveness.

5.1 Detection and Early-Warning Systems

5.1.1 Multi-Parameter Electrical and Thermal Monitoring

To achieve effective detection for a grid-scale BESS, it is vital that the combined interpretation of the coupled electrochemical and thermal signals be considered in the detection process, rather than just monitoring individual signals independently against detection thresholds. Şen et al. (2024) report that voltage, current, and temperature are coupled diagnostic signals, where the voltage signal serves as an indicator for overcharge and dendrite formation, the current provides important indication on structural degradation and the consequent heating, while the temperature indicates a cumulative effect of the above two conditions. Considering these diagnostic signals independently (as in the case with many commercial BMS architectures) does not provide sufficient insight. See et al. (2022), in their study on the functional safety of BMS of a large-scale battery pack, highlight the need for the voltage sensor readings at the individual cell level as the coupled voltage, current, and temperature signals detected at the pack level obscure the diagnostic variations at the cell level, which can have safety implications long before any warning limits are reached at the system level.

Expanding upon this study for internal short circuit detection, Cao et al. (2022) show that the conventional monitoring schemes detect subtle signals (slight voltage anomaly, marginally higher self-discharge rate) for internal faults in the early stages, before thermal runaway cascades are triggered. Their voltage anomaly detection algorithm improved the sensitivity, but it still emphasizes that the internal changes during the early stages can only be sensed by the effects they cause in the battery's electrical signals. More recently, Seo et al. (2020) reaffirm this gap in the detection of soft internal shorts using conventional voltage and current monitoring during a charge cycle, where typically no precautions are exercised to identify battery faults in the pack; the monitoring parameters do not identify nascent faults that are detected at a later stage. These studies indicate that battery voltage and temperature monitoring, while essential, are not sufficient for detecting internal faults such as internal short circuits in the early stages, which is an important point that single-layer detection strategies do not acknowledge.

5.1.2 Gas and Smoke Detection: Complementary Roles and Critical Limitations

Gas sensing is a different modality, as the eruption of specific volatile species (CO, H2, electrolyte vapors) may precede any notable temperature increase, thereby significantly augmenting the time window for intervention. Rappsilber et al. (2023)) argue that H2 and CO are the two major components that start being produced even during SEI decomposition, well before the exothermic chain reactions are self-sustaining. Larsson et al. (2017) add HF to the list, which is crucial not only for detecting the onset of thermal runaway but also for quantifying the danger it poses to the rescue teams and the public.

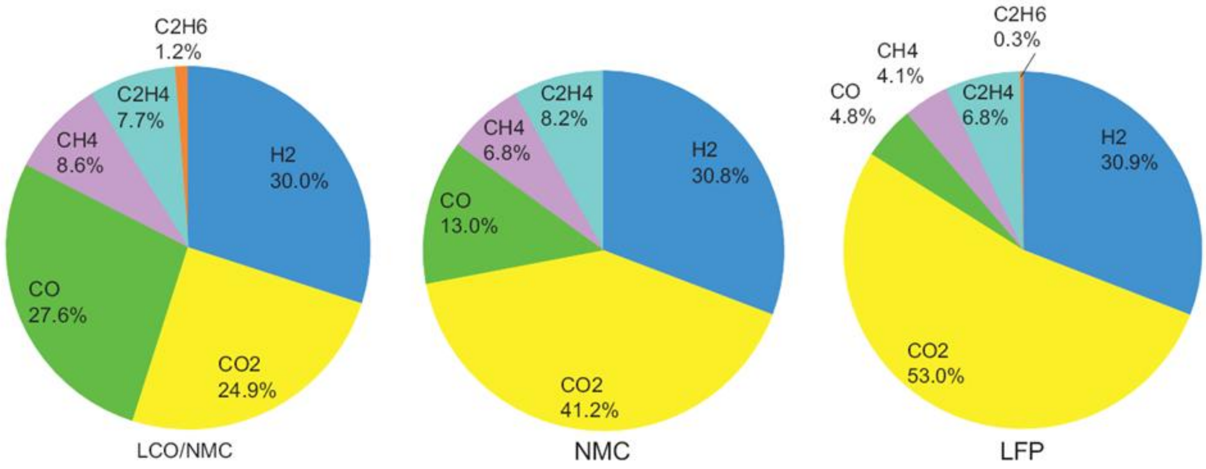

Figure 5: Gas composition from thermal runaway of 18650 cells with different cathode chemistries(Wang et al., 2019) .

While some authors, e.g. Mylenbusch et al. (2023) ,suggest smoke and gas detection together should be the minimal standard, both detection methods are important in different ways: smoke detection indicates that something abnormal is happening, and gas detection can provide information about the likely hazard before first responders arrive at the BESS. Incidents with slow-onset ignition have demonstrated the limitations of smoke-only detectors for early-stage battery failure detection (see Chapter 7). Researchers involved in investigations of explosion incidents, such as Zalosh et al. (2021), show that dangerous concentrations of flammable gases can build up without obvious smoke present. This is a critical and dangerous gap that is not addressed by any one detection method alone. It further suggests that the need for hydrogen detection, with its wide flammability range and extremely low ignition energy, should be considered a fundamental part of gas detection requirements in grid-scale BESS installations, which is not always the case in current installation standards.

5.1.3 Early-Warning Algorithms: Predictive Capability and Validation Gaps

Sensitivity to early warning could be better captured using data-driven or machine learning methods that detect trends across parameters or nonlinear interactions that a threshold-based method would miss. In their review of machine learning approaches for fault detection in batteries, Samanta et al. (2021) note that, while machine learning methods exhibit better detection of anomalies than threshold-based methods, the performance of these methods is ultimately tied to the quality and quantity of their training data. Incident data for grid-level BESS are unstructured and unstandardized due to a lack of mandatory incident reporting, so machine learning models trained on available data may not be sufficiently comprehensive to learn the full spectrum of possible degradation or failure modes present in various applications. Yu et al. (2023) highlight that high sampling rate local monitoring can detect fast electrical and thermal transients, while cloud-level analysis at lower sampling rates could not be used for protective actions. See et al. (2022) discuss incorporating real-time local monitoring and analytical layers of data science, but emerging standards and best practices for safety monitoring in BESS should address risks associated with breakdowns or failures in communication between these analytical layers. Results from suppression testing are typically reported considering conditions where visible flames are present, while BESS incidents have a dominating profile involving accumulation and delayed ignition of flammable gases. Subash et al. (2025) highlight for an aerosol agent that performance against premixed hydrogen-rich gas is much more challenging than under diffusion flame conditions, and the effectiveness of standard suppression testing protocols for providing useful guidance for suppression in BESS incidents may be limited.

5.2 Fire Suppression Technologies: Comparative Assessment

To evaluate the performance of suppression technology applicable to a grid-scale BESS, "knock down the visible flame" is not an adequate objective of a fire suppression agent. Thermal runaway of lithium-ion battery is characterized by continuous self-heating, continued generation of flammable gases, and potential re-ignitions after the flame is first extinguished. Therefore, four aspects are discussed hereafter: 1) cooling and 2) propagation, which are directly related to thermal runaway fire chemistry, 3) gas suppression 4) environmental impact after the event.

5.2.1 Water-Based Systems: Superior Cooling, Secondary Hazards

Water-based suppression in the form of mist and water spray and flow offers the most cooling effect among all agents and is the most effective way to arrest continuous heat generation inside the battery module. Xu et al. (2020) experimentally demonstrated that water mist significantly reduces the temperature of the cells and gases, reducing the likelihood of temperature propagation to other modules. More recently, Zhang et al. (2021) have conducted experiments with water spray and demonstrated the effectiveness of temperature reduction. But, Zhang et al. also note a critical penetration issue with water flow inside modules; for water flow to arrest temperature inside the battery module effectively, it needs to be in direct contact with the thermal heat sources inside the closely packed modules. If water flow is not in direct contact with the heat source, it may not arrest temperature propagation but delay it instead. The environmental implications are also significant here. Water flow tests generate contaminated water runoff containing dissolved metals, electrolyte, and HF products, which may pose challenges in handling the contaminated water runoff after the incident. This is a challenging trade-off that is not directly addressed by Xu et al. or Zhang et al. Water-based suppression methods may save more battery material compared to other suppression methods that may lead to thermal cascade, but it will also contaminate soil and drainage systems.

5.2.2 Gaseous Agents: Rapid Knockdown, Fundamental Re-ignition Risk

Because of the clean-extinguishing properties (no residue) and fast flame knockdown, gaseous fire suppression agents such as CO2, HFC-227ea, and C6F12O are often used in enclosed space BESS installations. The fundamental disadvantage of these in lithium battery applications is that they are not able to adequately cool the battery cells to stop the internal heat production that is the root cause of the thermal runaway. Zalosh et al. (2021) describe re-ignitions observed following deployment of gaseous suppression agent where internal processes continue even when flames are suppressed, and Close et al.

(2024) describe an escalation in explosions in battery installations where clean-agent systems worked as designed but failed to prevent subsequent build-ups of flammable gases and resultant explosions. Further complicating risk, Majeed et al. (2024) discover that HFC-227ea and other similar agents produce hydrofluoric acid (HF) during battery fires, a new risk to critical infrastructure that is overlooked in the clean-extinguishing evaluation. Even when a lithium-ion battery fire has been extinguished, there is still a significant risk of re-ignition.

5.2.3 Aerosol and Foam Agents: Supplementary Roles and Context-Dependent Limitations

In addition to the fast filling and effective flame extinction in confined spaces, Majeed et al. (2024) acknowledge these aerosol advantages but emphasize their inherent disadvantage in that the thermal performance of the aerosols is weak and the cell temperatures cannot be reduced once thermal runaway begins inside the cell — the visual extinction may only delay thermal runaway escalation. The closest to the actual dynamics in BESS incidents is test data by Subash et al. (2025) that show significantly reduced aerosol effectiveness in suppressing premixed hydrogen-rich gas flame compared to a diffusion flame, which is more relevant to the dynamics observed during suppression test methods.

Foam systems provide smothering and surface-quenching effects but are highly dependent on access and configuration. Fei et al. (2026) ,in their comparative study of foam application methods, observed a notable reduction in flame spread where there was direct access to the burning surface, but the effects are unknown in containerized BESS configurations where there is no direct internal access. Both aerosol and foam fire suppression systems pose a cleanup challenge following an incident, the environmental impacts of which have not been fully characterized in open literature – hopefully a topic for the post-incident environmental assessment.

Table 7. Comparative Assessment of Fire Suppression Technologies for Lithium-Ion Grid-Scale BESS

Agent	Cooling Capacity	Re-ignition Risk	Gas/Propagation Control	Environmental Impact	Key Reference
Water mist/spray	High — best thermal arrest	Low with adequate penetration	Effective if internal contact achieved	Contaminated runoff; HF/metal dissolution	Xu et al. (2020); Zhang et al. (2021)
CO_2	Low — insufficient for TR	High — internal decomposition continues	Limited; inert dilution only	Low direct impact; O_2 displacement risk	Mrozik et al. (2026); Zalosh et al. (2021)
HFC-227ea	Low	High — HF generation under heat	Rapid flame knockdown only	HF production; high GWP	Majeed et al. (2024); Mrozik et al. (2026)
Aerosol	Very low	High — no cell cooling	Effective vs. diffusion flame; poor vs. H_2 premix	Residue contamination; incomplete characterization	Majeed et al.(2024); Subash et al. (2025)
Foam	Moderate surface cooling	Moderate — access dependent	Geometry/access constrained in containerized BESS	Chemical residue; wastewater management required	Fei et al. (2026)

Source: Compiled from cited studies. TR = thermal runaway; GWP = global warming potential; HF = hydrogen fluoride

From the discussion above, it is clear that none of the suppression technologies examined in the literature provide a complete solution when applied to grid-scale BESS. Water is the most effective for cooling, gases provide quick knockdown, aerosols can supplement local suppression, and foam provides smothering for compatible configurations. None of these technologies address the full range of hazard concerns in BESS, which includes internal heat buildup, gas accumulation, re-ignition, and contamination after the incident, which supports the analytical rationale for developing integrated suppression and safety systems that include cooling, gas detection, mechanical ventilation, and a systematic waste management plan as part of the overall safety management plan.

5.3 Emergency Response and Operational Safety

5.3.1 Shutdown Procedures and First Responder Safety

As discussed previously, the BESS shutdown procedure for grid scale units involves a verified safe state, where the battery poles must be fully isolated, then auxiliary discharge applied to fully deplete stored energy in the battery modules. He et al. (2024) confirm that battery modules remain fully energized even after being disconnected from the grid. The Arizona McMicken BESS explosion demonstrated that the apparent cessation of flames did not ensure that the gas remained safely below flammable levels, and first responders who entered based on these visual cues sustained injuries from the subsequent powerful explosion (UL Firefighter Safety Research Institute, Universal Fire & Explosion Investigation Experts, Arizona State Fire Marshal & Office of the State Fire Marshal, Governor’s Office of Homeland Security, & Pima County Fire 2020). Mylenbusch et al. (2023) caution, based on this experience, if the interior conditions of a BESS unit are not known to be safe, shut down procedures should emphasize maintaining safe distances and remote monitoring to assess the internal conditions of the unit rather than assuming safety based on a visual assessment that the flames have died down.

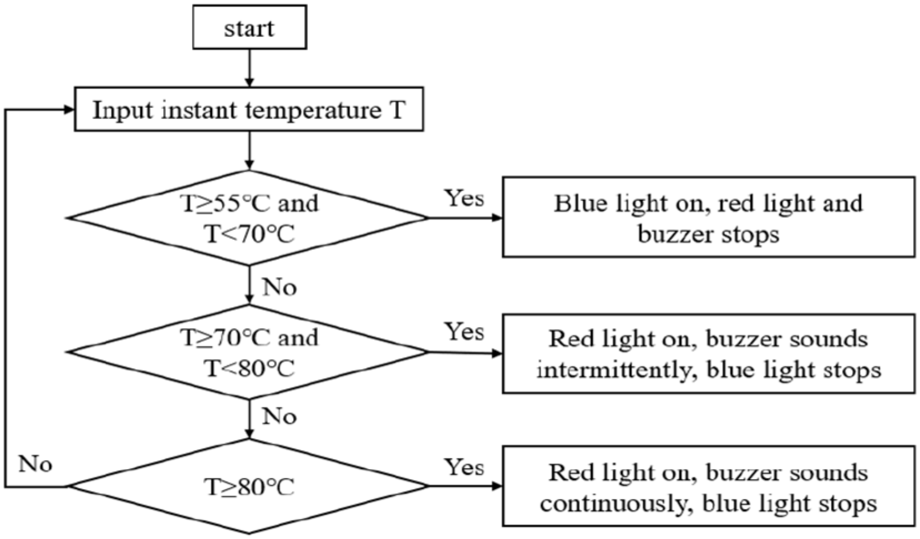

Figure 6: Three-stage temperature warning system for lithium-ion batteries(Yin et al., 2023) .

In addition, first responders face risks that are not traditionally taught in fire response. Lystianingrum et al. (2023) note in their review of lessons learned from multiple large events that maintaining a conservative distance during the initial response is more fruitful than aggressive interdiction, precisely the opposite of what conventional fire training drives the responders to do. As indicated in Chapter 3, emissions during combustion and contamination after an incident are environmental lifecycle impacts that are currently not required to be assessed by governing bodies.

5.3.2 Personnel Training, Maintenance Governance, and Incident Learning

Training and maintenance are the organizational elements underpinning all technical safety interventions and are the least regulated aspects of BESS safety. Shortcomings in maintenance – untaken component tests, coding errors and ineffective cooling systems – identified by Close et al. (2024) ,contributed to several incidents, indicating that maintenance is a safety-critical activity and maintenance errors have the same safety consequences as component errors. He et al. (2024) establish that training specifies the intended system behavior in abnormal conditions, while maintenance ensures the system will deliver the intended behavior when required. Existing frameworks that govern these functions individually do not sufficiently recognize their consolidated contribution.

In a closely related observation, Samanta et al. (2021) identify the primary reason machine learning algorithms are not performing better is due to the current absence of standardized incident data reporting, drawing a direct link between the operational governance gap and detection gap. Lystianingrum et al. (2023) observe unanticipated gas build-up, first-year vulnerability, and refrigeration system correlations as ongoing contributing factors in recent international incidents, indicating further the operational experience translation shortfall. A standardized incident data reporting system (that could be used to train incident detection algorithms and update safety standards) would address both the detection gap and the governance gap — a potentially transformative regulatory change, which has not been realized.

5.4 Integrated Safety Architecture

5.4.1 Layered Safety: Prevention, Detection, Containment, and Mitigation

The layered safety model — prevention, detection, containment, and mitigation — provides the most analytically coherent framework for grid-scale BESS safety, and its critical value lies in an embedded assumption: each layer is designed on the premise that the preceding layer may fail. Rosewater & Williams (2015), applying system safety analysis to lithium-ion grid storage, establish this design philosophy as foundational, arguing that safety architecture must accommodate realistic barrier failure rather than assuming any single barrier will hold. He et al. (2024) operationalize this across four interdependent functions: prevention reduces initiation probability through chemistry selection, BMS algorithms, and thermal management; detection creates the intervention window; containment limits propagation when prevention has failed; and mitigation manages consequences when containment proves insufficient. Close et al. (2024) add the critical empirical observation that safety in BESS is an emergent property of system interactions rather than the sum of individually specified components — a distinction that component-level testing and standards compliance cannot capture, and that explains why incidents occur in nominally compliant installations.

5.4.2 Subsystem Coordination and Compartmentalization

The coordination between BMS, thermal management, detection networks, and suppression systems is a BESS safety architecture aspect that is under digested in the literature and has the highest potential impact on actual performance. He et al. (2024) describe the connected control problem here where detection anticipates anomalies early enough for BMS to react appropriately; thermal management must act early enough to prevent irreversible conditions; suppression should act when containment is lost, not as the first line of mitigation that may miss earlier intervention opportunities. See et al. (2022) highlight the risk here: sensor firmware malfunction, communication delays, or BMS logic errors may inhibit coordinated system response even when individual subsystems are working correctly, and this risk cannot be detected through validation at the component level. This risk is compounded when subsystems are sourced, deployed, and validated separately without coordination testing.

Safety zoning and compartmentalization apply the logic of coordination to the design of physical spaces. Lystianingrum et al. (2023) show the boundaries of cells, modules, racks, and enclosures are designed to intentionally disrupt the propagation pathway, but this is not enough unless the risk of gas hazards is addressed at the same time. Flammable gases can spread between compartments and become trapped in confined spaces, creating a potential explosion hazard in cases where thermal containment is achieved locally. Effective compartmentalization requires gas detection, ventilation, and overpressure relief to be implemented at all levels of boundaries, and the management of gas and thermal risks to be addressed together and not sequentially, as currently addressed by the standards for installation practices.

Table 8. Integrated Safety Architecture — Layered Functions, Subsystem Roles, and Critical Gaps

Safety Layer	**Primary Function**	**Key Subsystems**	**Critical Gap**	**Reference**
Prevention	Reduce initiation probability	Chemistry selection; BMS; TMS	Latent internal defects undetectable by monitoring	He et al.(2024); Rosewater & Williams (2015)
Detection	Create intervention window	Multipara meter sensors; gas detection; ML algorithms	Training data gaps; communication dependency	Samanta et al. (2021); See et al.(2022)

Containment	Limit propagation	Thermal barriers; spacing; compartmentalization	Gas migration between compartments not addressed by thermal barriers alone	Close et al. (2024); Lystianingrum et al.(2023)
Mitigation	Manage consequences	Suppression; ventilation; emergency response	No agent addresses full hazard spectrum; post-incident contamination ungoverned	Mrozik et al. (2026); Mylenbusch et al. (2023)
Operational governance	Maintain system integrity over lifecycle	Training; maintenance; incident reporting	Mandatory reporting absent; coordination testing not standardized	M. He et al. (2024); Lystianingrum et al.(2023)

Source: Compiled from cited studies. TMS = thermal management system; ML = machine learning.

5.4.3 Lessons from Incidents and the Governance Gap

The case studies in major incidents present a collective argument that governing operational risk requires a recurring approach whose infrastructure is lacking. The Arizona McMicken example (UL Firefighter Safety Research Institute et al., 2020) revealed that escalation factors included system failure, no gas alarms, communication confusion, and emergency response actions that did not consider explosive or flammable gas behavior. The multi-causal escalation factors are not necessarily triggered by the failure of any one of these. Lystianingrum et al. (2023) and the case examples used in their study found the same escalation and contributing factors globally and conclude there is a collective lack of understanding about these factors – these include accumulated gas, commissioning related risk, and the impact of closed cooling systems – revealing a methodologically systemic problem not addressed by isolated incident investigations. As discussed in Chapter 6, the structural governance gap exists in existing verification approaches that assess components rather than integrated systems reflecting operational conditions. The identified pattern of incidents presented in Chapter 7 confirms that this gap leads to a number of predictable and recurring consequences that further elaborates on its operational governance implications presented in the six-layer framework discussed in Chapter 8.

5.5 Summary

This chapter has viewed detection, suppression, and integrated safety systems from a lifecycle and ecosystem perspective, drawing the following three conclusions. First, neither electrical detection mechanisms, gas detection, nor algorithms for early warning are effective in isolation, but depend on integration and the training data that a mandatory incident reporting regime can provide. Second, no suppression mechanism addresses all thermal runaway lithium-ion battery fire hazards; water is better for cooling, but leads to contaminated runoff, gas is better for knockdown, but allows for re-ignition, and aerosols and foams present use case-dependent drawbacks and unexplored residue effects, all environmental challenges that the existing regime does not attempt to study. Third, safety is an emergent property of multiple interconnected and interdependent mechanisms. The same types of incidents happening repeatedly in different countries and continents point to an oversight failure of verifying the integrated system level of safety before deployment. Chapter 6 views the regulatory regimes that govern these operational mechanisms and examine if they are scaled appropriately to the environmental risk of grid-scale BESS.

6 Safety Standards, Regulations, and Lifecycle Governance of Grid-Scale BESS

6.1 International Standards

The standards landscape for grid-scale Li-Ion BESS is rapidly evolving in response to the rising deployment of these energy storage technologies and significant battery fires over the last decade. The relevant standards for the design, manufacturing, transportation, and deployment of BESS include NFPA 855, UL 9540 and 9540A, IEC 62933, IEEE recommended practices, and UN 38.3. Collectively, these standards address the safe installation, certification, and operational performance of BESS, as well as Li-ion battery transportation. All these standards are primarily focused on the operational and fire safety of the battery and energy storage system.

6.1.1 NFPA 855: Installation Safety without Lifecycle Scope

NFPA 855 establishes requirements for location, separation distances, ventilation, fire suppression, and emergency response planning for building-integrated and outdoor BESS. Its explicit thermal runaway mitigation provisions for lithium-ion batteries represent a meaningful advance over earlier installation codes that did not specifically address electrochemical storage hazards(Vartanian et al., 2021) . By mandating suppression system specifications and ventilation baselines, NFPA 855 reduces the consequences of thermal events at the installation level.

Critically, however, NFPA 855 contains no provisions pertaining to battery manufacturing environmental performance, lifecycle assessment, end-of-life management, or the environmental characterization of toxic emissions from thermal events. A fully NFPA 855-compliant site may deploy batteries produced under environmentally harmful manufacturing conditions, without defined end-of-life pathways, and without any framework for toxic gas plume characterization that community-level incident response would require. This is not a critique of NFPA 855's design intent — it was not conceived to address lifecycle concerns — but it illustrates the structural incompleteness of a safety governance architecture that operates without a lifecycle dimension.

6.1.2 UL 9540 and UL 9540A: Thermal Propagation Testing and Its Limits

UL 9540 is a product safety certification standard for energy storage systems, and UL 9540A is for thermal runaway propagation testing of increasing scales from cell to module, to unit, and eventually installation scale (Vartanian et al., 2021). The UL 9540A testing method, which purposefully induces thermal runaway in controlled test conditions and characterizes the risk of fire and explosion, is a significant step towards understanding and characterizing the propagation behavior at the test scales. McKinnon et al. (2022) report on fire tests of full-scale containerized BESS, providing crucial information regarding the accumulation of gases inside the container and risk of deflagration that informs fire suppression strategies and ventilation requirements.

Speciation of toxic gases evolved from battery thermal runaway (e.g., HF, HCN, volatile organic compounds) and their release and dispersion to the surrounding environment outside the equipment or installation boundary are not currently part of the UL 9540A test methodology. As one example, Larsson et al. (2017) have reported that HF concentrations from Li-ion battery fire are acutely dangerous to first-responders and the community at very low atmospheric concentrations. The technical resources to incorporate this information into existing test protocols are available, and the omission of this information from the test method priority standard indicates an acceptable risk to human and environmental health relative to fire and explosion risk that is open to debate at the large-scale BESS deployment currently underway.

6.1.3 IEC 62933 and IEEE Standards: Operational Breadth, Lifecycle Gap

For stationary ES, IEC standards, particularly the series IEC 62933, are developed with respect to performance, safety, and testing of electrical energy storage systems. Technical standards for interconnection and integration into the grid include IEEE standards, such as IEEE 1547 for interconnection and IEEE 2030.2 for integration. Collectively, these sets of standards address technical aspects of the installation and operation of ES. The shortcoming shared by the IEC and IEEE standards is that they do not address the upstream (manufacturing) or downstream (end-of-life) phases of the lifecycle (Vartanian et al., 2021).

Currently, there are no harmonized international requirements for BESS products to disclose lifecycle assessment findings. Unlike in the construction sector and other electronic equipment where product environmental declarations are being increasingly required, no countries mandate the disclosure of lifecycle assessment results for grid-level energy storage in procurement policies. This puts environmentally preferable products at a disadvantage as they cannot compete with other products on cost alone, with no responsibility for environmental impact throughout the product lifecycle factored into the certification process.

The IEEE standards provide guidance primarily in the form of recommended practices in BMS integrity, system design, and performance metrics, which complement the hardware-centric approach of UL and IEC standards. According to M. He et al. (2024), a sound battery management system is essential to ensure battery cells operate within safe limits throughout the life of their installation. While the emerging IEEE working groups on BMS practices for energy storage are a step in the right direction, the focus areas of these groups do not address the lack of software integrity and commissioning oversight standards where incident investigations have found potential contributing factors to thermal events.

6.1.4 UN 38.3: Transport Safety as a First Quality Gate

UN 38.3 addresses transportation safety of lithium battery cells and modules from factories to installation locations worldwide. The qualification tests stipulated in this standard (including altitude simulation, thermal cycling, vibration, shock, external short circuit, and overcharge tests) are designed to validate that the cells can sustain the mechanical and environmental stresses during the transportation process without any latent defects that may cause failure upon use(Vartanian et al., 2021) .Thus, the UN 38.3 standard acts as a first quality gate in conjunction with the installation and use standards.

From a lifecycle perspective, it is important to note that the UN 38.3 covers only the transport phase of the lifecycle. This standard does not include the environmental performance, safety, or end-of-life considerations for the manufacturing, operational, or end-of-life phases. Plus, any damage that occurs during transport may not be immediately evident during commissioning and testing procedures following the installation of the BESS, which is an obvious limitation of poor-performing batteries in the context of the UN 38.3 certification process.

Table 9. Comparative Overview of Major International BESS Safety Standards

Standard	Primary Scope	Key Strengths	Lifecycle/Environmental Coverage	Critical Gap
NFPA 855	Installation safety: ventilation, spacing, fire suppression	Thermal runaway mitigation; baseline fire protection for Li-ion BESS	None — no LCA, EOL, or emission characterization requirements	No toxic plume or manufacturing environmental standards
UL 9540 / 9540A	System certification; thermal runaway propagation testing (cell to installation)	Staged TR propagation methodology; gas accumulation and deflagration risk data	Absent — toxic gas species (HF, HCN) not characterized; no environmental dispersion assessment	TR testing does not address ecological or public health hazard profile
IEC 62933	System performance, safety, and testing for stationary storage	Broad technical requirements across performance and safety dimensions	No mandatory LCA disclosure; lifecycle blind spot upstream and downstream	Market failure: cost-only procurement decisions externalize environmental costs

IEEE Standards	System design, BMS practices, grid interconnection	Operational safety via BMS integrity; augments UL/IEC hardware focus	Minimal lifecycle coverage; operational focus only	Software integrity and commissioning governance remain underdeveloped
UN 38.3	Transport safety of lithium cells and modules globally	Quality gate prior to installation; detects latent defects from transport stress	Focused on transportation only; no operational or EOL provisions	Pre-installation damage from transport may go undetected post-installation

Source: He et al. (2024); Larsson et al. (2017); McKinnon et al. (2022); Vartanian et al. (2021)

An overview comparison between the standards is given in Table 6.1. In summary, the most comprehensive in addressing thermal runaway propagation testing is UL 9540A; installation-level fire safety standards is NFPA 855; operational system standards is IEC 62933 and IEEE; and transport integrity is the UN 38.3. A major deficiency in all the standards is the lack of embedded environmental and lifecycle accountability aspects, such as manufacturing impacts, toxic emissions governance, second life usage validation, recycling safety, and post-fire contaminant remediation.

6.2 Regional Regulatory Frameworks

While lithium-ion BESS present similar physiochemical risks in a technical sense regardless of location, regulatory approaches differ as they are shaped by differing institutional contexts, energy transition paths, and policy priorities. A comparison of North American, European, and Asia-Pacific regulatory contexts suggests that overall they have been shaped by concerns about integration into an existing market or grid system and grid safety. Other issues related to battery use and end of life, including recovery of materials, hazardous wastes, and other contamination impacts related to accidents and spillover effects, have only marginally been included (Elliot et al., 2025).This is a crucial and compounding imbalance.

In North America, regulatory oversight is generally designated to federal, state, and local authorities. Access to the storage market is governed by the Federal Energy Regulatory Commission, while safety standards, such as NFPA 855, are enforced by local authorities having jurisdiction(Vartanian et al., 2021) .While federal and state deployment incentives, including production tax credits, energy storage mandates, and portfolio standards have fueled the significant uptick in battery deployment, the environmental standards governing battery life cycle and remediation after accidents are established and enforced by different authorities. Without a unifying federal standard that addresses environmental impacts of BESS life cycles, installations are rapidly rolling out.

Within Europe, energy storage is also positioned explicitly as a decarburization tool. The Clean Energy for All Europeans Package states that storage should be used to decarbonize energy systems and that member states must remove obstacles to the market Elliot et al. (2025) Regarding safety, the European system follows the lead of the International Electro technical Commission (IEC) for standards, ensuring harmonization with the international standard-setting body. But, there is no attention to environmental impacts such as sourcing of critical raw materials, toxicity of battery electrolytes, or the ecological effects of large-scale fires. The EU policy framework also considers circularity, more so than the North American frameworks—the EU Battery Regulation sets new requirements for using recycled material in batteries, disclosing the carbon footprint, and collecting used batteries at end-of-life—but still not enough to oversee the lifecycle of batteries fully. Slight harmonization complexity is added for storage system developers who want to offer grid services in multiple countries, with individual member states setting their own rules for participation in grid support services, but this does not add any controls for environmental impact.

In the Asia-Pacific region, various regulatory approaches match the ambition and scale of energy transition. China’s state-led approach to deployment has focused on volumes and the integration with grid infrastructure; but, the centrally controlled approach does not equate to an encompassing oversight over the full lifecycle or environmental impact, with recycling infrastructure being one regulatory area that lags behind relative to deployment. The regulatory approach of Japan changed significantly after the Fukushima disaster with resilience of the grid as a crucial focus through institutional support for BESS; though, the oversight over the full lifecycle or environmental impact lags behind relative to the ambition for increasing BESS. In Australia, the largely market-driven approach allows for storage to participate in different energy markets, including wholesale or ancillary service markets; however, the provisions for lifecycle governance lag behind relative to the scale of current and proposed deployment(Elliot et al., 2025).

In comparison, it is clear that in all three regions, the regulations that influence the deployment of BESS are motivated by concerns related to energy markets and safety for the electric grid, while issues related to the environmental and life cycle aspects of these technologies—such as toxic waste, harvesting of rare earth materials, and chemical emissions from fires—are viewed as secondary rather than equally important. Considering the hazardous nature of materials used in and disposed of by batteries, this poses a risk in governing these technologies that is not adequately highlighted in the literature that compares all three regions. Moving forward, each region will need to explore regulatory developments where safety, environmental, and life cycle aspects are considered equally vital.

6.3 Evolution and Gaps in Safety Standards: A Critical Assessment

The development of safety standards for grid-scale lithium-ion BESS has been reactive to incidents, with the efforts moving upward in scope and scale regarding system safety. For example, in the last decade, safety standards have evolved from addressing only electrical or component safety to consideration of thermal runaway, fire spread, and gas emissions (Mylenbusch et al., 2023). Although this is progress, the reactive nature of the standards means that these hazards are not addressed until there is a clear demonstration of the consequences, which potentially could have cumulative impacts on the environment or public health.

The McMicken, Arizona fire and the Victorian Big Battery fire (in Australia) are recent examples where the facility was within the existing standards. In both these fires, the currently used standards underestimated the coupling of cell failure mechanisms with system-level factors such as installation geometry, ventilation, and cascading behavior, which is essential for understanding the environmental impact of large thermal events (release of toxic and site contamination beyond the cell installation).

Concerning lifecycle-relevant gaps, I highlight two additional areas of flammable gases and toxic emissions from fire that are critically lacking. Regarding the former, when thermal runaway occurs, hydrogen and other flammable gases such as methane are generated in the immediate space. While NFPA 855 does have some requirements for ventilation and detection, we do not have standardized testing that would help characterize the generation and diffusion of the gases under real-use conditions at the installation scale (Lystianingrum et al., 2023). The latter—lithium-ion battery fire toxic emissions—are known to be toxic to first responders and the public in the immediate areas of a fire event. Larsson et al. (2017) and Rappsilber et al. (2023) provide valuable information regarding hydrofluoric acid (HF) production rates and smoke gas analysis of different battery chemistries. Presently, there is little guidance that comes from the existing standards in providing guidance to first responders and understanding the risks after an event. This is also an environmental stewardship failure since contaminated firefighting water and released toxic chemicals present real environmental risks far beyond the immediate event.

Another underestimated gap relates to operational and software governance. Software errors and commissioning procedures have contributed to thermal incidents according to incident investigation reports, but the current standards predominantly address hardware design rather than operations, system monitoring procedures, and software checks (Lystianingrum et al., 2023). This approach reflects a conceptual gap in the definition of safety, which is defined as a property of an installation at a given time rather than a continuous safety obligation in terms of operational practices.

Most critically, while existing standards (e.g., UL 9540A, NFPA 855, IEC 62933, UN 38.3) provide relatively strong guidance for installation and operational safety, the end-of-life, second-life battery testing, recycling safety, and environmental contamination after incidents are lacking. As noted by Christensen et al. (2021), risk management for lithium-ion batteries must be considered throughout the lifecycle, from raw materials, manufacturing, use, and end-of-life processing, but existing certification processes do not. A system can be fully compliant with regulations over its operational life and have no path for dismantling, recovering hazardous materials, or remediating contaminated waste. The environmental impacts over the lifecycle of the battery systems are effectively externalized from the official certification process.

Future iterations of these standards will need to consider the safety certification process as a lifecycle process, where the battery installed in the system evolves through use. This will require not only a broadening of the standards to include LCA disclosure, a characterization of toxic emissions, and end-of-life management, but also a shift in the regulatory process that drives the creation of these standards.

7 Case Studies of Major BESS Incidents — Failure Mechanisms, Environmental Consequences, and Governance Gaps

Grid-scale lithium-ion battery energy storage systems (BESS) have experienced a series of high-profile incidents whose consequences extend well beyond the boundaries of conventional fire safety analysis. This chapter examines four primary case studies — McMicken (USA, 2019), South Korean ESS fires (2017–2019), the Victorian Big Battery (Australia, 2021), and a set of additional global incidents — to conduct a critical comparative analysis of failure mechanisms, cascading environmental hazards, and the lifecycle dimensions that incident-centred safety governance has systematically underestimated. Across all cases, a structurally consistent pattern emerges: the most consequential outcomes arise not from the initiating thermal event itself, but from the subsequent release and delayed ignition of flammable and toxic gases, the environmental contamination associated with fire suppression, and the irreversible loss of recoverable battery materials — impacts that current safety standards are not designed to capture or govern.

7.1 McMicken Battery Fire, Arizona, USA (2019)

A prominent event in the history of grid-scale Li-ion safety incident was 19 April 2019 at McMicken BESS, a 2.16 MWh grid support systems (UL Firefighter Safety Research Institute et al., 2020) ,which showed a sequence of failure where the peak hazard was after the apparent fire suppression, not during it.

Items 1 through 8 show a failure that appeared to progress along the well understood path of a thermal runaway that begins when electrochemical reactions inside a cell outpace the ability of the battery management system to prevent excessive heat buildup independent of the presence of external oxygen(Feng et al., 2018; Mylenbusch et al., 2023). Instead of there being a thermal barrier between cells and modules, a design deficiency led to propagation across the entire installation. Close et al. (2024) note that the design element of heat transfer pathways between the cell and module levels being controlled and not optional failed at McMicken, which enabled multiple electrochemical failures.

At McMicken, the environmental risk was not actually the fire itself, but the buildup of gases that preceded the fire. Thermal runaway produces hydrogen, hydrocarbons, and other toxic fluoride-containing gases such as hydrogen fluoride (HF), which can accumulate in confined spaces with limited ventilation (Baird et al., 2020; Larsson et al., 2017). At McMicken, four first responders were injured when the enclosure was opened, oxygen mixing with trapped gases that caused a deflagration (UL Firefighter Safety Research Institute et al., 2020). Larsson et al. (2017) note that HF levels from Li-ion battery fires can become elevated beyond acute exposure levels well outside the immediate area where the batteries are installed, and no assessment of toxic gas spread was undertaken in the environmental remediation after McMicken. In other words, the environmental and health impacts of the airborne release of hydrogen fluoride and contaminated fire suppression runoff were unknown and unregulated.

Comparing McMicken to the generic literature on hazards, two features stand out. First, Baird et al. (2020) indicates that the build-up of gases and explosion risk is a predictable outcome of confined thermal runaway, but the test regime at the time of McMicken did not include gas speciation or dispersion. Second, the battery chemicals that are burned at the end of the fire (lithium, cobalt, and manganese compounds) are effectively lost, leaving a pathway of these materials that is currently non-existent to close at the end of life of the battery. The combination of toxic release with no controls over dispersion and end of life destruction of battery chemicals is the quintessential failure of controls to a risk assessment at a certain point in time as the sole governance mechanism.

7.2 South Korean ESS Fire Incidents (2017–2019)

The twenty-three ESS fire incidents reported in Korea between 2017 and 2019 are the closest to a detailed recurrent series of failures available in the global BESS incident record, and they are notable for their unexplained root cause(Na & Jeon, 2023) .Two government agencies came to different conclusions, and the incidents recurred despite interim remedies.

Both studies point out that the majority of the fires observed were at or near the maximum charge level; a number of the sites had raised their SoC limits shortly before the fires (Na & Jeon, 2023). Liao et al. (2020) show experimentally that a high SOC significantly lowers the thermal runaway initiation energy barrier, increasing the risk posed by latent defects, thermal fatigue, and anomalous cell behavior. In this regard, Na & Jeon (2023) are cautious to not consider high SoC as a causal factor, but rather an exacerbating condition that contributed to the failure. This has implications in the standards perspective - SoC limits if set alone, without addressing the root defects in the cells and BMS error reporting, are a corrective measure halfway done.

From the perspective of detection and monitoring, the research from South Korea clarified that while the anomalies at the voltage level were detected, they were not at the temperature level. Through an analysis of BMS data, they found low-voltage anomalies, indicating the onset of internal short circuits, emerged much earlier than did temperature-related readings as currently available sensors did not sense the temperature within modules (Na & Jeon, 2023). Consistent with this finding, Jeevarajan et al. (2022) observe that the lag between electrochemical early signals and existing thermal alarms is a shortcoming of the BMS. The implication is that early signs of onset were not captured by the monitors and sensors in place at the Korean sites, and the difficulty in reconstructing what happened post-incident has been overlooked in revisions to codes and standards.

The most troubling aspect of this series is that, despite the corrective measures taken, the incidents continue to occur. Unlike the other incidents in this chapter, this series suggests that where systemic design issues exist within an installed base, point-in-time fixes addressing the aggravating factors are futile. With each recurrence of the incidents, irrecoverable battery materials were lost, harmful waste products were produced, and toxic fires ignited, none of which differences in the cumulative environmental impact of the series of incidents were discussed nor factored into the corrective actions. This is the great gap in the literature on safety silos: the cumulative environmental impact of a series of recurring incidents has not been examined.

7.3 Victorian Big Battery, Australia (2021)

Another example is the Victorian Big Battery (VBB) fire, which occurred during commissioning on 30 July 2021 when protection systems were deactivated, providing a qualitatively different example of how compliant components can generate noncompliant outcomes in situ (Blum, n.d.; Matich, n.d.).

The official investigation identified the initiating fault as a coolant leak inside one Tesla Mega pack unit, which created an internal short circuit that developed into thermal runaway and fire (Blum, n.d.). The commissioning context is critical. The affected Mega pack was out of service for maintenance, which disabled telemetry, active cooling, and protection systems — multiple safety layers were concurrently taken out just as the initial fault occurred (Blum, n.d.). This is not a design failure but a governance failure, failing to realize that the transitional operational state of commissioning is a period of heightened system vulnerability that requires compensatory monitoring and protective protocols.

This propagation from the first to the second, active Mega pack used in the test under prevailing wind conditions points to a second key takeaway: the thermal runaway propagation testing under UL 9540A the compliance test for the separation at the unit level did not replicate the actual test conditions of wind direction, installation configuration, and radiant heat flux that resulted in propagation at VBB(Mylenbusch et al., 2023) .Karmakar et al. (2024) show analytically the extreme sensitivity in propagation in a battery module to boundary conditions such as airflows and thermal loads that are difficult to replicate in lab tests. The VBB test therefore points to a limitation in safety based on compliance testing: the test conditions of the test may not replicate the expected deployed conditions, especially for larger scale outdoor installations where environmental parameters can differ.

From an environmental and lifecycle perspective, the VBB event also represents a total loss, as two Mega packs were considered unrepeatable. The water used to suppress the fire and contaminated with battery electrolyte, fire, and fire-extinguishing agent chemicals was an unassisted risk to soil and runoff. Again, similar to the extensive literature review of BESS incidents, there is an absence of standards, codes, practices, or guidance that addresses accountability for the environmental impact after an incident, as there is no mention of this in the literature discovered. The response, including creating a risk perimeter, use of white suits, and active presence over several hours or days as opposed to efforts to extinguish a fire in a thermal runaway chain, as observed at VBB, seems to be developing as best practice(Matich, n.d.), and this should also be reflected in any official guidance.

7.4 Additional Global Incidents: Beijing, Liverpool, and Moss Landing

The independent investigations by Lystianingrum et al. (2023) of the Beijing Jimei Dahongmen incident (2021) and by Zalosh et al. (2021) of the Liverpool Carnegie Road fire (2020) confirm from the McMicken experience that effects from confined accumulations of gases, generated after a thermal runaway event, are of greater damage than the fire(Lystianingrum et al., 2023; Zalosh et al., 2021) .In both the Dahongmen and Carnegie Road cases, accumulated flammable gases, hydrogen and hydrocarbons generated during thermal runaway, slowly vented into poorly ventilated areas where delayed ignitions created pressure impulses that damaged the structure. Zalosh et al. (2021) review several explosion events related to BESS and EV battery packs and conclude that risk of confined deflagrations is not properly treated in ventilation requirements. Ventilation calculations are being done to mitigate against combustion occurring on a single battery cell or module during normal thermal events rather than the potential rates of gas generation if a large number of battery cells or modules undergo a cascade of thermal runaways in a container. (Baird et al., 2020) provide quantitative analysis of vent gas explosion risk and similarly conclude that ventilation calculations based on a normal operation scenario are not adequate to deal with thermal runaway scenarios involving venting of individual battery cells or packs in containerized systems.

Environmental impacts from either event (release of toxic aerial compounds, explosion debris, and polluted fire suppression water) were not studied, and no standards applied. New experiments (Austin Zhang, 2025) on battery waste leachate show clearly measurable toxic effects on plant growth from lithium and nickel compounds at environmentally relevant levels, indicating that the environmental impacts of fire suppression water contamination at BESS fires may be far greater than previously thought. The disconnect between known chemical toxicity of battery materials and environmental remediation standards after incidents is one of the largest blind spots in BESS safety standards.

The latest incident from California, at Moss Landing, indicates another failure mode where the cause of operational disruption includes not only thermal runaway but also equipment and software sequencing errors (Lystianingrum et al., 2023). Water discharge, precipitated by error in the control software, led to extensive operational disruption and shut down—without the fire propagation dynamics seen in the other incident cases. This case is significant in demonstrating that risks in BESS systems at grid scale are not limited to electrochemical failure alone. As cited above, fault propagation through software is one of the areas not sufficiently explored in detecting faults in BESS systems (Samanta et al., 2021). This incident indicates that software commissioning rules, largely outside the mainline certification documents and standard practices, are a potential risk factor for safety and operational incidents. The impact of water discharge on contamination was not assessed in this incident case, similar to all other above-mentioned cases.

7.5 Comparative Analysis and Lessons for Lifecycle-Informed Safety Governance

A comparative summary of the incidents discussed in this chapter is shown in Table 7.1. Beyond the uniqueness of each case, the comparisons highlight recurring patterns that present issues in relation to current safety governance regimes, particularly with regard to environmental and lifecycle aspects.

Table 10. Comparative Summary of Major BESS Incidents (2017–2021)

Incident	Year	Location	Primary Failure Mode	Cascading Hazard	Environmental / Lifecycle Impact	Key Regulatory Gap
McMicken BESS	2019	Arizona, USA	Thermal runaway; inadequate gas venting	Flammable gas accumulation; delayed deflagration injuring first responders	Contaminated suppression residue; destroyed recoverable battery materials; toxic HF release	No gas speciation or dispersion standard; no toxic emission protocol
South Korean ESS fires	2017–2019	South Korea	High-SOC electrochemical stress; latent cell defects	Cell-to-module fire propagation; recurrence despite interim corrective action	Repeated destruction of battery assets; materials unrecoverable; persistent hazardous waste streams	No mandatory SOC ceiling in standards; inadequate BMS fault-logging requirements

Victorian Big Battery	2021	Victoria, Australia	Cooling-system leak causing internal short circuit	Inter-unit fire spread under wind conditions exceeding test parameters	Loss of two Megapack units; suppression water contamination; end-of-life pathway undefined	UL 9540A tests do not replicate real-world wind/geometry; commissioning safety gap
Beijing Jimei Dahongmen	2021	Beijing, China	Flammable gas accumulation in confined space	Explosion; severe structural damage to installation	Site contamination from explosion and suppression; hazardous debris; material loss	Ventilation standards insufficient for confined large-scale installations
Liverpool Carnegie Road	2020	Liverpool, UK	Thermal event with gas build-up	Explosion following delayed ignition of accumulated vent gases	Toxic gas release to atmosphere; contaminated runoff; no post-incident LCA framework	No real-time gas accumulation detection requirement in standards
Moss Landing (Phase 1)	2021	California, USA	Equipment integration failure; software/control error	Accidental water discharge; operational disruption; system shutdown	Suppression discharge environmental contamination; loss of capacity; recovery undefined	Software and commissioning governance absent from certification standards

Sources: Austin Zhang (2025); Blum (n.d).; Lystianingrum et al. (2023); Matich, (n.d).; Na & Jeon (2023); UL Firefighter Safety Research Institute et al. (2020); Zalosh et al. (2021)

This temporal displacement manifests as the most hazardous impacts — gas accumulation, delayed ignition, explosion, toxic compound release, and suppression contamination occurring not at the moment of thermal runaway, but as follow-on effects, being the most structurally significant factors in all incidents. Both Lystianingrum et al.

(2023) and Zalosh et al. (2021) recently observe that this cascade of events leading to harm is also a feature of grid-scale BESS incidents, but in the safety governance literature, this insight has yet to be reflected in standards that address the cascade of consequences, not just their trigger.

In every instance examined, the failures of apparently standards-compliant installations were not the result of the malfunction of individual components. The standards being written and assessed against components rather than systems and their real-world function. This strategic absence of standards is analyzed in Chapter 6, along with governmental reaction to this gap in Chapter 8.

The environmental and lifecycle impact chain is even further missing for all incidents discussed. In all incidents, the lifecycle value of the battery material – lithium, cobalt, manganese, nickel, among other components – was lost, and irreparable. It is not clear what extent of hazardous waste and toxic gases were generated by burning and suppressed fire or in what manner the toxic suppression chemicals have contaminated the environment; these details were again missing in all these published incident reports. Close et al. (2024) comment on the structural 'lack of responsibility for the lifecycle or end-of-life phase' regarding the safety aspects of BESS; this comparative analysis of the different incidents provides examples that confirm this observation. None of the incidents reviewed had a post-incident evaluation of lifecycle impact, or the standards cited in the precedent case studies demanded one.

Collectively, the main lesson from these examples is not the failure of any one of these protections, but how safety governance more broadly is structured to address the point-in-time compliance of establishing an installation, rather than the broader trajectory of electrochemical failure, emission, and loss of materials. Safety governance going forward will need to consider the safety of BESS not as being in a state of safety at the time of installation, but a lifecycle responsibility of mitigating the consequences of thermal events, understanding the toxic cocktail, controlling discharges from fire suppression, and recycling lost materials – none of which is currently addressed in the relevant standards that we reviewed in Chapter 6.

8. Discussion and Synthesis

8.1 Synthesis of Identified Safety Challenges

The safety issues for grid-scale Li-ion BESS discussed in Chapters 2 to 7 have something in common, and that is: these safety issues are not limited to the operational phase only, as traditionally assumed, but are distributed across the entire lifecycle of the battery, including extraction, manufacturing, commissioning, operation, second life, and end-of-life disposal. Having a safety framework addressing only the operational phase leaves out addressing the risks occurring at the boundaries of various lifecycle phases, where they are often the most severe and environmentally impactful.

Manufacturing quality is a safety input that cannot be compensated further down the safety mitigation chain. A cell that leaves the factory with even a minor defect—such as a metallic particle, micro perforations in the separator, misalignment of electrodes—has a temperature-triggered time bomb installed in its chemistry. Chapter 3 shows that incidents are most common in the early deployment phase. Manufacturing quality improvements and stricter commissioning governance represent the highest use actions from a safety standpoint. They are also among the most effective strategies for reducing environmental impact. Galushkin et al. (2018) show that higher states of charges and cumulative cycles independently lead to lower thresholds of a thermal runaway to trigger, and Hwang et al. (2025) show that the risk of thermal runaway increases non-linearly from the beginning-of-life to end-of-life. Thus, our research points to manufacturing quality improvement as one of the highest-use safety interventions with minimal cost, which is currently completely ignored by safety standards.

The environmental impact from this manufacturing-safety coupling is similarly significant. Le Varlet et al. (2020) calculate manufacturing-stage greenhouse gas emissions of 40–100 kg CO2-equivalent per kWh for the prevalent grid-scale chemistries. The embodied environmental costs of a latent-defect-induced failure cell are lost, and then compounded by hazardous gas emissions, fire suppressant contamination, and permanent loss of the easily recoverable electrode materials. The fact that a failure in the manufacturing stage results in wasted embodied carbon and contamination from the incident makes improving manufacturing quality the most effective safety remedy and, as I will discuss, one of the most effective environmental remedies. The existing regulatory regimes do not directly account for this dual role. Chapter 2 showed that, compared with NMC and NCA, LFP is safer with respect to convergent safety and environmental considerations, which has implications for the risk and lifecycle aspects of the system.

Operational risk is dynamic and accumulates as the battery ages. By far the most demanding use for a BESS is frequency regulation, which involves high-rate partial cycling. This use accelerates the growth of SEI, causes lithium plating, and introduces mechanical fatigue in the electrodes. All these aging mechanisms not only reduce the service life of the batteries but also gradually reduce the thermal safety margin. To the best of our knowledge, this coupling among the operational strategy, the safety margin, and the environmental effects has not been considered in any existing operational framework controlling the BESS dispatch.

At the other end of the lifecycle, end-of-life challenges present potential hazards that are not accounted for in operations and maintenance frameworks but will increase in magnitude as the first wave of grid-scale systems reach end-of-life. Christensen et al. (2021) detail that spent batteries with lower electrochemical stability, remaining charges, and degraded separators will require novel and standardized processes for pre-treatment and recycling that are currently unavailable. Wu (2026) highlights that the generation of flammable gases and exposure to reactive materials are the key hazards asSoCiated with spent battery recycling and are exacerbated relative to primary precautions for operating cells of the same mass as cell wear is already present. Austin Zhang (2025) shows that release of electrode materials has phytotoxic impacts at realistic concentrations, highlighting the need for protocols and infrastructure to manage the end-of-life of LIBs as deployment scales up.

8.2 Evaluation of Mitigation Strategies

Collectively considering Chapters 4 and 5, the most protective set of mitigation strategies is the set including the strategies targeted to the specific hazard stage in combination with the strategies addressing the neighboring stages. Developing BMS strategies independent of thermal management and fire suppression strategies independent of gas buildup mitigation strategies lead to a system that is not integrated where that system integration is needed and where incidents regarding BESS have occurred (see Section 2.4).

Currently deployed systems direct the first safety action upstream in the BMS-based monitoring. Inside the battery, this approach is inherently limited by the challenge of internal fault detection. The dominant battery defects that can cause a thermal runaway event such as manufacturing flaws or dendrite regrowth are initially indistinguishable from cells undergoing normal aging when viewed through the lens of external measurements. Guo et al. (2026) prove experimentally that aged external battery cells with internal defects respond identically to healthy cells aged externally. Zhang et al. (2018) show the degradation of SOC estimation accuracy in cells as they age. The promising technologies highlighted in the literature review above—electrochemical impedance spectroscopy, multiple gas sensing, and machine learning-based anomaly detection methods—can potentially help increase the lead time and improve detection but the fundamental challenges remain. Machine learning methods are constrained by the quality of training data (Samanta et al., 2021)—an issue that is dominantly a data governance problem that requires a regulatory fix and not a technological one.

Thermal management systems provide a second layer of defense. Active liquid cooling with sufficient temperature homogeneity reduces the risk of thermal runaway initiation by keeping cells in their safe operating area during high power charge and discharge. PCMs offer a further delay to propagation by passively absorbing latent heat, providing additional time gap between thermal runaway initiation and propagation(Calborean et al., 2025; Hemavathi et al., 2026; Olabi et al., 2022). Neither can prevent thermal runaway once triggered, thus upstream risk mitigation remains paramount. Environmental consequences of thermal management systems, including waste/liquid coolant and embedded carbon of PCM, are seldom quantified in safety analysis.

Fire suppression (final escalation), where the evidence for efficacy in lithium-ion fire hazard mitigation is the most controversial. As discussed in Chapter 5, effective mitigation requires combined suppression strategies, including cooling, gas management, and detection systems. Water mist is more effective at cooling the test environment, but the water runoff is contaminated with toxic residues from the burnt battery components. Gaseous suppression agents, such as CO_2 or halon replacements, rapidly knock down fire flames, but these agents do not suppress the internal chemical degradation that fuels subsequent flame re-ignition. In addition, halon replacement agents like HFCs have global warming potential thousands of times greater than CO_2. Aerosol suppression agents (dispersing fine particulate matter to snuff out free radicals that self-sustain fire flames) were assessed by Subash et al. (2025) and found to be less effective in extinguishing a premixed hydrogen-rich flammable gas environment which can build up prior to ignition during lithium-ion venting. The global warming impacts of the choice of suppression agents have not been considered in safety comparison studies to date.

Emergency response is the last line of defense. Its success is dependent on the development of protocols specific to BESS and the training of first responders in those protocols. Chapter 7, in the analysis of the McMicken incident, illustrates this point: the lack of development embedded in the response communicated apparent suppression success that gave little indication of the actual state of gas accumulation in the interior, and personnel entering that area based on visual cues rather than gas concentration readings were harmed by the ensuing deflagration. Together, these findings confirm the regulatory critique developed in Chapter 6. Compliance-based approaches focus on validating installation states rather than lifecycle system behavior, leaving governance structures incomplete for the most critical risk categories.

8.3 Multi-Layered Safety Framework

Drawing from the discussion of the evidence presented in Chapters 2 through 7, this thesis proposes an integrated safety and sustainability framework consisting of six layers. The proposed framework differs from a traditional safety and sustainability framework in two respects: (i) it is an explicitly lifecycle-oriented framework that addresses the lifecycle of a system from material sourcing to end-of-life, and (ii) it includes environmental alongside safety performance in each layer, where environmental and safety outcomes are addressed together instead of separately as two equal objectives.

Prevention in Layer 1: Manufacturing quality and chemistry selections. As established in Chapter 2, chemistry selection is an irreversible lifecycle commitment. LFP is identified as the preferred option for stationary grid applications due to its aligned safety and environmental advantages. Manufacturing quality assurance with tighter quality controls, standardized inspection procedures, and third-party audits will help minimize latent defect rates which have been identified from the incident data to be the primary cause of failures in the first few years of deployment.

Layer 2—Monitoring, Detection, and Condition Assessment: Continuous monitoring of multiple parameters including voltage, current, temperature, gases, and electrochemical impedance provides information about the precursor conditions. See et al. (2022) show that cell-level voltage monitoring is critical as measurements at the pack level obscure important deviations at the individual cell level that could have safety implications long before the pack-level parameters are reached. Machine learning in conjunction with multi-sensor and multi-parameter monitoring enhances detection capabilities beyond that of a threshold-based model, and the battery SOH monitoring can be used for condition-based end-of-life decisions to extend the life and delay the environmental impact of replacement.

Layer 3 − Thermal Management and Passive Containment: The active liquid cooling can provide a temperature management function over normal operation, while the incorporation of PCM can also provide some time delays for the incipient thermal events. Thermal barriers, ceramic, intumescent, or integrated with PCM, can provide passive containment of one cell or module independent of the active systems and even after they have ceased to function. The environmental characteristics of the thermal management systems should be taken into account as part of the LCA of the whole system, such as the chemistry of the coolant, energy requirements, and potential replacement, and disposal at EoL.

Layer 4—Gas management, ventilation, and explosion prevention. The gas detection, ventilation, and explosion relief addressed in this layer both address the pre-ignition venting that is unique to lithium-ion thermal events as well as the subsequent cause of the most damaging BESS incidents. Rappsilber et al. (2023) estimate total gas volume of (3-48 mmol/Wh) depending on chemistry and state of charge. Baird et al. (2020) show increasing concentrations of hydrogen and CO as state of charge increases, meaning the most operationally desirable state is also the most explosively dangerous state. This layer is the most regularly missing from current safety practice and regulatory requirements.

Layer 5—Active fire suppression and emergency response: Fire suppression agents should be considered based on their intended fire protection and potential environmental impacts after the event. Combining various technologies, such as water cooling, gas ventilation, and waste removal strategies, will provide more effective hazard mitigation than using any one suppression agent alone. Emergency response procedures should be tailored to the BESS and the site. In particular, the potential for delayed ignition and re-ignition distinguishes lithium-ion battery incidents from traditional fires. Provisions for potential environmental impacts after a fire event, including management of respective gas plumes and suppression water run-off and treatment, as well as soil and drainage monitoring, should be an integral part of emergency site plans.

Finally, Layer 6, Lifecycle Governance, End-of-Life Management, and Incident Learning, which surrounds all inner layers. For its importance, this is the one that is currently least developed. A standardized incident reporting including chemistry-related information, battery lifecycle phase, and subsequent characterization of environmental impact is essential to provide data for predictive safety analysis and standard updates based on evidence. Harmonized lifecycle regulation incorporating environmental standards for manufacture, safety requirements for use and operation, second life qualification, and directives governing end-of-life would provide the key governance framework within which responsible scale-up can take place.

8.4 Safety, Cost, and Performance Trade-offs

As established in Chapter 2 and supported by the mitigation evidence in Chapter 4, procurement frameworks that priorities liveliest cost tend to externalize lifecycle safety and environmental costs. This means decisions are often driven by short-term economics rather than long-term system performance and risk. Vykhodtsev et al. (2022) explain the underlying mechanism, showing that degradation-aware modeling largely absent in current commercial practice changes the economic picture. Without it, optimization for near-term revenue can unintentionally accelerate capacity fade and system stress. This in turn increases the likelihood of thermal events while also driving higher replacement demand over time.

The exclusivity on safety versus cost extends to the selection of battery chemistry. NMC is also popular due to its lower cost per kWh compared to LFP; but, it results in higher CO2e manufacturing impacts, greater supply-chain emissions and risks in terms of cobalt and nickel mining and refining, more significant thermal runaway risk, and more complex end-of-life processes compared to LFP battery chemistries. Kiemel et al. (2021) evaluated the criticality of material supply risk in different battery chemistries and concluded that NCA is the most and LFP is the least at risk of material supply disruptions. If the true costs of thermal incident probability, supply chain environmental costs, and end-of-life complexity were incorporated, LFP batteries used for stationary applications would have a greater cost advantage.

A similar problem is that safety and environmental aspects are not sufficiently considered in system sizing. Jaradat & Khatib (2025) conclude that an optimal sizing exercise must consider, in addition to cost, the degradation pattern, safety factor, end-of-life (or end-of-design) limits, and environmental factors. Due to the absence of holistic techno-economic-environmental-safety models, the current practice either uses cost-based optimization, which may result in undersized systems with high safety and environmental risks, or applies arbitrary safety factors, which may result in oversized systems with unnecessarily high environmental impact.

Policy and market structure impact internalization of safety and environmental considerations. Without market structures that price ancillary services according to the risk of reliability and safety incidents and the impact on environmental burden across the lifecycle, there is an inherent push for reducing cost over improving quality. Likewise, without policy that requires the disclosure of LCA, third-party validation of safety standards, and a standardized reporting of safety incidents, externalities build up into public incidents whose cost is borne by the operators, the public, and the ecosystems rather than by the purchasing decision that created the inherent vulnerabilities.

8.5 Implications for Future Grid-Scale BESS Deployment

While there are certainly small gaps at the margins of individual research fields, the most significant gaps appear to be at the intersections of independently progressing research domains. The foremost of these is the absence of lifecycle assessment in the safety research literature and vice versa. LCA research provides key characterizations of environmental impacts but not the likelihood of safety incidents. Safety research provides insight into failure modes, but not the lifecycle environmental consequences of these failure modes. Direct emission of combustion products from potential thermal runaway incidents (kg-scale HF clouds, heavy metal particulates, VOC plumes, etc.) are not evaluated at all within the system boundaries of the lifecycle assessment, furthering the underestimation of the environmental impact throughout the lifecycle at an increasing rate with the severity and frequency of incidents.

The community is currently lacking a structural prerequisite for evidence-based improvement: a database of incidents. Al-Mahmodi et al. (n.d.) found that the concentration of failures in the early period following deployment is the most important conclusion that can be drawn from their small, patchily documented incident dataset. Machine learning approaches for fault detection, described by Samanta et al. (2021) as the most promising detection frontier, are similarly hindered by the absence of data. It is the missing elements of regulation on which the safety community can currently not draw to transform and improve governance based on experience that are recommended here: mandatory standardized incident reporting with chemical-specific data, lifecycle stage of failure, classification of failure mode, and description of environmental consequences.

First-generation large-capacity battery packs from grid-scale installations are expected to retire in the late 2020s and early 2030s, leading to an urgent need to address end-of-life safety and environmental management. Key research areas are standardized electrochemical testing for second-life applications involving further development of accelerated test methods that are sensitive to higher-temperature impacts on aged cells (Hwang et al., 2025); safe processing of heavily damaged batteries prior to disposal; development of recycling processes for LFP cells that lack the manufacturing infrastructure of NMC; and economic and environmental analysis of reuse, direct recycling, and hydrometallurgical recycling. Safety matrices of fire and explosion risks of recycling plants remain an underexplored area according to Wu (2026), who also addressed the need for safe recycling plants.

This research direction is critical to deploy advanced monitoring and predictive safety analytics but it is limited by the fact that the gap between sensed data and internal battery states that are relevant to battery safety is not directly addressed by further development of existing sensors. If these mentioned research needs are met, it can potentially lead to a significant reduction in the gap between the detection of internal faults to the protective actions, which is the safety gap responsible for escalation of thermal runaway in practical battery packs.

8.6 Recommendations for Industry and Policymakers

The BESS industry must embrace safety by design as its modus operandi. The selection of chemistry, separators, the thermal management architecture, BMS capabilities, gas management, and enclosure design will ultimately dictate the lifecycle environmental impact. Design optimization in the context of safety and environmental factors collectively, as opposed to one after the other in the hands of separate groups of engineers, is certainly possible but requires the organizational structure that connects safety engineers, environmental experts, and system designers at design inception.

A comparison can be drawn to lifecycle risk management and operational safety management. The former needs to come under significantly more stringent controls. The UK's infrastructure railway sector can provide an example. Before project approvals, grid-scale BESS installations should be required—by planning conditions—to supply lifecycle plans for the batteries. These lifecycle plans would need to outline details such as safety validation requirements during commissioning, monitoring the batteries in operation for safety validation through accepted degradation thresholds, maintenance schedules, end-of-life assessment criteria, and recycling plans. The lifecycle plans should undergo third-party audits at set points within the lifecycle and be revised according to the realized degradation patterns.

The implementation of mandatory LCA disclosures, combined with setting minimum environmental performance standards, can provide the mechanism to curb the market failure identified earlier where environmentally inferior products compete solely on purchase price. Similar to the EU Battery Regulation’s mandatory declaration of the carbon footprint per kWh, the percentage of recycled content, a responsible sourcing scheme, and disclosure of the battery recycling path at end-of-life, the regulations could be extended globally and adapted to the unique nature of the lifecycle of large-scale grid-connected systems. It should be a priority for policymakers to seek to harmonize the lifecycle regulations between jurisdictions to resolve the identified lack of governance at lifecycle transition points, where incident data highlights the hotspot areas of risk.

We must not wait for the end-of-life wave to hit before catching up on those areas. Research and development are needed to achieve safe lithium-ion battery recycling at grid scale, especially for LFP cells. Emergency response teams must be trained on the characteristics of lithium-ion battery fires and explosions to provide a quick and safe response.

8.7 Future Research Directions

The most significant research recommendation derived from this thesis is the development of integrated safety-LCA models. These would provide a mechanism, for the first time, to allow the environmental cost of a thermal runaway event (in terms of embodied carbon destroyed, toxic emissions generated, and subsequent contamination needing to be cleared) to be considered in comparative environmental assessments of BESS deployment.

Effective, large-scale techno-economic modeling is currently hindered by simplistic electrochemical battery models that inaccurately represent battery degradation and lifecycle costs. Achieving large-scale hybrid electrochemical-systems models that capture the multifaceted dynamics of battery degradation over multiple timescales (sub-second electrochemistry, cycle-level ageing, and multi-year lifecycle) is a computational science challenge with direct relevance to safety management.

Research questions around safety and the environment at end-of-life are immediate, dictated by the timing of the first generation installations reaching retirement rather than research programme schedules. There is a need for developing second-life battery qualification protocols, incorporating electrochemical characterization, thermal abuse testing, and probabilistic safety assessment that could identify the subset of aged cells as fit for repurposing. Development of recycling processes for LFP is particularly urgent because the chemistry with the best safety and environmental profile is the one for which commercial recycling routes are least developed, providing a perverse incentive to mismanagement at end of life, and requiring policy change and targeted research funding.

Developing the data infrastructure for incidents should also be a regulatory goal, not solely a research goal. The research contribution that we will need is a taxonomy to describe incidents—which includes the classification of the type of failure, the stage of the battery lifecycle, characterization of environmental consequences, chemistry description, and data fields to be logged in the BMS. This taxonomy will feed into mandatory incident reporting regulations via respective jurisdictions. These research directions described above reveal the genuinely interdisciplinary nature of the grid-scale BESS challenge, where the most difficult challenges lie at the boundary of electrochemistry, environmental science, data analytics, safety, economics, and regulations. Research approaches that encourage and help interdisciplinary will be the most fruitful in advancing this research field that has as much Social and environmental value as the rate of the energy transition that it aims to enable.

9. Conclusion

9.1 Summary of Key Findings

This thesis has provided a qualitative synthesis of the safety challenges and risk mitigation approaches of grid-scale stationary lithium-ion BESS, where the unifying perspective of the lifecycle and environmental aspects has received limited attention by existing research. It includes cell chemistry and manufacturing quality, operational failure mechanisms, risk mitigation architecture, regulation, and case studies of failure incidents, followed by integrative discourse and a proposed governance framework for risk management. The principal conclusions are largely interconnected, where each supports the argument that safety and environmental sustainability of grid-scale BESS emerge from a common set of design, operational, and governance practices.

The results of this research show that safe operation of grid-scale, lithium-ion BESS is not only a risk-management priority but a determinant of the sustainability outcomes across the lifecycle. Unsafe incidents especially thermal runaway will prematurely end the operational lifecycle of the system and its components, leading to the waste of embodied energy and materials, and create additional environmental impact from toxic emission and contamination. The findings show that system lifecycle sustainability benefits from BESS deployment will only be achieved if the systems are kept safe across all stages of the lifecycle. Safety and sustainability are co-determined and intertwined.

The first key finding of this thesis is the concept of co-determination as its central conclusion. First introduced in Chapter 1, it is demonstrated at the chemistry level in Chapter 2 and confirmed through emissions analysis in Chapter 3. The concept is further developed through mitigation strategies in Chapters 4 and 5. It is then exposed as a regulatory gap in Chapter 6 and empirically verified in Chapter 7. Across all chapters, this consistent pattern establishes co-determination as the unifying and most strongly supported finding.

The second key finding is that the choice of chemistry is an irreversible commitment whose life cycle impacts must be considered. As I showed in Chapter 2, LFP has convergent advantages over NMC and NCA regarding thermal safety, material criticality, manufacturing burden, and end-of-life recyclability, which procurement processes judged on cost-per-kWh do not take into account. As I argue in Chapter 4, this leads to externalizing the safety and environmental costs that ultimately impact deployment risk.

The third insight is that safety governance needs to be in place prior to normal operation. As discussed in Chapters 3 and 7, we learn from the early deployment period where incidents have a higher concentration due to integration failures, commissioning errors, and latent manufacturing defects that commissioning is the riskiest part of the lifecycle; this is evident from the Victorian Big Battery and South Korean incidents.

The fourth finding is that the current mitigation means are not sufficiently connected along the safety cascade. Detection, suppression, and control means will work effectively only when they have been thought out together as a part of a system and are not simply separate technologies. The cascade safety approach reveals how major incidents tend to have deficiencies at the interfaces of systems. The six-layer approach presented in Chapter 8 answers this need by conceptualizing prevention, detection, thermal management, gas management, suppression, and governance as layers in a system design.

The fifth and final finding relates to management of BESS end-of-life (EOL). As discussed in Chapters 3, 6, and 8, EOL is one of the largest governance holes in the evolving safety standards and regulations for BESSs. Used, spent, or otherwise EOL batteries can retain significant residual charge, reduced electrochemical stability, and damaged internal structures that pose an increased risk of fires and explosions and release of toxic chemicals and heavy metals in their storage, transportation, recycling, and disposal. The standards for the EOL stage of BESSs remain in their infancy. Hence, the deployment of BESSs in a safe and sustainable manner requires much stronger governance of their EOL stage, including recycling, potential second-life use verification, safe transport, and environmental risk management after their service lives.

9.2 Main Conclusions on Safety Challenges and Mitigation Strategies

The key contribution of this thesis is bringing lifecycle and environmental assessment perspectives to the safety of grid-scale BESS, an area previously dominated by operational and installation perspectives. This work contributes not only to the analysis of safety and environmental outcomes, but also has the effect of reformulating these outcomes as jointly determined, as opposed to independent. By coupling safety and environmental outcomes, the developed framework in Chapter 8 provides recommendations to the governance approach that independent safety and environment approaches cannot provide. This thesis has argued throughout, and the findings in Chapters 2 to 8 support, that there is a need to link operational and lifecycle boundaries; a safety framework centered at the operational layer without consideration of lifecycle boundaries will lead to incomplete safety governance when considering the most significant risk categories.

This is argued in the development of the six-layer integrated safety and sustainability framework presented in Chapter 8, showing that safety in BESS requires the consideration of every stage of the system lifecycle. The six-layer safety framework offers a unified approach incorporating prevention, monitoring, thermal management, gas management, suppression, and lifecycle management where environmental performance is embedded within the design and not treated as an adjunct. The key to the success of the framework is the coherence of the layers and their interaction, as shown in the incident analysis presented in Chapter 7, where failures occurred at the boundaries between different elements of the system.

Finally, the thesis presents three conclusions regarding the mitigation strategies. First, early-stage internal faults are difficult to detect because the conditions that lead to thermal runaway often do not leave easily noticeable traces on the outside. Using multi-parameter sensing and machine learning techniques will enhance the detection ability, but the level of enhancement depends on the availability of data. To help data collection, the regulators have an important role in setting up data standards and sharing mechanisms. Second, there is no one-size-fit-all suppression strategy. Multiple layers of fire protection are needed in combination, including cell cooling, gas handling, and thermal runaway detection and mitigation systems. Third, the worst-case incidents involve, by and large, the lack of validated integration between the components of the safety architecture, rather than the component-level failure of the safety architecture itself.

9.3 Contributions of the Literature Review

Taken together, this thesis contributes four interconnected aspects to the extant grid-scale lithium-ion BESS safety literature. These four aspects address the structural gaps revealed through the synthesis of the literature, i.e., Chapters 2 to 8.

Firstly, the proposed research designs an inclusive comparative framework that links chemistry choice, safety risk, and lifecycle environmental impact. Currently, comparative chemistry assessment (Kiemel et al., 2021; Le Varlet et al., 2020), thermal safety analysis(Chen et al., 2021; Hwang et al., 2025) ,and LCA (Jaradat & Khatib, 2025) are conducted independently without much synthesis. Table 2 and the associated discussions in Chapter 2 integrate all these disparate sources into a single comparative framework where the benefits of LFP for stationary grid application are reflected in thermal, environmental, supply chain, and end-of-life aspects simultaneously, which is not available in any single literature. This provides a holistic evidence to guide chemistry procurement decisions which alone is enough to alter the decision from cost-per-kWh based chemistry assessment frameworks used by existing literature.

Second, this thesis highlights the nature of thermal events in BESS as lifecycle events whose chain of consequences is not accounted for in lifecycle assessments. Literature on lifecycle assessment and battery energy storage systems (for example, Christensen et al., 2021; Jaradat & Khatib, 2025; Le Varlet et al., 2020) consider safety events as low probability events at the tails and outside the system boundaries. The literature on safety briefly describes the nature of failure, the chemical emissions from it, but does not integrate these into environmental lifecycle assessments. This thesis draws the literature together and demonstrates that the combustion phase of thermal runaway releases alarming quantities of HF (in kilograms), heavy metals particulates, and VOC cloud that represent real lifecycle environmental impacts, which cumulatively have increasing impacts as the installed capacity increases, that is not accounted for in any regulatory framework. The cited work of Austin Zhang (2025), contextualized in Chapters 3 and 7, demonstrates the impact on plants at concentrations relevant to an environmental release and serves as a direct primer for the ecological risk of the oversight in analyses.

Third, the comparative analysis provides an assessment of the international standards and regulatory frameworks for grid-scale BESS (NFPA 855, UL 9540/9540A, IEC 62933, IEEE standards, and UN 38.3) and identifies the lifecycle and environmental governance gaps common to all major sets of standards. Existing literature reviews of these standards individually(He et al., 2024; Mylenbusch et al., 2023; Vartanian et al., 2021) do not provide a comparative analysis to identify the common structural gaps. Chapter 6 of this thesis fills this gap by providing an analysis that brings to light how the lifecycle and environmental accountability gaps that covers manufacturing impacts, toxic emissions, second-life validation, recycling safety, and remediation of contamination after incidents are not oversights among the sets of standards but that the regulatory frameworks are characteristically built around controlling risk for newly installed systems to prevent fires and explosions, with very different expectations for environmental stewardship.

The fourth contribution is the incident case study analysis in Chapter 7, which brings a lifecycle-environmental analysis to documented BESS failures not found in previous incident reviews. The most detailed prior published incident studies are those of (Lystianingrum et al., 2023; Zalosh et al., 2021); neither addresses the environmental consequence chains (material lifecycle loss, toxic emission without dispersion analysis, firefighting effluent discharge without environmental analysis) identified by this thesis as the most important gap in BESS incident understanding. As shown in the comparison table 7.1, the main incidents cited by the researchers all had environmental and material lifecycle impacts that the applicable standards do not require to be understood or controlled, which has implications for incident accountability reporting requirements.

9.4 Study Limitations

Limitations exist in this thesis that affect the breadth and accuracy of the conclusions that may be drawn from it, and these should be taken into account when considering the results as a basis for research, policy, or practice.

The above literature review is inherently dependent upon the quality, completeness, and representativeness of the published evidence. The peer-reviewed or otherwise published evidence of grid-scale BESS safety and environmental behavior may be subject to publication bias (e.g., more formal publication of major incidents over partial failures or near misses) and, as noted by Al-Mahmodi et al. (n.d.), the main limitation preventing predictive analytics for BESS safety is the inconsistent evidence. Therefore, conclusions based on the incident record are qualified to assume tentative where the data may be sparse or methodologically inconsistent, especially for finding the distribution of failure rates, frequencies of chemistry-specific incidents, or magnitude of environmental consequences for each incident.

The LCA data contained in the mentioned studies (Jaradat & Khatib, 2025; Le Varlet et al., 2020 and others) and cited throughout the thesis differ with regards to system boundaries, functional units, assumptions on the electricity grid, and end-of-life treatment. Therefore, a direct comparison between results in different studies is approximate and data from the LCA studies should only be considered indicative of the trend and order of the magnitude of the differences in environmental impact. Future work needs to be conducted with harmonized LCA studies and system boundaries to provide data that can be directly compared and evaluate the environmental differences reported in this thesis.

Emerging batteries, such as solid-state batteries and sodium-ion batteries, are briefly discussed when they help provide context or an overarching message. But, large-scale deployment of these batteries is not yet mature enough to account for a comprehensive safety and environmental analysis. For example, Yu et al. (2023) report that LCA data for the solid-state cell at the grid scale are not yet available in the literature. As these batteries develop and scale up in their deployment, the work in this thesis that considers safety and environmental impacts as independent but intertwined lifecycle factors will evolve to encompass these batteries with substantially different chemistries, production methods, and end-of-life approaches.

The analysis of regulation within Chapter 6 is reflective of the current frameworks as at the time of writing. The EU Battery Regulation, NFPA 855, along with other recently adopted or updated frameworks are in a state of rapid evolution based on the learning from deployment and political impetus for energy transitions. Some of the arguments regarding governing gaps may have been addressed by regulatory action by the time the thesis is being read, particularly with respect to specific compliance requirements, but for the broader analytical framework, the core contention regarding the disparate treatment for safety and lifecycle environmental governance is unlikely to be addressed by minor changes in the standards.

Finally, this thesis does not undertake any original quantitative modeling, experimental testing, or empirical data collection. Therefore, the results of this thesis cannot be independently verified against a new body of evidence within this work. The lack of quantitative verification is the most significant epistemological weakness of any qualitative literature review, and it represents the main distinction between the contribution of this thesis and the quantitative research agenda that it concludes as the next logical step.

9.5 Final Recommendations

The findings presented in Chapters 2-8 show that a lifecycle integrated approach to safety and environmental management is required for the responsible deployment of grid-scale BESS. The following recommendations describe the minimum conditions required to achieve this.

From the industry perspective, safety by design should be viewed as a lifecycle obligation rather than an installation requirement. System design, in particular chemistry, thermal design, monitoring architecture, gas management, and enclosure design, should be optimized in safety and environmental integrated design frameworks. Lifecycle management plans, including commissioning validation, condition-based monitoring, maintenance, and end-of-life, should be mandatory and independently verified by a third party at various points in the life of the battery system.

Policymakers should require all grid-scale BESS to disclose LCA and perform environmental evaluation after incidents. Standardized incident reporting via a global taxonomy of BESS incidents could enable predictive safety analytics and data-driven regulation. Gas management and explosion prevention (detection, ventilation, pressure relief, etc.) should be considered basic safety mandatory requirements in certification.

The industry must quickly develop the infrastructure and standards for recycling and second-life qualification to effectively tackle battery end-of-life issues in a safe and environmentally friendly manner. Regulations should promote mass recycling and battery repurposing infrastructure to decrease environmental impact and safety risk of battery end-of-life. Emergency response capabilities must be developed in conjunction with deployment and must address mandatory training, site-specific emergency planning, and environmental protection issues related to toxic gas release and contaminated firefighting water runoff.

Future research efforts should focus on developing integrated models for safety-lifecycle assessments that measure the environmental impact of thermal events and provide a comparative evaluation of BESS technologies. Better data infrastructure with standardized reporting is vital to help this research and to advance predictive safety approaches. A transition from a fragmented, compliance-driven approach to an integrated, lifecycle-based approach is required to realize the safe and sustainable deployment of large-scale BESS. Safety and environmental impact are linked.

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