ELECTRIC POWER RESEARCH INSTITUTE

LESSONS LEARNED: LITHIUM ION BATTERY STORAGE FIRE PREVENTION AND MITIGATION—2021

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TABLE OF CONTENTS

INCIDENT TRENDS

Over the past four years, at least 30 large-scale battery energy storage sites (BESS) globally experienced failures that resulted in destructive fires.[1] In total, more than 200 MWh were involved in the fires. For context, roughly 12.5 GWh of globally installed cumulative battery energy storage capacity was operating in March 2021, implying that nearly 1–2% of deployed capacity had failed in this way.[2] At least one incident resulted in life-threatening injuries to multiple first responders, creating significant backlash for this emerging asset class. Although many of the incidents did not involve harm to personnel, they showed that hazards can be severe. Safety incident reports for damaged stationary storage projects are not always immediately available, so this may be an incomplete picture.

In 2019, EPRI and 16 participant utilities kicked off the "Battery Storage Fire Prevention and Mitigation—Phase 1" collaborative project. While conducting site visits, reviewing available public information and official reports, and participating in fire incident investigations, four themes have emerged as likely root causes for these events:

1. **Internal cell defect.** Manufacturing quality control issues introduce unintended distortions, debris, or other contaminants in the cell assembly or chemistry that either induce or, by fatigue, develop into an internal short circuit.
2. **Faulty battery management system (BMS).** Inadequate protection settings or unreliable software or hardware performance result in exceedance of nominal operating thresholds (such as voltage, temperature, or duration at a certain state of charge).
3. **Insufficient electrical isolation.** Ground fault, short-circuit, or DC bus power quality that leads to electrical arcing within a module or string.
4. **Environmental contamination.** Exposure to humidity, dust, or otherwise corrosive atmosphere that breaks down existing electrical isolation or insulation.

Although proper design and maintenance can regularly prevent the persistence of failures due to Causes 2, 3, and 4 above, no currently available mitigation technology can prevent an internal cell defect from causing a thermal runaway event once that cell leaves the factory. Regardless of the cause, these incidents demonstrate the possibility of fire, release of flammable gases, and explosion. Therefore, effective solutions consider the inhibition of thermal runaway propagation beyond that cell and the mitigation of off-gas generated.

Table 1. Prevention

Lesson Learned	Hazard Control Processes
Maintaining strict operational limits via a robust BMS can inhibit thermal runaway.	Software Design, Validation, and Version Control
Cell level failures and thermal runaway should be planned for at a cell level due to cell defects and aging.	Quality Assurance and Vendor Coordination with Engineering Design, Material Handling, Transportation Safety Practices, Maintenance, and Disposal Activities
Cell-to-cell thermal runaway propagation depends on many factors, such as chemistry, cell packaging, and thermal resistance of the module.	Subsystem Integration and Interface Control During Design Thermal Barriers and Separation
Monitoring of voltage, current, temperature, and gases may may notify operators of failure pre-conditions failure pre-conditions or related insight.	Detailed Data Acquisition, Gas Detection, Storage, Analysis, Trending, and Alarm Management

1. https://storagewiki.epri.com/index.php/BESS_Failure_Event_Database
2. *Project Database—Energy Storage*, Wood Mackenzie Power and Renewables, March 2021.

Table 2. Mitigation

Lesson Learned	Hazard Control Processes
Clean agent fire suppression (alone) is often incapable of stopping propagating thermal runaway.	Hazard Identification and Mitigation Solution Trade-Off Studies Product Selection Thermal Barriers and Layout
Propagating thermal runaway generates large amounts of heat—continuous water suppression may be the best option to abate.	Project Siting, Resource Planning, and Coordination with Utilities
Explosive off-gases can build quickly—detection and ventilation are essential to avoid deflagration.	System Envelope Modeling and Design
Coordination, planning, and communications before, during, and post-event can save lives and equipment.	Response Procedures, Information Sharing, and Training

SAFETY REVIEWS OF SITES IN OPERATION AND DESIGN

EPRI conducted evaluations of energy storage sites (ESS) across multiple regions and in multiple use cases (see Table 1) to capture the current state of fire prevention and mitigation. Of those sites, six are operational, two are under construction, and two are in design. Several battery technologies and design configurations are represented in this industry cross-section.

The evaluations all included four key elements:

1. Data discovery (curating a shared repository of available design documents, equipment certifications, operational and commissioning procedures, and test data)
2. Site visit and walk-through
3. Assessment of the site using the *Energy Storage Integration Council (ESIC) Energy Storage Reference Fire Hazard Mitigation Analysis*[3] as a template

Table 3. Ten planned energy storage sites for evaluation

Country	Region	Project Status	Power (MW)	Energy (MWh)	Battery Chemistry	Integration Type	Fire Suppression System Type
USA	Southwest	Operational	1	1	NCA	Products	None
USA	Southwest	Operational	2.8	5.6	NMC	Containers	Clean Agent
USA	Southwest	Operational	10	4.6	NMC	Buildings	Clean Agent
USA	Southwest	Operational	2.5	3.9	LFP	Buildings	Clean Agent
USA	West	In Design	4	8	LFP	Containers	TBD
USA	West	Construction	182	730	Unknown	Products	None
USA	Southeast	Construction	1.5	1	NMC	Building	Clean Agent
USA	Southeast	Operational	1	2	NMC	Containers	Clean Agent
USA	Southeast	Operational	0.3	0.6	NMC	Building	None
South Africa	West	In Design	80	320	TBD	Containers	TBD

4. Final report of lessons learned and recommendations for improvements to site safety

EPRI identified additional guidance during the evaluations that can be grouped into four points, described next.

1. COMMON SAFETY DATA SUPPORT COMMON EVALUATION PROCESSES

A small change in the chemical makeup of a battery or the way in which an energy storage system (ESS) container is assembled can have a large impact on the type and magnitude of a safety incident. Although models can offer important results at a lower cost, testing at each level of integration (from cell to system) is the only way to accurately and confidently quantify the hazards in an ESS.

The test method and report are as important as the results of the testing. In two sites reviewed by EPRI, the analysis of test data provided to the site hosts from the manufacturers indicated minimal explosion hazard, but the reports included some gaps:

- A high level of hydrogen (H_2) was present in the collected gases during the test. Although this is possible, the trend has been linked to faulty hydrogen sensors in other tests. Without proper details of all equipment used for testing, an end user or fire protection engineer may be challenged to discern actual hazards from apparent ones.
- Incorrect or confusing units were provided for multiple results. These may have been typos or proper measurements represented using an alternative method, which caused confusion during review.
- The reports lacked complete information about gas release. Ventilation design cannot be assessed with confidence without the off-gas peak generation rate, the total gas evolved, and the off-gas constituents.
- The incorrect data set was provided. Independent consultants discovered that the test data represented a different battery module (from the same manufacturer) than the one planned for use at the site. The new data revealed a different explosion risk and indicated that a significant redesign of the enclosures may be necessary.

These concerns could not have been addressed by a model of a similar system. Unless a specific model had been calibrated to that chemistry in that installation configuration (which would have required testing), site engineers may not have adequately addressed the hazards.

As codes, standards, and regulations continue to evolve, the data relevant to the compliance of an energy storage project are also changing. For example, sites built in 2017 may have been authorized by an authority having jurisdiction (AHJ) that had not yet adopted NFPA 855 (which requires UL 9540 listing) at the time of its permitting. Although the UL standard was initiated in 2016, it was not published until 2019—and NFPA 855 is still not universally adopted in 2021.

Because applied codes may not have required UL 9540A (or other relevant safety tests), site developers and owners did not regularly request these reports. In fact, EPRI found this situation at every operating site evaluated. Owners and operations or legacy systems produced little, if any, data. Sometimes, when approached by the current site operators, the site suppliers still did not have these test reports.

2. SAFETY EVALUATIONS ARE INFLUENCED BY SUBJECTIVITY

Testing for energy storage performance or failure modes is a quantitative, objective process, but safety combines objective probabilities with subjective assessment of the acceptability of ever-present hazards. As one of the site hosts indicated, there is no "silver bullet" to address battery energy storage fire and explosion hazards, but rather many solutions are needed.

Though the risk of a fault in an ESS may be low, certain issues can never be truly eliminated, and the tolerance to such risk is up to the storage asset's owner and operator. Interpreting objective test results and assigning a value to the severity of a failure incorporate the reviewers' perspectives. In addition, different experts may focus on various threats and treat them with unique attention or concern based on their familiarity and personal experience.

Safety evaluations rely on a group of multidisciplinary experts asking "what if" questions and comparing observations of project features (for example, requirements, design characteristics,

[3] *Energy Storage Integration Council (ESIC) Energy Storage Reference Fire Hazard Mitigation Analysis.* EPRI, Palo Alto, CA: 2019. 3002017136.

operational procedures, or physical status) to conditions presented in incident reports, previous experiences, or other lessons learned. For example, all of the fire protection experts employed for the evaluations have experience in hazardous material fire events. Some have more specific experience with lithium ion BESS design (and fires), while others have more experience with other technologies and facility types.

Multiple safety evaluation processes exist, such as process hazard analysis (PHA), failure modes and effects analysis (FMEA), hazard mitigation analysis (HMA), layer of protection analysis (LOPA), and fault tree analysis (FTA). Each serves different goals to assess the safety of a site or project. For the Battery Energy Storage Fire Prevention and Mitigation supplemental project, EPRI chose to use the report *Energy Storage Integration Council (ESIC) Energy Storage Reference Fire Hazard Mitigation Analysis* (3002017136) as the starting point. This format identifies possible concerns of fire and thermal runaway propagation as well as gaps in suitable defense measures (or mitigation barriers). The method still relies on focused observation and interpretation of the effectiveness of different barriers to appropriately characterize the gaps in safety. In addition, because none of these sites has yet been involved in safety events known to EPRI, the leading practices can only be assumed in reference to lessons from other sites, relying on expert experience.

EPRI found that aligning safety evaluation expert experience to specific site attributes can be instrumental in these processes. Experts, when familiar with the site-specific configurations and conditions, eased the data discovery and site review process by anticipating and prioritizing issues, ultimately reducing the iterations and total time required. This is expected to help avoid confusion or gaps in the assessment.

3. OWNERSHIP MODELS DETERMINE SAFETY MANAGEMENT AND RESPONSIBILITIES

Every energy storage site (as with any commercial or industrial site with multiple potential hazards) includes many different subsystems with various support personnel. Larger sites may be managed by a combination of the owner and multiple vendors. Sites often lack clear designation of accountability among these various parties. Moreover, site information and specific safety features are sometimes missing and the causes for the gaps remain unresolved, possibly resulting in safety shortcomings at these sites. In addition, the variety of ownership models available for energy storage sites—including utility, independent power producer (IPP)/merchant, and customer-sited—presents potential for underserved safety management.

4. PLANNING FOR FAILURE REQUIRES CHOICES: VARYING LEVELS OF ACCEPTABLE DAMAGE

As is illustrated in the EPRI *Energy Storage Integration Council (ESIC) Energy Storage Reference Fire Hazard Mitigation Analysis*, lithium ion batteries are subject to several failure modes. Each mode may occur with different probabilities, based on the battery product and its integration. Further, the same battery module design in the same installation may fail differently on separate occasions.

Hazard mitigation efforts can address the issue by preventing the hazard from occurring; protecting equipment, personnel, and environment from the hazard (primarily fire and explosion for lithium ion systems) once it occurs; or using a combination thereof. EPRI found that some of the sites evaluated in recent projects prioritized prevention. They also prioritized protection, considering site exposures, module test data, and estimated probabilities of failure. Often, these decisions weighed the cost of safety against the expected loss of service or fundamental business principles and priorities.

In a recent study of trade-offs between ESS safety design features and total cost of ownership, EPRI defined a "fault block," or a designated unit of acceptable loss in the event of a failure (3002020573). Depending on the failure modes and the integration details (site size, exposures, propagation rate, vented gas generation rate, vented gas constituents, rack separation and propagation barriers, and so on), site owners may consider failure of a module, string/rack, or even subarray as acceptable. Partial system loss may result in significant cost, requiring cleanup from smoke and heat damage in addition to detailed work to remove "stranded energy"—energy remaining in modules damaged beyond repair but not yet completely reduced to ashes—and replacement of the failed subsystem.

On the other hand, full failure may eliminate stranded energy but still require detailed, labor-intensive cleanup to investigate, decommission, and dispose of the entire system. A catastrophic fire may obscure evidence and convolute the forensics process. It may also degrade the structural integrity of the enclosure and require specialized processes to access the batteries and mobilize the equipment.

NEXT STEPS

Because most codes and standards are developed in reaction to a need or concern, their value is proportional to the data available to inform them. Currently, data from real-world energy storage systems are relatively sparse and mostly proprietary, which hinders the progress of safe system design. To address this need, EPRI is pursuing the development of a safety toolbox centered around data from real-world site operations, tests, and validated models:

- Safety design and operational cost trade-off tools
- Standard compliance test guidance
- Safe operations and alarm management guidelines
- Environmental impact models
- Community and first responder outreach and training materials
- Site-specific hazard analysis and design studies (safety retrofits and new designs)
- Sensor efficacy testing

Many safety metrics are also relevant to ESS performance and reliability. Expertise and experience in installation, commissioning, operational procedures, control algorithms, high-fidelity data acquisition and analysis, component failure rates, and real performance specifications largely reside within the institutional knowledge of individual private companies.

Now a new wave of energy storage technologies is advancing to commercial readiness, with expectations that lessons learned from the earlier generations can be captured, codified, and leveraged for their development to smooth adoption and use. End-user and research community engagement with technology developers in the demonstration of pre-commercial and commercial technology presents an opportunity to accelerate safety and reliability characterization.

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