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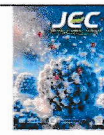
Journal of Energy Chemistry
Volume 92, May 2024, Pages 422-439



Review

A holistic approach to improving safety for battery energy storage systems

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Abstract

The integration of battery energy storage systems (BESS) throughout our energy chain poses concerns regarding safety, especially since batteries have high energy density and numerous BESS failure events have occurred. Wider spread adoption will only increase the prevalence of these failure events unless there is a step change in the management and design of BESS. To understand the causes of failure, the main challenges of BESS safety are summarised. BESS consequences and failure events are discussed, including specific focus on the chain of events causing thermal runaway, and a case study of a BESS explosion in Surprise Arizona is analysed. Based on the technology and past events, a paradigm shift is required to improve BESS safety. In this review, a holistic approach is proposed. This combines currently adopted approaches including battery cell testing, lumped cell mathematical modelling, and calorimetry, alongside additional measures taken to ensure BESS safety including the requirement for computational fluid dynamics and kinetic modelling, assessment of installation level testing of the full BESS system and not simply a single cell battery test, hazard and layers of protection analysis, gas chromatography, and composition testing. The holistic approach proposed in this study aims to address challenges of BESS safety and form the basis of a paradigm shift in the safety management and design of these systems.

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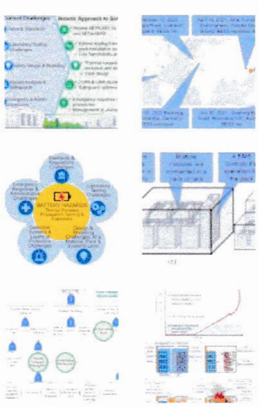

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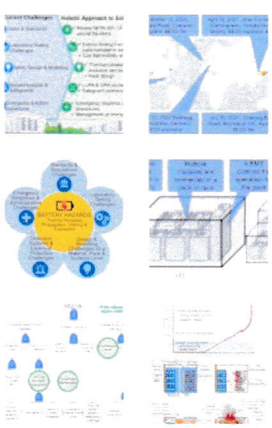

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2. BESS consequences and failures

The consequences and failure causes will be assessed in this section to highlight the challenges associated with BESS safety and how these failure modes will aid in forming a holistic approach. BESS consequences can fall into two main categories.

Operational impacts: Batteries that fail during operation can result in the system to be out of service. Operational failures can result in loss of a BESS to provide electricity for example.

Environmental and safety impacts: Pertains to potential property damage, safety, and environmental consequences, including severe consequences such as thermal runaway, which can lead to fires, explosions, and the release of toxic gases [7], [22], [23], [24], [25].

A major consequence is a BESS fire or explosion, fires resulting from BESS failures can pose serious safety risks to nearby personnel, communities, and emergency responders. The release of toxic fumes and hazardous materials during a battery fire can further exacerbate health and safety concerns. Fires and the release of toxic pollutants can have adverse effects on the environment, including soil, air, and water contamination.

BESS can fail in numerous ways; a brief overview of potential failures that can lead to BESS fires is provided in the fault tree analysis (FTA) diagram in Fig. 4 [26]. Some BESS failures presented in Fig. 4 should be more carefully considered during a hazard analysis than others (highlighted in Fig. 4). Incorrect installation practices highlighted in Fig. 4 should be carefully considered; one of the key findings of the month long investigation into the BESS fires by Korea's Ministry of Trade, Industry and Energy found that poor installation was a contributing factor to the fire incidents occurring in South Korea within the years 2017 to 2019 due to potential spark and short circuit generations creating a source of heat or ignition [12], [26], [27], [28]. Incorrect practices can result in mechanical damage to components and cells, faulty wiring and improper ventilation, leading to overheating of the system and abuse of the cells within the system [26], [28].

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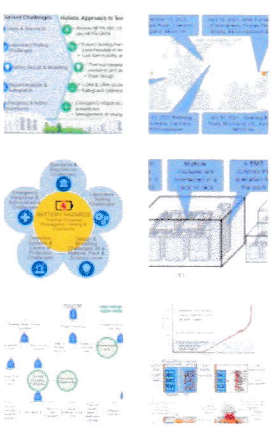

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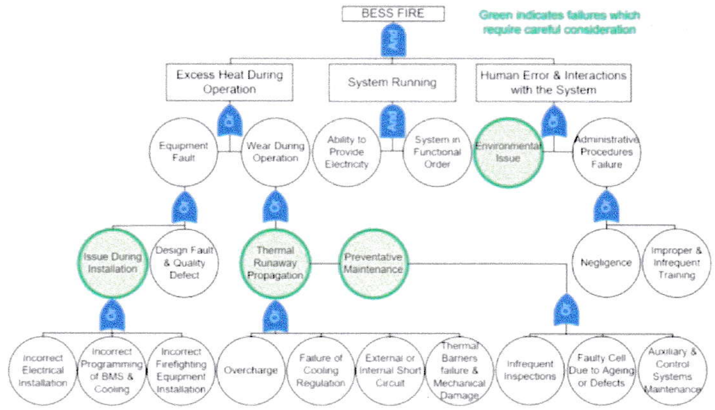

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Fig. 4. An example of a fault tree analysis (FTA) for a BESS Fire [adapted image] [26].

External fires, failure to apply firewalls, adequate spacing between equipment, minimal consideration for the operating environment, and adverse weather conditions were other factors highlighted in the investigation conducted by Korea's Ministry of Trade, Industry and Energy; these environmental issues are highlighted in Fig. 4 [6], [8], [26], [27], [28]. Large temperature swings and high humidity damaged the insulation between the cells and module ground, resulting in short circuits [12], [26], [27], [28]. In the chemical process industry, the external environment is considered during the placement or design of a chemical facility or, in this case, a BESS; these external factors are included in facility siting studies for the installation and design phase and are considered in the holistic approach.

Improper maintenance, programming and testing of the BMS and thermal management systems can lead to battery abuses and overheating of the BESS. These factors are considered under the incorrect installation, thermal runaway propagation and preventative maintenance categories in Fig. 4 [6], [8], [27]. The BMS is crucial for monitoring and managing the health of individual battery cells. Failures in the BMS can lead to inadequate monitoring, overcharging, or overdischarging of cells, increasing the risk of fire or cell thermal runaway due to lack of temperature, charging and discharging control [6], [8], [27]. Failures in the cooling strategy could also lead to system overheating, leading to thermal runaway, as shown in Fig. 4 [6], [30]. Failure of the cooling system and BMS could be categorised

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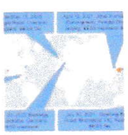

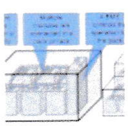

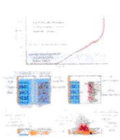

Failure of the cooling system and BMS could be categorised as a design fault. However, failures of the control systems could be due to design changes and systems that needed to be modified to accommodate system changes such as cell type, capacity, and size but were not.

Preventative maintenance is a broad category and covers failures such as cell, auxiliary and control systems maintenance, testing and replacement. One factor is the maintenance of the cell systems when defects occur, the cell is worn during operation, or when manufacturing defects are present in cells before operation [12], [26], [27], [28]. During Korea's Ministry of Trade, Industry and Energy committee investigation into the numerous BESS fires in South Korea, plate folding, cutting defects and electrode coating defects were identified and could potentially lead to internal short circuits and thermal runaway [12], [26], [27], [28]. Through cell cycle tests, the committee concluded that cell defects are not the direct cause of the BESS fires; defects coupled with other factors could lead to a situation where failures and defects could lead to perfect conditions for fires and explosions [12], [26], [27], [28].

Other factors, such as training, design faults, and negligence, can also cause BESS failures. These factors are only sometimes considered during a BESS hazard analysis. However, this does not mean they are not necessary to consider and depend on the stage of the system's life cycle when the analysis is conducted.

Although training issues can be perceived as optional throughout the analysis, they may need to be given more attention during a hazard analysis because, most of the time, when an analysis takes place, it might be considered beyond the scope of the study. Depending on stages in the system development, such asduring the operation stage, first response or performing an analysis on a recent incident, it may be a priority to consider human factors.

Design reviews, testing and faults can still occur and are a category of failures that can contribute to BESS fires. They may not be singled out for consideration as significant flaws in a hazard analysis, as they can occasionally be assumed to be identified and addressed during the design phase. The testing data and design documentation to specific standards such as NFPA 855 on a cell, module and container basis should be assessed in parallel with the other factors in the

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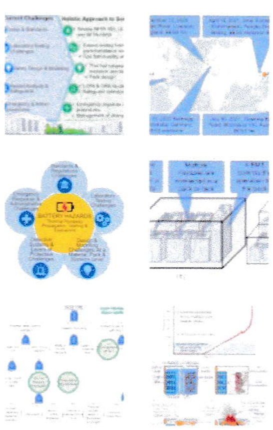

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4. A holistic approach to improving safety for BESS

There have been many thermal runaway incidents in energy storage systems. Although safety systems, equipment and procedures were put into place based on recent codes and standards, fires and explosions still occur. Heavy reliance on codes and cell testing can create installation safety gaps.

Similar to process safety in the chemical industry, a holistic approach to battery safety summarised in Fig. 10 should be considered to provide a combination of modelling, risk-based assessments, consequence modelling, design and testing solutions that are necessary to improve the understanding of credible hazard scenarios and the adequate safeguards that can be implemented to prevent failures and minimise consequences that can occur from low probability high-impact events.

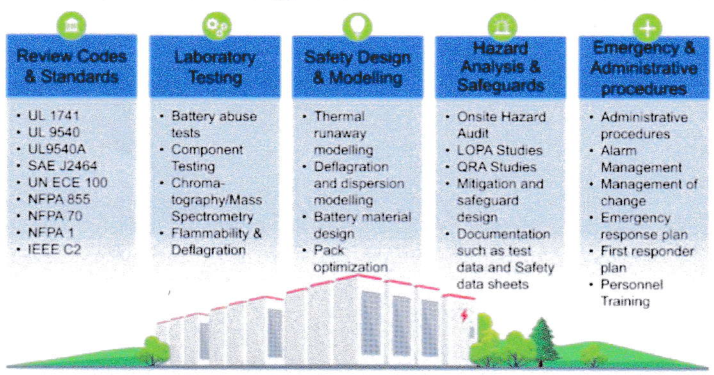

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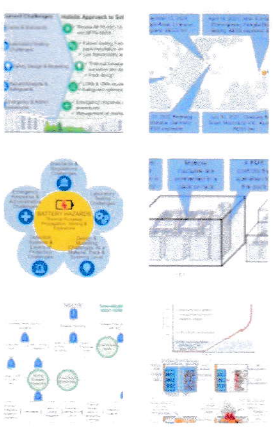
Fig. 10. The overview of the holistic approach to battery safety.

4.1. Standards and regulation challenges

Despite rapid battery evolution, codes and standards development has lagged, though they are crucial for safety, reliability, and interoperability. However, they mainly focus on generating data and pass/fail criteria, making reliance on testing alone unadvisable. UL 9540A and other standards offer different tests but lack guidance on understanding energy storage system risks, designs, and mitigation.

Some regulations and standards struggle to keep up with evolving technologies and have overlooked critical inherent hazards like gases produced during thermal runaway and



hazards like gases produced during thermal runaway and thermal propagation. Hence, standardising pass/fail criteria, best practices, and test setup is a challenge. A battery passport scheme is being attempted to trace, standardise, audit, and compare battery data [64], [65].

A holistic battery safety approach involves using current codes and standards as guidelines and a basis for good engineering practice for design, testing, installation and operation of BESS units, some examples of codes and standards are presented in Table 2 to provide a starting framework in BESS safety [8], [13], [27], [29], [62], [66], [67], [68], [69], [70], [71], [72], [73], [74], [75], [76], [77], [78]. However, there are blind spots in standards which the battery industry has recognized such as the adaptation of UL 9540 to UL 9540A which includes more large scale and rigorous testing of the gas release, NFPA 855 also discusses the need for risk based approaches, if the local jurisdiction/organization has a description of a tolerable amount of risk but leaves it to the reader to determine an appropriate risk based approach [29], [61], [62].

Table 2. Examples of energy storage systems standards.

Category	Standard	Description	References
Energy storage system	UL 9540 and UL 9540A[a]	UL 9540 is a standard for safety of energy storage systems and equipment; UL 9540A is a method of evaluating thermal runaway in an energy storage systems (ESS); it provides additional requirements for BMS used in ESS.	[8], [13], [27], [62], [66]
	NFPA 855[a]	NFPA 855 applies to the design, construction, installation, commissioning, operation, maintenance, and decommissioning of ESS (including mobile and portable ESS installed in a stationary situation and the storage of lithium metal or lithium-ion batteries). NFPA 855 discusses thermal runaways but does not	[27], [29], [67]