SAFETY & RISK CONSIDERATIONS FOR LI-ION BATTERIES IN GRID ENERGY STORAGE APPLICATIONS

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Abstract

With the increasing investments in grid scale energy storage research and development, particularly for Li-ion batteries, there is an urgent need to understand and address issues related to hazards and risks associated with these battery systems. Due to the size and complexity of the battery systems, the hazards associated with these systems are related not just to cell-level defects, but also to other electrical components, controls, environmental factors, and system-level failures. To ensure a safe and smooth integration of battery systems with the grid, it is also important to understand the relevant industry regulations and standards during the development, installation, and maintenance of these systems. This paper presents an overview of the safety and risk considerations for a typical grid-scale battery storage system, with a focus on lithium-ion (Li-ion) batteries.

Introduction

Advanced energy storage technologies are becoming a vital part of the modern, reliable power system. The success of rechargeable batteries due to rapidly decreasing prices, high power density and wide market availability has resulted in a marked increase in the deployment of Li-ion batteries in grid energy storage systems. Li-ion batteries are reactive in nature and may present a fire or explosion hazard when damaged or operated outside their specifications. As the number of installed Battery Energy Storage Systems (BESS) using Li-ion batteries is increasing, the industry is also seeing more field failures and safety incidents related to these systems [1]. These incidents have highlighted certain safety-related challenges and gaps such as inadequate fire protection systems, lack of appropriate first responder training, inadequate battery protection systems and insufficient management of operating environment for BESS. They have also prompted the stakeholders such as utilities, battery manufacturers, government groups and technical organizations to put considerable effort into safety standards and best practices for Li-ion based BESS [1]. In addition to understanding the relevant safety standards, it is also important to systematically identify hazards associated with these systems using one of the many available hazard mitigation analysis techniques.

This paper presents an overview of a typical grid-scale battery storage system with a focus on Li-ion batteries, a discussion of the types of hazards associated with Li-ion battery systems in this application and an approach to perform a safety and risk analysis of these systems. In this paper we also discuss relevant standards and regulations along with safety requirements and emergency response plans. Finally, the paper will present a case study that highlights the importance of safety controls and hazard mitigating measures for a BESS.

Grid-scale Battery Energy Storage Systems

Some of the most common battery technologies currently utilized in grid-scale BESS are lithium-ion (Li-ion), lead–acid, sodium-based batteries, nickel–metal hydride (Ni-MH), nickel–cadmium (Ni-Cd), and flow batteries. These battery chemistries differ in various key technical characteristics such as specific energy, specific power, nominal cell voltage, energy efficiency, cycle life and rate of self-discharge [2]. According to the data collected by the United States Energy Information Administration (EIA), since 2008, Li-ion batteries have been one of the most popular battery technologies in terms of installed or planned capacity in grid applications accounting for more than 80% of the battery energy storage capacity [3]. **Figure 1** illustrates the total installed energy capacity for various battery chemistries from 2008 to 2019.

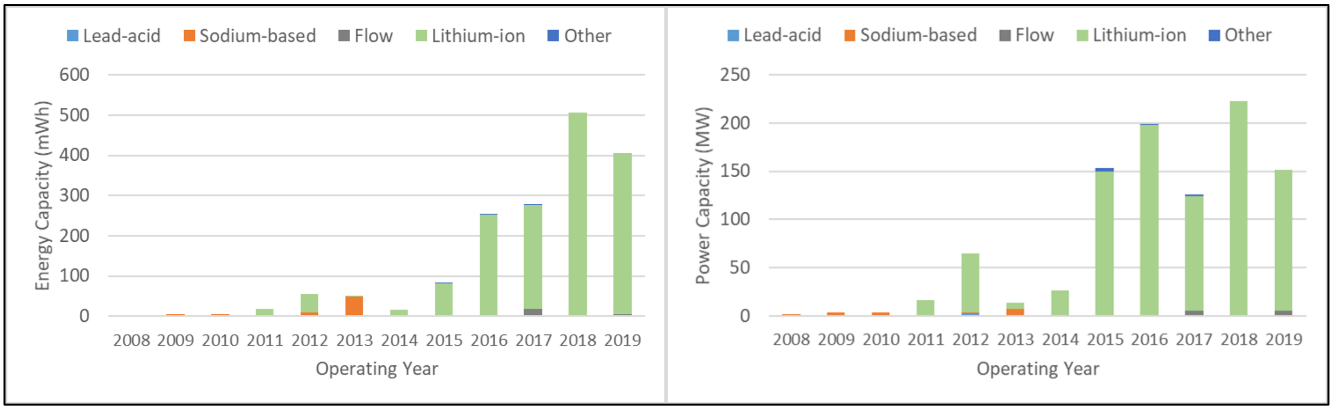

Figure 1 U.S. utility-scale battery storage capacity by chemistry (2008-2019) [Source: U.S. Energy Information Administration, 2019 Form EIA-860, Annual Electric Generator Report]

A BESS is a collection of rechargeable batteries that charge (or collect energy) from the grid or a power plant and then discharge that energy when needed to provide electricity or other grid services [4]. These batteries are essentially used to balance the grid, improve its stability, and provide backup power as needed. **Figure 2** depicts a typical battery system architecture used for grid storage. The main components of a Li-ion system are:

- Racks comprising multiple battery modules
- Battery modules consisting of several cells in varying series-parallel combinations
- Cells that are fundamental to the system
- Battery management system (BMS) associated with each module and the entire battery system
- Battery thermal management system to provide cooling that typically includes fans and ventilation
- Safety controls and protection circuits such as fuses and contactors
- Power electronics that interface the battery system with the grid

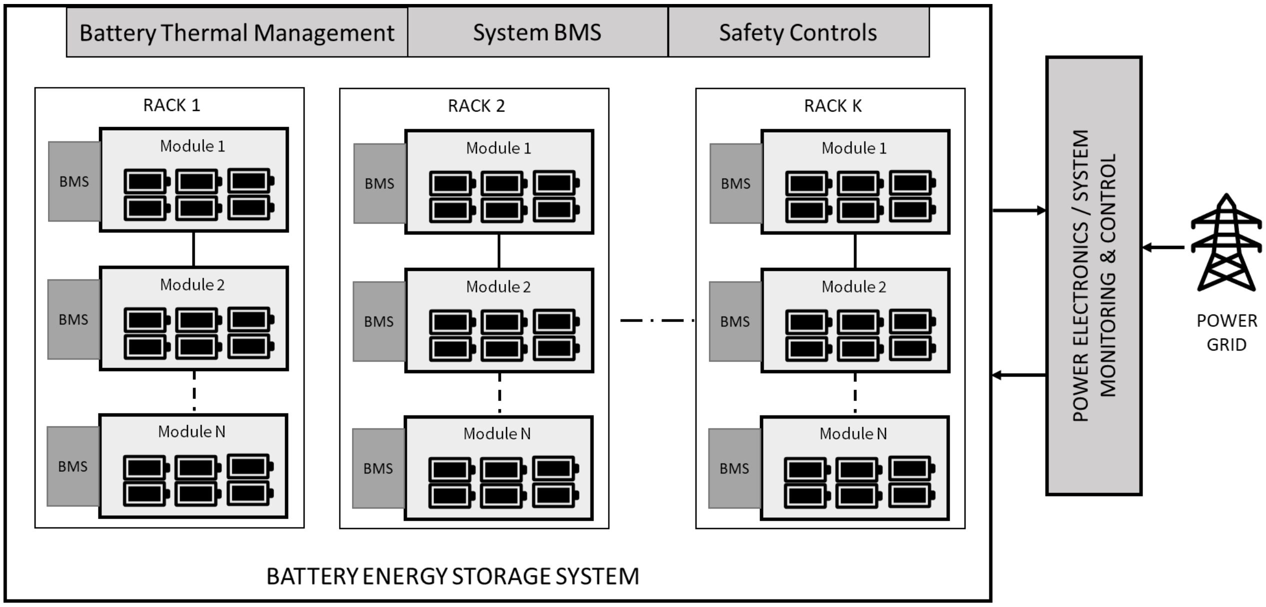

Figure 2 Typical Grid Storage Battery System Architecture

The battery racks are typically installed in a container-like enclosure equipped with the system-level BMS, an HVAC system, a fire detection system (e.g., smoke detectors) and a fire suppression system. Depending on the energy storage requirements, a typical installation may include more than one such container in the overall BESS. Such installations are typically located closer to solar farms or other power generators for charging the battery.

Li-ion batteries have been in the news owing to their widespread use in consumer products and the failure incidents that have accompanied these products. Unfortunately, the risk severity increases manifold when it comes to large-scale Li-ion batteries such as the BESS which is apparent by the numerous fire incidents in these past few years. For e.g., in South Korea, which had the largest number of energy storage battery installations as of 2021, there were 23 reported fires between August 2017 and December 2018 according to the Korea Joongang Daily (2019) [5]. **Table 1** lists the failure incidents involving BESS installations in the U.S. in just the last 3 years [6].

Table 1 BESS (Li-ion) failure events in the U.S. in the last 3 years

Location	Energy (MWh)	System Age (Years)	State During Accident
US, PA, Millvale			Operational
US, CA, Moss Landing	730	0.5	Operational
US, AZ, Chandler	40	3	Operational
US, CA, Valley Center	560	0.2	Operational
US, CA, Moss Landing	400	1	Operational
US, CA, Moss Landing	1,200	0.8	
US, IL, LaSalle	72	1.6	

All these incidents have been attributed to several factors such as temperature, failure of protection systems, aging of batteries and/or other components, manufacturing defects, lack of appropriate fire suppression infrastructure, etc. The kinetics of a BESS failure is complicated, and the extent of failure varies largely based on the mitigation approach. One of the biggest challenges in streamlining the mitigation techniques for a BESS is the lack of appropriate codes and standards that mandate or recommend the risk assessment and hazard analysis for large battery systems or provide strategies to perform these. Also, there is still only a limited amount of BESS failure data available to fully understand the failure and risk scenarios and hence design mitigative protections for these systems.

Hazards & Risks

The hazards and risks associated with BESS depend on many factors such as size and capacity of the battery system, design of the protection scheme, characteristics of the components involved in the BESS and fire protection system design. Some of the main causes of these failures can be categorized into the following [7]:

1. Electrical abuse: this includes overcharging the cells, over-discharging the cells, external short-circuits, arcing between high voltage components, etc.
2. Mechanical abuse: this includes physical or mechanical damage to the battery systems, exposure to shock, impact, or vibration.
3. Environmental abuse: this includes exposure of the system to elevated external temperatures, operation of the system at too low of an external temperature, electrical surges, lightning, moisture, dust, etc. that can lead to damage or accelerated degradation of components.
4. Manufacturing defects: this includes internal cell faults due to poor manufacturing, installation errors, inadequate protection schemes, inadequate thermal barriers between cells allowing propagating thermal failure [8], etc.
5. Other electrical faults or system failures: this includes inappropriate fire suppression system, inadequate ventilation, and emergency response plans.

Figure 3 shows an example of a metallic contaminant within a Li-ion cell (left) introduced during manufacturing and evidence of lithium plating[1] (right) as a result of either exposure of a Li-ion cell to very low temperatures or high charging C-rate. lithium plating can cause internal short-circuit within a cell and can initiate thermal runaway.

Figure 3 Cell Level Hazards - Metallic Contaminant (left) and Lithium Plating (right)

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[1] Lithium plating is the deposition of lithium metal on the surface of the anode which can lead to a metallic path to form through the separator and cause a short-circuit.

Safety & Risk Analysis

Newer and more complex designs of BESS have resulted in a need for a holistic and systematic approach to system safety. More comprehensive hazard analysis, risk assessment and more demanding risk mitigation and fault diagnostics are needed for BESS. The main purposes of a safety and risk analysis are to reduce the probability of a hazardous event, to minimize the level at which it occurs, and to limit the consequences; this process also helps determine effective ways of integrating fire prevention with emergency response into such systems to avoid interruptions [9]. In general, risk assessments are performed to identify potential risks, their causes and consequences, and to determine high-level design requirements to mitigate those risks and prevent propagation of failure. Some of the most commonly used methods in risk analysis are preliminary hazard analysis (PHA), hazard and operability analysis (HAZOP), failure modes and effects analysis (FMEA) and fault tree analysis (FTA). Although all these techniques have their own unique procedures, they are all based on a process that includes the following three steps:

- Identification of risk
- Risk analysis and
- Risk mitigation

Electric Power Research Institute (EPRI) has developed one such hazard mitigation analysis methodology called the "Bowtie Analysis" with the intent of providing guidance to boost safety of both planned and deployed BESS [10]. **Figure 4** provides an example of a hazard scenario and the range of identified threats which may lead to a failure event (top event), from which other consequences may result. "Barriers" represent the mitigation methods placed both on threat and consequence sides [10].

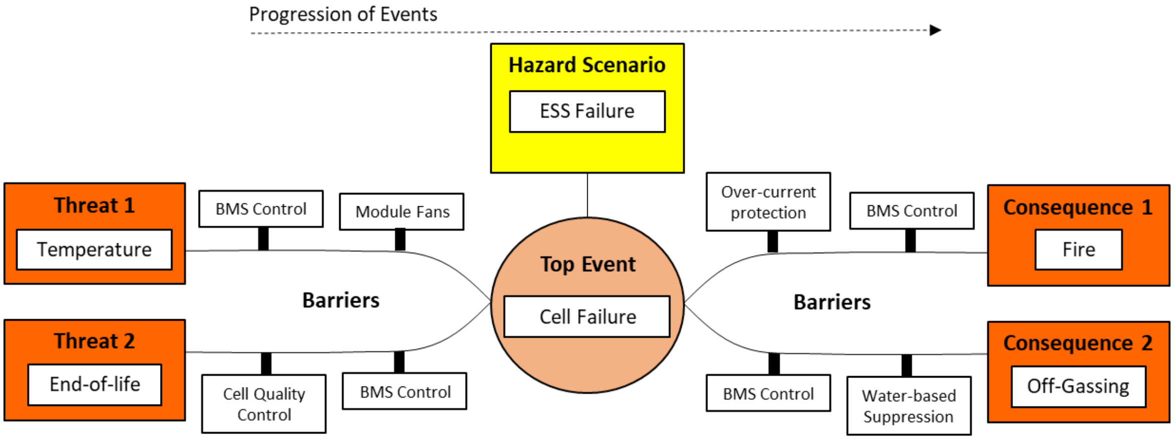

Figure 4 Bowtie Analysis [10]

Some of the other identified hazards include:

- Cell internal failure which can lead to thermal runaway and ultimately to a fire
- Controls failure caused by a failed sensor which can ultimately lead to cell off-gassing
- Environmental risk due to dust and dirt accumulation which can lead to excessive degradation of electronics

Industry Standards & Regulations

As the number of BESS installations have increased across the world, a lot of effort has been put in by all the stakeholders involved (government groups, utilities, battery manufacturers, system integrators, etc.) into developing safety standards and best practices for design, deployment, and maintenance of BESS. In 2014, the U.S. Department of Energy (DOE) created the "Energy Storage Safety Initiative" with the objective of exploring gaps in safety structures, developing codes, standards, and regulations, and educating first responders on energy storage system safety [1]. Some of the developed standards are listed in **Table 2**:

Table 2 Codes, Standards and Best Practices Related to BESS

Code/Standard	Description	Category
UL 1973	Batteries for Use in Stationary and Motive Auxiliary Power Applications	Cell, Battery
UL 9540	Energy Storage Systems and Equipment	BESS
UL 9540A	Standard for Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems	BESS
IEC 63056	Safety requirements for secondary lithium cells and batteries for use in electrical energy storage systems	Cell, Battery
IEC 62619	Safety requirements for secondary lithium cells and batteries, for use in industrial applications	Cell, Battery
IEEE P2686	Recommended Practice for Battery Management Systems in Energy Storage Applications	BMS
IFC, NFPA 1	International Fire Code, National Fire Protection Association Fire Code	BESS (Fire Code Regulation)
NFPA 13	Standard for the Installation of Sprinkler Systems	BESS (Fie Suppression)
NFPA 855	Standard for the Installation of Stationary Energy Storage Systems	BESS (Installation)

Apart from the standards listed above, there are also other application specific standards such as IEC 61427-1 (for cells in Photovoltaic off-grid application), and other electrical system related standards such as UL 1741 (Inverters, Converters, Controllers and Interconnection System Equipment for Use With Distributed Energy Resources), UL 489 (Molded-Case Circuit Breakers, Molded-Case Switches, and Circuit-Breaker Enclosures), IEC 62933-5-2 (Electrical energy storage (EES) systems - Part 5-2: Safety requirements for grid-integrated EES systems - Electrochemical-based systems), etc. which can be used as a guide during the design, installation and commissioning of BESS. Although these standards cover most aspects of the design and installation of BESS, a preventive approach such as performing a safety assessment of the system, complements these standards.

Safety Requirements & Emergency Response Plans

Despite the existence of codes, standards, and regulations, both international and within the U.S., these generally don't exist at the local level specific to each BESS site. Every BESS location and utility is different and has distinct properties such as cell type, capacity of BESS, design, environmental conditions of the location, water proximity, access to first responders, etc. Site-specific safety requirements, regulations and emergency response plans are therefore important [11].

Some of the typical requirements include presence of:

- Smoke detectors, gas detectors, temperature sensors and voltage and current sensors within the BESS container to detect hazardous conditions
- Fire suppression systems such as sprinklers, clean agents like FM-200, abundant water supply and fire extinguishers to douse and avoid re-ignition of fire
- Appropriate deflagration ventilation techniques for explosion prevention and protection [12]
- Appropriate HVAC systems within the container
- Access to appropriate personal protective equipment (PPE) on-site
- Training documents and safety protocols efficiently documented for the personnel involved
- And others such as lockout/tagout (LOTO) procedures, lighting, centralized control room, signs, etc.

In addition to the above-mentioned measures, provisions for controlling spread of hazardous material should a failure occur, must also be implemented. A damaged Li-ion battery or BESS can contain residual energy and can pose a fire, shock, or explosion hazard to first responders and other personnel involved [7].

Case Study

The following section presents a case study that involved a hazard mitigation analysis for a newly commissioned site using the “Bowtie Analysis” method discussed in the previous section. **Figure 5** depicts the steps in the process that were used to perform the analysis.

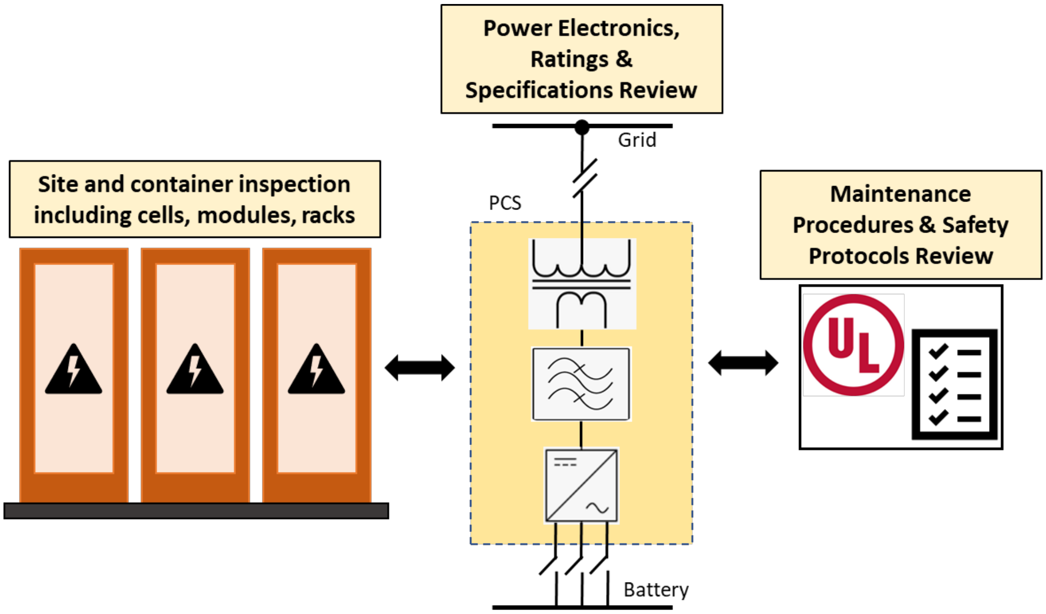

Figure 5 Hazard Mitigation Analysis Steps

Observations were made based on a site inspection which included inspection of the battery container, cells, modules and racks, power electronics connected to the battery system, external factors such as lighting, ground connections, water availability and other house-keeping items. The assessment also involved a review of all relevant documents including but not limited to cell and module specifications, certifications, one-line drawings and ratings for the power electronics, maintenance schedules, safety protocols and emergency response plans. These documents served as one of the inputs to the “Bowtie Analysis” that was used to perform this analysis. Some of the observations made are listed below:

1. Battery modules did not have any UL certification.
2. The NEMA rating for the PCS enclosure was not appropriate for the site location.

3. No cameras were installed in the BESS container.
4. The fire suppression system had expired.
5. The containers did not have a manual shutdown at the entry door.
6. Loose connections were observed between modules.
7. The switchgear in the PCS system was corroded and rusted.
8. Emergency response plan did not include extinguishing, ventilation, and entry procedures.
9. No document existed detailing necessary clean-up activities in the event of an incident.

These observations along with the hazard mitigation analysis provide value to the utility, battery manufacturer and other involved parties, helped alleviate some of the identified "immediate" threats and facilitate the process of modifications and improvements.

Summary

With growing energy demand, the number of energy storage installations have increased worldwide and thus more failure incidents are on the rise. It has thus become even more important for all the stakeholders to understand the associated risks and strategize the mitigation methods for the overall safety of the system, environment and personnel involved. Performing a hazard analysis of a BESS provides an understanding of the primary failure modes and consequences specific to Li-ion energy systems.

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