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Worker and First Responder Safety Concerns Related to Battery Energy Storage Facilities

A Review of the Literature and Interviews with Local Fire Departments

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Technical Update, December 2018

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ABSTRACT

Battery energy storage systems (BESS) are a growing class of energy storage systems that use battery technology to store electrical energy as chemical energy. Utility-scale BESS facilities can include hundreds or thousands of individual batteries, which present potential thermal, electrical, chemical, and mechanical hazards to workers and first responders. Additional chemistry-specific hazards are present for the different rechargeable battery chemistries used in BESS facilities. Common rechargeable battery chemistries include lithium-ion (Li-ion), lead-acid, nickel-based, sodium-based, redox-flow, and metal-air chemistries. Each of these battery chemistries has unique susceptibilities and reactions to abuse scenarios.

This project was conducted to review and identify the gaps in the current knowledge base of worker and first responder safety concerns and practices at utility-scale BESS facilities. The project included review of published literature as well as codes, standards, and regulations being developed to guide safety practices that address known BESS and battery hazards. These safety practices include proper signage, air monitoring systems, fire suppression systems, central alarm systems, and emergency shut-off systems. The project also included review of training materials for an online BESS safety course provided by the National Fire Protection Agency (NFPA) and interviews with local fire departments to gain first-hand accounts of the safety practices currently being implemented during emergency response at BESS facilities and other battery-related incidents. These safety practices include pre-incident planning with the BESS facility, hazard mitigation upon arrival to an incident, and emergency response to electrolyte release, overheated batteries, BESS fires, and environmental events (such as seismic activity and flooding).

A comparison of the information gathered from published literature, current and upcoming codes and standards, and first responder safety practices shows that there are gaps in the current knowledge base of worker and first responder safety practices. These gaps include knowledge of new battery technologies and associated hazards, BESS and battery fire behavior and fire suppression tactics, post-incident activities, and awareness of available education and training.

Keywords

Battery energy storage system (BESS); worker safety; first responder safety; BESS installation; BESS safety practices.

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PRIMARY AUDIENCE: Electric utility companies interested in battery energy storage technologies.

SECONDARY AUDIENCE: Other energy, environment, and health/safety stakeholders, and researchers.

KEY RESEARCH QUESTION

Battery energy storage systems (BESS) are associated with a number of potential safety risks, including fire, explosion, electric shock, and chemical exposure. Some of these hazards are well-documented in the scientific literature while others remain active areas of academic research. This project was conducted to review and identify the gaps in the current knowledge base of worker and first responder safety concerns and practices at utility-scale BESS facilities.

RESEARCH OVERVIEW

The goals of the project were to 1) identify the current knowledge base of safety hazards associated with BESS facilities, 2) identify current worker and first responder practices at BESS facilities and battery-related incidents, 3) identify gaps in the current knowledgebase and safety practices at utility-scale BESS facilities, and 4) present considerations for future research that promote worker and first responder safety. These goals were addressed through a review of published literature; current and upcoming codes, standards, and regulations; select first responder interviews; and gap analysis related to BESS technology, hazards, and related safety measures.

KEY FINDINGS

- Active battery research is developing new battery chemistries and advancing existing chemistries. It is important to reassess the new battery technologies for thermal, electrical, mechanical, and chemical hazards because subtle changes to existing battery chemistries can change the associated hazards and present new hazards. Updated safety data sheet (SDS) documentation is crucial for conveying new information to workers and first responders.
- The extent of worker and first responder exposure to chemicals released from batteries and to products of combustion during battery fires is still being studied. This includes the health effects of the less common chemicals released by batteries and of the particulates released in the air during and after a battery fire.

- Effective firefighting techniques for containing and extinguishing large BESS fires are still in development. Current fire suppression strategies are borrowed from procedures used for electric fires, chemical fires, and ammunition fires, all of which involve using copious amounts of water. Scientific research into the behavior of BESS fires and the behavior of BESS structures during a fire will likely improve the effectiveness of current firefighting techniques used in response to BESS fires.
- Post-incident activities by first responders—including overhaul of BESS facilities, fire watch, and incident reporting—are being developed independently by individual fire departments. In the absence of a standardized or an industry-wide adopted procedure, a given fire department may practice procedures based on the collective anecdotal experience of that individual fire department. The development of guidelines and best practices agreed upon by a larger population of the fire departments can help create more consistent protocols for post-incident activities specific to BESS and battery-related incidents.
- Procedures for handling and storing post-incident batteries are not well-established. Damaged batteries from an incident can result in latent battery failures, such as thermal runaway and reignition of nearby combustibles. Methods to predict these latent failures are being developed. Workers and first responders have developed their own procedures for handling damaged batteries based on anecdotal evidence as opposed to scientific research. Systematic research to investigate the mechanisms and predictors of latent battery failure can provide data-driven guidelines to develop safe procedures for handling post-incident batteries.
- Interviews with first responders indicate that they are typically not informed of battery hazards and not formally trained in handling large-scale battery fires. However, training tools are available to fire departments from agencies like the NFPA. Increased awareness of this type of training is needed to better prepare fire departments for BESS-related incidents.

WHY THIS MATTERS

This research is useful for stakeholders assessing the health and safety impacts of energy storage. Identified knowledge gaps can guide future research in this area to inform the development of guidelines for handling BESS safety and fires and to improve first responder best practices.

HOW TO APPLY RESULTS

This report provides details on occupational and first responder health and safety issues related to battery energy storage systems. The information contained herein can help the user identify relevant information on this issue to aid with the protection of workers and first responders from thermal, electrical, mechanical, and chemical hazards. The results can also be used to guide future reseach to better characterize risks and develop mitigation measures.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- Electric utilities, battery manufacturers, storage solution providers, and fire departments are likely to be interested in this report.

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PROGRAM: Project Set 197B, Environmental Aspects of Energy Storage

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Acronyms and Abbreviations

A	ampere
AC	alternating current
ACGIH	American Conference of Governmental Industrial Hygienists
AED	automated external defibrillator
AEGL	acute exposure level guideline
Ah	ampere-hour
AHJ	authority having jurisdiction
BESS	battery energy storage system
BMS	battery management system
CFR	Code of Federal Regulations
CID	current-interrupt device
CV	constant voltage
DC	direct current
EMF	electromagnetic field
EPRI	Electric Power Research Institute
EV	electric vehicle
FPRF	Fire Protection Research Foundation
HAZMAT	hazardous materials
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IFC	International Fire Code
ISO	International Standards Organization
kWh	kilowatt-hour
LEL	lower explosive limit
LFL	lower flammability limit
Li-ion	lithium-ion
MAQ	maximum allowable quantity
MWh	megawatt-hour
NAC	National Advisory Committee
NFPA	National Fire Protection Association
NIOSH	National Institute for Occupational Safety and Health
OEL	occupational exposure limit
OSHA	Occupational Safety and Health Association
PCS	power conversion system
PEL	permissible exposure limit
PPE	personal protective equipment
ppmv	parts-per-million-by-volume
PTC	positive thermal coefficient
REL	recommended exposure limit
SCBA	self-contained breathing apparatus
SDS	safety data sheet
SOC	state-of-charge
SOP	standard operating procedures
STEL	short-term exposure limit

TLV	threshold limit value
TWA	time-weighted average
UL	Underwriters Laboratory
V	volt
W	watt
Wh	watt-hour

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1 BACKGROUND

1.1 Project Overview

Battery energy storage systems (BESS) are a growing class of energy storage systems. BESS use battery technology to store electrical energy generated during times of peak production and lower demand and to deliver that stored energy during later times of peak demand. A variety of battery chemistries can be chosen for BESS, each with different safety risks, including potential risk of fire, explosion, electric shock, and chemical exposure. Some of these hazards are well-documented in the scientific literature while others remain active areas of academic research. Overall, the risks and mitigation strategies for battery-related hazards, especially in the context of BESS, are not well established. Safety codes and standards related to BESS are currently in development to provide guidance for the BESS industry. In the meantime, workers and first responders have established their own local practices for handling BESS safety.

The primary research objectives were to review and identify the gaps in the current knowledge base of worker and first responder safety concerns and practices at utility-scale BESS facilities. These identified gaps guide considerations for future research that promote worker and first responder safety in current and upcoming utility-scale BESS installations. This research is part of a larger EPRI initiative related to Environmental Aspects of Energy Storage (Project Set 197B).[1]

1.1 Research Objectives and Project Scope

The research objectives of this work are to:

- Identify the current knowledgebase of safety hazards associated with BESS facilities.
- Identify current worker and first responder safety practices at BESS and battery-related incidents.
- Identify gaps in the current knowledgebase and safety practices at utility-scale BESS facilities.
- Present considerations for future research and implementations of safety practices that promote worker and first responder safety.

These objectives were addressed through a review of published literature, current and upcoming codes, standards, and regulations, select first responder interviews, and gap analysis related to BESS technology, hazards, and related safety measures.

The scope of work included the following primary tasks:

1. Review the technologies used in BESS, the associated BESS and battery hazards, and safety measures implemented at BESS facilities.

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1 EPRI. EPRI Research Program Index: PS197B: Environmental Aspects of Energy Storage, 14 Jun 2018.

2. Review the current and upcoming codes, standards, and regulations applicable to safety measures implemented at BESS and worker and first responder safety practices at BESS facilities.
3. Collect current first responder safety practices regarding BESS and other battery-related incidents from firefighting training materials, interviews with local fire departments and BESS safety training programs for fire departments.
4. Identify gaps in the current knowledgebase of worker and first responder safety concerns and practices at utility-scale BESS facilities.
5. Present considerations for future research to advance the current knowledgebase of worker and first responder safety concerns at BESS facilities.

Review of Battery Energy Storage System Technologies

The available literature related to BESS, common BESS battery technologies, and safety hazards associated with BESS was collected, reviewed, and summarized. The literature was sourced from peer-reviewed scientific journals, industry publications, fire protection references and training guides, and BESS manufacturer documentation.

Current and Upcoming Codes, Standards, and Regulations

Relevant codes, standards, and regulations related to BESS were collected and reviewed, and progress of upcoming BESS standards was tracked. Codes, standards, and regulations were sourced from standards and regulatory bodies, such as the National Fire Protection Agency (NFPA), Occupational Safety and Health Association (OSHA), International Standards Organization (ISO), and Underwriters Laboratory (UL).

Worker and First Responder Safety Practices

Current firefighting practices related to BESS were collected and reviewed through training materials provided by the NFPA and through interviews with local fire departments about current practices and exposure to battery-related fires. Participating fire departments include those from Menlo Park, California; Cosumnes, California; and College Park, Maryland.

Gap Analysis and Considerations for Future Research

Based on the technologies, associated hazards, and safety measures reviewed in the literature and gathered from first responders, gaps in both the BESS knowledge base and current safety practices were identified. Based on these gaps, considerations for future research to help develop better safety practices in current and upcoming utility-scale BESS installations were presented.

2
REVIEW OF BESS TECHNOLOGIES

2.1 BESS Overview

Battery energy storage systems are technologies that use electrochemical reactions to store electrical energy and provide that stored energy for later use. The main motivations for incorporating BESS into energy grids include improving grid operating efficiency, reducing aggregate costs, increasing energy security, and enabling the incorporation of renewable energy sources.[2] The ability to store energy during times of excess energy production and then redistribute it on demand reduces the inefficiencies of electricity production and permits cost saving through energy peak shaving.[3] Peak shaving refers to the process of storing low-cost energy during times of low demand and accessing it during peak energy demand when electricity prices are higher. By storing low-cost electricity and using it at times of higher-cost electricity, the average price of consumed electricity can be significantly reduced.

Additionally, BESS are frequently used to store electricity generated from intermittent renewable power sources, such as wind and solar.[4] This can support the electric grid during times of high demand and improve the economics and viability of renewable power sources. BESS are also capable of increasing the electrical system security and reliability by providing a consistent flow of electricity during grid outages and times of intermittent supply.

While the use of batteries has been limited in large-scale electric power systems due to their relatively small capacities and higher costs, newer battery technologies have been developed that can provide significant utility-scale capabilities.[5] In addition to utility-scale applications, smaller commercial and residential BESS are also becoming more prevalent. This report focuses on a variety of BESS technologies that are currently available for utility application. A summary of the more widespread battery technologies, including their individual advantages, limitations, and inherent hazards, is provided in the following sections.

2.2 BESS System Design

BESS can be found in various sizes, spanning residential, commercial, and industrial applications. Small residential BESS are sized to supply electricity to a residential building for time periods on the order of hours. For example, the Tesla Powerwalls store 6.4 kWh or 13.5 kWh, depending on the model. Physically, the Powerwall is approximately the size of a large suitcase that can be mounted on the floor or on the wall.[6] On a larger scale, BESS can be grouped into larger systems addressing utility resource needs as well as "microgrids" to power

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2 DOE. Energy Storage Safety Strategic Plan, U.S. Department of Energy, December 2014.

3 AIG. Lithium-ion Battery Energy Storage Systems - The risks and how to manage them. AIG Energy Industry Group, 2018.

4 AEG. Battery Energy Storage Systems (BESS). AEG Power Solutions, 2013.

5 Wald, Matthew, L. Wind Drives Growing Use of Batteries, *The New York Times*, July 27, 2010.

6 Tesla. Powerwall | The Tesla Home Battery, 2018 https://www.tesla.com/powerwall.

neighborhoods, commercial complexes, and college campuses. In September 2017, the National Renewable Energy Laboratory screened 15 universities in the United States for photovoltaic and battery storage potential. The proposed battery systems were recommended between 14 kWh – 2.3 MWh.[7] Depending on capacity, these microgrids can range in size from a large refrigerator to a small portable storage container. At the utilities level, systems can range from 250 kWh – 30 MWh.[8] These batteries can be stored in racks in dedicated battery rooms, in lots of individually spaced refrigerator-sized units, or in full separate facilities the size of storage containers or buildings. Figure 2-1 shows examples of such utility-scale BESS facilities as refrigerator-sized (top) and building-sized (bottom).

Figure 2-1
Examples of individually spaced refrigerator-sized BESS units (top) [9] **and of a building-sized BESS facility (bottom, with original annotation).** [10]

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7 National Renewable Energy Laboratory (NREL). "NREL screens universities for solar and battery storage potential," NREL/FS-7A40-70037, Sept 2017.

8 Department of Energy (DOE) and Sandia National Laboratories. "DOE Global Energy Storage Database," DOE Office of Electricity Delivery and Energy Reliability, 2018 http://www.energystorageexchange.org/projects.

9 Southern California Edison. "Battery Storage: A Clean Energy Resource."

10 Gaillac, L. "SCE Energy Source Perspective." The Irvine Smart Grid Demonstration Closing Symposium, 2015.

Despite the various sizes and applications, most BESS share similar system designs and construction.[11] The basic building blocks of BESS are the individual battery cells that store the electrical energy. An individual battery cell uses a specific electrochemistry (such as lithium-ion or lead-acid chemistry) to store electrical energy as chemical energy. A set of battery cells can be grouped together into a battery module. The modules can then be further grouped into larger constructions based on the electrical design of the BESS. The "grouped" batteries can be electrically connected in parallel or in series to increase the current (and capacity) or voltage of the battery "group," respectively. The precise electrical configuration of the BESS is typically designed to accommodate the desired capacity and power specifications of the BESS.

In addition to the batteries, BESS typically have electrical and safety systems installed. Such systems can include inverters, transformers, charge controllers, battery management systems (BMS), and circuit breakers.[12] For some BESS manufacturers, these electrical and safety systems can be collectively grouped as a power conversion system (PCS).[13,14] For others manufacturers, the PCS refers only to the inverters.[15] Inverters convert electricity between direct current (DC) used by batteries and alternating current (AC) used by the electric grid. Inverters are crucial to BESS operation because DC and AC electricity are not compatible: AC current can damage internal battery components and DC current does not transmit efficiently through the electric grid. Transformers are components of the AC power distribution system that step the AC voltage up and down between transmission and source power to the BESS. Charge controllers and BMS are safety systems that regulate the electrical conditions the batteries are exposed to. Charge controllers regulate charging of the BESS and ensure that the batteries are not overcharged or overdischarged, because both conditions can adversely affect battery performance. In extreme cases, these conditions can lead to severe battery failure. The BMS monitors the individual conditions of the batteries and alarms for issues such as abnormal temperature fluctuations, electrical faults, and excessive discharge rates. BMS can also potentially isolate certain cells or modules from the system and allow the system to continue operating during local fault incidents or local maintenance procedures.

In residential settings, battery modules are typically housed in battery cabinets that can be floor- or wall-mounted. Typically, residential BESS are found in garages or in external enclosures near the main electrical service panel. Recently, the installations of residential BESS have accompanied solar panel installations. When configured with solar panels, batteries can be charged either through DC power from the solar panels or through AC power from the electric grid. To facilitate the different types of electrical power, these residential BESS can have one or more inverters, which convert between the DC power of the batteries or solar panels and the AC power of the residential building and electric grid. Each inverter typically has a dedicated disconnect switch, which isolates the different power sources (solar panels, batteries, and electric grid) from each other. First responders are trained to look for these disconnect switches when

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11 National Fire Protection Association (NFPA). Energy Storage System Safety Training Program, Fire Service Edition, June 2018.

12 Hopper, H. "Energy Storage Systems – Fire Safety Concepts in the 2018 International Fire and Residential Codes" Columbus International Code Council, 2017.

13 ABB. "Energy Storage Solutions – EssPro energy storage – Power Conversion System (PCS)," 2017.

14 Murai, T. Energy Storage System. *Meiden Review.* Series No. 169 2017 No. 1.

15 Dhunna, L. "Energy Storage Systems: more than just the battery." Did You Know? Schneider Electric, 30 Sep 2016.

they secure (disable) utilities during emergency response. In most cases, these disconnect switches at the inverter(s) are separate from the main service breaker disconnect, which isolates the residential building from the electric grid. Because a residential building equipped solar panels and BESS can be powered by either the solar panels, the BESS, or the electric grid, all disconnect switches that isolate the different power sources must be closed before power is fully secured.

In non-residential settings, BESS can vary widely depending on the designed capacity. For large installations, battery modules are typically stored in seismically secured racks. These racks can be installed either in dedicated battery rooms inside existing buildings or in separate external enclosures. With many batteries and modules in operation, groupings of batteries and modules may have open bus bars or heavily insulated cables that connect the groupings in the designed electrical configuration. Depending on the battery chemistries present, containment measures may be installed to contain potential electrolyte leakage. Due to the increased number of batteries in non-residential BESS, additional safeguard—including signage, fixed suppression systems, gas detection systems, emergency power-off systems, and a database of safety data sheets (SDS)—are typically implemented. These safeguards are discussed in detail in later sections of this report.

2.3 General Battery Technology

Batteries are a form of electrochemical energy storage in which electrical energy can be converted to chemical energy for storage and later returned as electrical energy on demand.

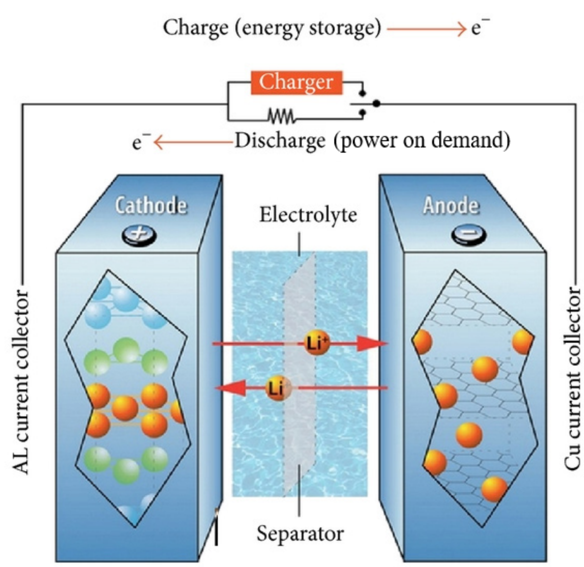

Figure 2-2
Basic construction of a Li-ion battery.[16]

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[16] Mebarki, B., Belkacem, D., Allaoua, B., Rahmani, L., and Benachour, E. Impact of the Air-Conditioning System on the Power Consumption of an Electric Vehicle Powered by Lithium-Ion Battery, *Modelling and Simulation in Engineering*, Volume 2013, Article ID 935784, 2013.

Batteries have four main elements: two electrodes, a separator, and electrolyte, as shown in Figure 2-2. As a battery is charged, electrons are forced from the positive electrode (cathode) to the negative electrode (anode) through a circuit external to the battery. Simultaneously, ions are produced into the electrolyte inside the battery at the cathode and absorbed into the anode. This results in a net motion of ions from the cathode to the anode across the separator in the electrolyte between the electrodes.[17] As the flow of electrons or "current," measured in amperes (A), continues to flow towards the anode, an electrochemical potential or "voltage," measured in volts (V), begins to build across the cathode and anode. Because this process goes against the natural tendency of ion and current flow, this charge process requires external energy. In the context of BESS, charging is typically performed by the excess electricity that is to be stored in the batteries. This is analogous to how excess electricity is stored in other types of energy storage systems. For example, in compressed air storage systems and pumped-storage hydroelectricity, excess electricity-to-be-stored powers compressors and pumps to compress air and elevate water, respectively.

During battery discharge, in which electricity is produced by the battery to meet demand, the reverse process occurs when the positive and negative terminals of the battery are placed in electrical connection. Much like how compressed air expands and elevated water cascades to turn generators in compressed air storage systems and pumped-storage hydroelectricity, ions in electrochemical energy storage systems are produced at the anode and absorbed into the cathode due to the voltage of the battery. This ion movement causes electrons, and thus current, to flow from the negative terminal to the positive terminal of the battery. The power output of the battery, measured in watts (W), is the rate of energy delivered by the current output. The corresponding energy output, measured in watt-hours (Wh), is the total amount of energy delivered by the current output of the battery. These units are equivalent to the power and energy ratings of other energy storage systems.

An additional battery specification common in BESS is capacity, which is measured in ampere-hours (Ah). The capacity of a battery indicates the theoretical amount of current that can be discharged. For example, a 100 Ah battery can theoretically deliver 100 A of current for an hour, or 50 A of current for two hours, before fully discharging. In reality, the discharge current does not scale linearly with voltage across the voltage range of the battery. This is analogous to how discharge flow rate in pumped-storage hydroelectricity is not constant during the draining process of an elevated water reservoir; as the reservoir elevation decreases, the hydrostatic pressure behind the discharge flow rate and the discharge flow rate itself decrease. In this analogy, the flow rate, reservoir elevation, and reservoir size represent the current, voltage, and capacity of the battery.

2.4 Common Battery Failures and Hazards

In general, there are several ways in which batteries can fail and present hazards to nearby personnel, including thermal runaway, fires, electrolyte spills, and release of toxic gases. These failures can be initiated by thermal abuse, mechanical abuse, electrical abuse, internal faults, or environmental impact.

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[17] The Fire Protection Research Foundation. (2011) *Lithium-Ion Batteries Hazard and Use Assessment*. The Fire Protection Research Foundation.

2.4.1 Thermal Abuse

Typical examples of thermal abuse of batteries can include proximity to external heat sources, including contact with overheating adjacent cells, as well as storage and operation at temperatures outside the intended battery operating range. When batteries are operated at temperatures outside of their expected range, either above the upper or below the lower limits, undesired chemical reactions can occur that may permanently degrade the cell performance and cause safety issues. Common degradation mechanisms for lithium ion batteries include undesired reactions between the electrolyte and electrodes, and thermal decomposition of materials, particularly the electrolyte. These degradation mechanisms may result in increased internal cell resistance and evolution of hazardous gaseous compounds, which both increase the probability of a thermal failure incident. At temperatures below the minimum of the expected operating range, reaction kinetics and ionic diffusion become slower, which can cause localized heating in the cell and undesirable metal plating. At high temperatures, polymeric materials—such as the separator or plastic casing—can melt and allow internal shorting between the electrodes. This internal shorting can also lead to thermal runaway.

Another form of thermal abuse involves creating or allowing large temperature gradients across a cell or battery pack. Large gradients are commonly caused by the application of an external heating or cooling source that only contacts a portion of the cell or pack. Inducing a large temperature range on an individual cell or pack can cause chemical gradients in the cell that may lead to undesired chemical reactions or metal plating. Metal plating is a substantial concern for Li-ion cells and has been linked to thermal runaway incidents. Standards, such as Institute of Electrical and Electronics Engineers (IEEE) 1725 5.6.6, contain standardized testing to reduce the likelihood of lithium-plating-related incidents.[18]

2.4.2 Mechanical Abuse

Typical examples of mechanical abuse of batteries include dropping, crushing, or penetrating the cell. Cells are generally not designed to withstand mechanical impact and mechanical forces that cause deformation or puncture to the cell. For this reason, battery enclosures and the degree of accessibility to the cells play a large role in the susceptibility of batteries to mechanical abuse. For batteries typically arranged in racks and cabinets, mechanical damage to cells is less likely, especially for stationary systems like those in BESS applications. Creating protective enclosures for cells and eliminating potential sources of mechanical damage to the cells can ensure the mechanical integrity of the cells. Additional caution is typically exercised when handling the cells outside of protective casings, such as when the cells are transported or installed.

Mechanical abuse can lead to cell failure mainly through creating a short-circuit and by allowing the loss of electrolyte. Any mechanical damage to a cell, whether from dropping, crushing or penetration, can potentially lead to short-circuiting the cell. Shorting may occur inside the cell by electrically bridging both electrodes, forcing the electrodes into direct contact with each other, or by creating sites where plating or increased current density may occur.[19] Mechanical damage to the external circuitry or wiring may also cause shorting of the cell. Regardless of whether a short

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18 IEEE 1725-2006, Standard for Rechargeable Batteries for Cellular Telephones

19 Hendricks, C., Williard, N., Mathew, S., and Pecht, M., A failure modes, mechanisms, and effects analysis (FMMEA) of lithium-ion batteries, *Journal of Power Sources,* 297 (30), 2015, pgs 113-120.

is internal or external, shorting can be very hazardous because it can cause thermal runaway, flammable gas evolution, and various electrical hazards.

2.4.3 Electrical Abuse

Typical examples of electrical abuse of batteries include overcharge, overdischarge, rapid charge and discharge rates, and prolonged exposure to elevated electric potentials. While different battery chemistries have different susceptibilities and reactions to electrical abuse, electrical abuse is a common failure mechanism that can create hazards in any battery system. Overcharge and overdischarge are the processes of allowing the cell potential to exceed the intended limit and can cause cell failure in similar ways. By exceeding the recommended cell potential window, irreversible chemical reaction—such as electrolyte decomposition, metal dissolution, and metal plating—can occur, which can lead to cell degradation through various methods, including venting of hazardous gases, increased internal resistance, and thermal failure incidents.

Using rapid charge and discharge rates beyond battery specification can also cause cell failure and safety hazards. When cycling at high rates, large chemical concentration gradients develop, which may induce undesired chemical reactions that lead to increased cell resistance and the formation of hazardous chemical products. Additionally, high rate charge and discharge will increase the magnitude of resistive heating within the cell, potentially raising the temperature of the cell to the point where thermal failure becomes more likely.

Prolonged cell exposure to potentials near or beyond the recommended limits can cause cell performance loss and/or failure through similar methods as overcharging or overdischarging. As a result, cells should not be left in highly charged or fully discharged states for extended periods of time. One common charging mode for some battery chemistries involves ending with a constant voltage (CV) charge, which involves holding the cell at the maximum charge voltage until the current drops below a predetermined level. If the current limit is set too low, the cell may remain at the maximum potential for an unnecessary amount of time, and parasitic electrolyte reactions can occur. These parasitic reactions may result in the degradation of the electrodes and electrolyte as well as in the formation of hazardous gases.

2.4.4 Internal Faults

Internal faults are typically the result of poor battery design, low-quality materials, or deficiencies in manufacturing processes. While even the most experienced and highest-volume battery cell manufacturers cannot guarantee zero failures, robust vetting of the cell quality and evaluation of the cell's performance can largely reduce the probability of failures. Irrespective of direct cause, internal faults generally lead to shorting and failure of the cell.

2.4.5 Environmental Impacts

Environmental impacts can lead to cell failure by inducing either thermal, mechanical or electrical abuse. Common environmental impacts include extreme ambient temperatures (thermal), seismic activity (mechanical), flooding (mechanical or electrical), and rodent damage to wiring (electrical). Even though completely preventing environmental damage is not possible, there are multiple preventive measures that can reduce the probability and severity of environmental sources on the BESS. Such measures may consist of utilizing active temperature management systems, building robust protective housing for individual cells and battery packs, and in appropriately choosing geographical locations for the BESS.

While all battery types are susceptible to each failure method, the design and chemistry differences between cells will cause each type of battery to react differently. Thus, failure methods and associated hazards need to be thoroughly evaluated for each specific cell type prior to implementation in a BESS.

2.4.6 General Thermal Hazards

All batteries, especially high-energy-density Li-ion batteries, present thermal hazards. As previously discussed, there are a multitude of causes for a battery to have a thermal incident or to induce thermal runaway. In general, thermal runaway results from internal temperatures increasing faster than the heat can be dissipated. Concomitant with thermal runaway is often fire, significant smoke, and the release of hazardous chemicals.

During thermal failures, temperatures within individual cells can reach over 1000°C. Between the electrolyte, separator and other polymer components in and around the cell, Li-ion batteries have ample amounts of flammable materials and can sustain fires for extended periods of time. Other cell types, even those using aqueous electrolytes, can also be highly flammable. Gases released during cell failures are often highly combustible and can produce jets of flames which propagate the fire. First responders should be aware that cells commonly ignite in a cascading series, where damaged cells eventually generate enough heat or fire to ignite neighboring cells, which in turn continue to burn and spread the fire. This process can happen slowly or explosively fast and depends largely on the cell type, module packing, and safety measures implemented. Furthermore, even after combustion has been extinguished, remaining cells and post-combustion debris may remain exceedingly hot and reignition is possible.

In addition to the release of heat, many hazardous chemicals are emitted from the cell or its housing during thermal failure. First responders should be aware that electrolyte and other active materials from the cells may be exposed and are often hazardous upon physical contact or inhalation. SDS documentation typically includes the battery-specific chemical hazards to consider. As with all fires, workers and first responders should be cautious of smoke inhalation, especially because many hazardous gases are often produced during battery failures. Signs of a thermal failure include observation of fire or smoke, venting of gases, and the development of substantial excess heat. Gas detection systems can be instrumental in rapidly detecting thermal events because cells often vent gases due to electrolyte degradation prior to or in the beginning of the failure. Similarly, temperature monitoring systems can provide advanced warning of a thermal failure or give insight into the approximate state of the cells during the incident.

2.4.7 General Mechanical Hazards

Because batteries are generally static systems with minimal moving physical parts, the mechanical hazards intrinsically associated with BESSs are limited to violent failures of the batteries. Batteries can overpressurize or eject internal components when a substantial pressure develops in the cell. Most battery housings and enclosures include mechanical vents that relieve excess pressure. Overpressure events can be the result of mechanical vent failure or if the pressure rise rate overwhelms the vent. Even during instances in which cell vents function properly, highly pressurized gases and electrolyte released from the cell can contain enough force to present a mechanical hazard to personnel and equipment nearby. Most commonly, this internal pressure builds up because of gas formation from electrolyte decomposition. Batteries using either aqueous or organic electrolytes are likely to develop and release gases when they are overcharged or overheated. Furthermore, batteries in thermal runaway may also pose a mechanical hazard because the rapid release of energy during the thermal event can cause the ejection of cell components or cause structural damage to materials and equipment neighboring the cell.

2.4.8 General Electrical Hazards

Electrical hazards can be particularly dangerous for workers and first responders at BESS facilities because it may not be obvious which conductors are energized. Identifying electrical hazards during emergency response when the state of the battery system is unknown can be especially difficult. While the individual batteries of some battery chemistries may not present electrical hazards themselves, BESS facilities are likely to have components with sufficiently high voltage potentials to cause serious electric shock or electrocution. In addition to the DC electrical hazards presented by the battery modules, BESS facilities also have AC electrical hazards near the inverters that transmit power to and from the electric grid.

Similar electrical safety hazards can exist from electrical circuits for both AC and DC current. A safety hazard can arise when personnel or electrically conductive material unintentionally contact a component at an elevated voltage potential and create an unintended current pathway. If personnel are a part of an unintended current pathway, typically between an elevated voltage and ground, current can pass through them causing electrical shock, severe burns, or other bodily injury. Techniques for assessing electric shock are outlined in International Electrotechnical Commission (IEC) 60479-1: *Effects of current on human beings and livestock*.[20] The degree of shock and resulting symptoms are dependent on the voltage differential contacted by an individual and the impedance of the individual between the contact points, which determines the current passing through an individual. The duration of current flow also affects the resulting shock. The human body can be modeled as a series of impedances. Impedances vary between individuals but are highly dependent on the current pathway through the body between contact locations (i.e. between fingers, from an arm to an arm, or from an arm to the feet) and the quality of skin contact with the energized components (i.e. dry skin, wet skin, or damaged skin). Higher voltage levels are particularly dangerous because the increased electrical potential results in higher currents through similar body impedances. Extremities and the skin have higher impedances than the body torso and legs. As such, breaches in skin or wet skin substantially lowers the total body impedance and increases current that can flow through the body at a fixed voltage.

Depending on the current through the body and the duration of the current flow, IEC 60479-1 outlines the following physiological effects, in increasing severity, expected in an individual experiencing electric shock: perception, involuntary muscular contraction, strong muscular contraction and reversible heart disturbances, cellular damage, and ventricular fibrillation. Muscular contraction in extremities can compound the severity of the electric shock because an individual may not be able to release contact with an energized conductor, thus prolonging the duration of current flow in a response known as grip tetanus. The current path through the body can also determine the severity of electric shock. The heart is particularly at risk from electric shock because it relies on internal electrical signals to synchronize the heartbeat. External

[20] International Electrotechnical Commission (IEC) 60479-1 (2015): Effect of Current on Human Beings and Livestock – Part 1.

electrical current through the heart may disrupt the rhythm of the heart, and it can be difficult to return the heart to its original rhythm with or without the use of emergency equipment, such as an automated external defibrillator (AED).

First responders are particularly concerned with the electrical hazards associated with using water to extinguish components at elevated voltages. Recent reports demonstrate that water can be safely applied under certain conditions to extinguish a thermal event.[21,22,23,24] However, contact with pooling water in contact with an energized AC component or conductor can present a shock hazard. When responding to an incident involving a BESS, it is generally a best practice to electrically isolate the affected system as soon as possible to prevent additional energy from being added to the damaged system or component(s) and reduce the electrical hazards to workers and first responders.

Arc flashes can be an additional hazard associated with elevated voltages, such as those present at the emergency disconnect switches in BESS facilities. Breaking a current pathway between conductors or components at elevated voltages can potentially result in an arc-flash, which may injure personnel opening a disconnect. The NFPA recommends that first responders, when safe to do so, disconnect smaller breakers before the main service breaker. When actuating a disconnect switch, the NFPA recommends that first responders look away from the panel to minimize injury if an arc-flash does occur.[25]

Due to their less frequent occurrence, DC arc flashes are not as thoroughly understood as AC arc flashes. From what is known, DC arc flashes are more difficult to extinguish because they lack the zero-crossings AC current have. Zero-crossings are the instantaneous points at which there is zero voltage present in each AC cycle. At these points, AC arcs may extinguish themselves. However, exposure to AC voltage is considered to be three times more dangerous than exposure to DC of the same voltage because it is more likely to result in muscle tetany (involuntary contraction of the muscles), extending the duration of exposure."[25,26] There has been a significant amount of research into the causes of AC arc flashes, the predicted levels of energy and damage resulting from them, the harm and injuries they cause, and the safety measures designed to reduce their potential for injury. A report by the Fire Protection Research Foundation describes injuries resulting from arc flash events.[27] An Eaton white paper provides introductory level information concerning arc flashes and what steps can be taken to safeguard employees.[28] IEEE 1584 quantifies potential arc flash incident energy levels while NFPA 70E defines thresholds for appropriate PPE based on the potential severity of an arc flash.

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21 National Fire Protection Association. Electric Vehicle Emergency Field Guide. Quincy, MA. 2012.

22 Delphi Corporation. Hybrid Electric Vehicles for First Responders. Troy, MI. 2012.

23 Long RT, Blum AF, Bress TJ, and Cotts BRT. "Emergency response to incidents involving electric vehicle battery hazards." Fire Protection Research Foundation Report, July 2013.

24 Egelhaaf, M., Kress, D., Wolpert, D., Lange, T., Justen, R., and Wilstermann, H., "Fire Fighting of Li-Ion Traction Batteries," SAE Int. J. Alt. Power. 2(1):37-48, 2013, doi: 10.4271/2013-01-0213.

25 National Fire Protection Association (NFPA). Energy Storage System Safety Training Program, Fire Service Edition, June 2018.

26 M. A. Cooper, "Emergent Care in Lightning and Electrical Injuries," Seminars in Neurology 15, 2015.

27 R. B. Campbell and D. A. Dini, "Occupational Injuries from Electric Shock and Arc Flash Events," The Fire Protection Research Foundation, March 2015.

28 D. G. Loucks and J. Collins, "What You Need to Know About Arc Flashes" Eaton White Paper, July 2013.

2.4.9 General Chemical Hazards

Typical gases released from batteries during battery venting, thermal runaway, or combustion are outlined in Table 1. Additional less common gases specific to certain battery chemistries may also exist and it is recommended to consult the SDS documentation associated with the battery or battery chemistry to become familiar with all gases that may be potentially generated.

Table 2-1
List of gases known to be released from batteries and their associated hazards.

Released Gas	Associated Hazard
Carbon dioxide (CO_2)	Potential asphyxiant*; any adverse health effect would likely result from inhalation and not from dermal or ocular exposure.†
Carbon monoxide (CO)	Toxic gas; displaces oxygen in blood causing oxygen deprivation. Adverse effects would result from inhalation exposure and not from dermal or ocular exposure#; odorless gas.
Ethane (C_2H_6)	Potential asphyxiant*; any adverse health effect would likely result from inhalation and not from dermal or ocular exposure; flammable.
Hydrogen (H_2)	Potential asphyxiant*; any adverse health effects would likely result from inhalation and not from dermal or ocular exposure, flammable.
Hydrogen chloride (HCl)	Corrosive to skin and eyes; can cause severe burns. If inhaled, it may cause respiratory irritation.
Hydrogen cyanide (HCN)	Systemic asphyxiant. Adverse effects would likely result from inhalation but HCN is also well-absorbed systemically through the skin. May cause skin, eye, and respiratory tract irritation.§
Hydrogen fluoride (HF)	Corrosive to skin and eyes; can cause severe burns. If inhaled, it may cause respiratory irritation.
Methane (CH_4)	Potential asphyxiant*; any adverse health effects would likely result from inhalation and not from dermal or ocular exposure; flammable.
Propylene (C_3H_6)	Potential asphyxiant*; any adverse health effect would likely result from inhalation and not from dermal or ocular exposure; flammable.
Sulfur dioxide (SO_2)	Irritating to eyes, nose, throat, and lungs. This gas has a strong, irritating odor.

* An asphyxiant gas is a nontoxic or minimally toxic gas which displaces oxygen in breathing air when present in high concentrations; at low concentrations, these gases have no physiologic effects. Intake of oxygen-depleted air can cause asphyxiation (suffocation). Asphyxiant gases are relatively inert and odorless, and their presence in high concentrations may be unnoticed.

† CO_2 is a normal product of metabolism and is expelled through the lungs. The acute effect of elevated CO_2 exposure is referred to as hypercapnia, which is the condition of abnormally elevated CO_2 levels in blood and is a subcategory of asphyxiation.

\# CO is classified as a toxic gas and primarily causes adverse effects by competing with oxygen on a molecular level by displacing oxygen in hemoglobin, which is an oxygen-carrying protein in the blood. When CO combines with hemoglobin, it produces carboxyhemoglobin, which cannot deliver oxygen to tissues, depriving them of oxygen.

§ HCN is classified as a toxic gas and is a systemic asphyxiant. HCN inhibits cytochrome oxidase, an enzyme that plays a critical role in cellular respiration; inhibition of this enzyme prevents cellular utilization of oxygen. This gas has a faint odor of bitter almonds; however, this does not provide adequate warning of hazardous concentrations.

Occupational exposure limits (OELs) exist for some chemical agents and are recommended as guidelines or promulgated as standards to promote worker health and safety. An OEL is an upper limit on the acceptable concentration of a hazardous substance in workplace air for a particular agent. OELs can be established for time-weighted average (TWA) exposures (i.e. 8-hour work day) or for short-term exposure limits (STEL) (typically 15-minute exposures). OELs are established as standards by regulatory agencies or as guidelines by research groups or trade organizations. Sources that establish OELs include the following:

- Permissible Exposure Limits (PELs): legally enforceable standards set by OSHA.[29]
- Recommended Exposure Limits (RELs): guideline values recommended by that National Institute for Occupational Safety and Health (NIOSH).[30] Although RELs are not legally enforceable limits, NIOSH RELs are considered by OSHA when setting PELs.
- Threshold Limit Value (TLV): guideline values developed by the American Conference of Governmental Industrial Hygienists (ACGIH).[31] Although not legally enforceable, TLVs are frequently reevaluated and generally widely accepted by industry.
- Acute Exposure Guidelines Levels (AEGLs): recommended values developed through the National Advisory Committee for Acute Exposure Guideline Levels for Hazardous Substances (NAC/AEGL Committee), which is a federal advisory committee.[32] AEGLs are not confined to occupational exposure scenarios; they are used by emergency planners and responders as guidance (i.e. not legally enforceable) in dealing with accidental releases of chemicals into the air. They are designed to protect sensitive individuals.

Although OELs and AEGLs have not been specifically established for all the agents listed in Table 2-1, values can be sourced from PELs, RELs, and TLV to aid in understanding acceptable limits to protect worker health.

In addition to the chemical hazards presented by the gases in Table 1, these gases can also present thermal hazards because gases released from batteries undergoing thermal runaway are at temperatures exceeding 500 °C and are released under pressure. In addition to their elevated temperature, vented gases are generally highly flammable and can generate additional thermal hazards if ignited.

Other sources of chemical hazards include exposed active materials, electrolyte leakage, and water run-off after emergency response. Because electrode and electrolyte composition varies widely between battery chemistries and between manufacturers of the same battery chemistry, reviewing SDS documentation is recommended to become familiar with the chemical hazards present. In the event of a battery failure that requires the use of a water suppressant, the runoff water can be contaminated with electrolyte and debris from the incident. Depending on the battery chemistry, these contaminants can be considered hazardous waste. For example, electrolyte leakage from flow batteries can be particularly hazardous due to the large volume of potentially corrosive and toxic electrolyte used. In most cases, water used by fire departments to extinguish battery fires is not collected or processed. Therefore, if the chemical hazards are not properly identified for a given incident battery system, containment of water runoff and leaked electrolyte can be unintentionally neglected by first responders.

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29 https://www.osha.gov/dsg/annotated-pels/

30 https://www.cdc.gov/niosh/npg/default.html

31 https://www.acgih.org/tlv-bei-guidelines/tlv-chemical-substances-introduction

32 https://www.epa.gov/aegl/access-acute-exposure-guideline-levels-aegls-values#chemicals

There are numerous different battery chemistries and form factors used in BESS, each with unique properties and hazards.[33] The following sub-sections provide introductions to the more prominent battery technologies for BESS applications and their associated safety hazards for workers and first responders.

2.5 Li-ion Battery Technology and Hazards

Lithium-ion (Li-ion) batteries are a class of secondary, or rechargeable, batteries that use lithium ions as the charge carrier in and out of the electrolyte during charge and discharge. This class of batteries benefits from the light molecular weight of lithium, fast ionic diffusion (with appropriate electrolyte), and high-operating potentials of the fully charged battery. As a result, Li-ion batteries generally have higher volumetric and gravimetric energy densities, as well as exceptional power capabilities compared to other battery chemistries. These superior characteristics of Li-ion batteries drive widespread use in consumer electronics, electric vehicles, and BESS. Li-ion batteries account for over 62% of the BESS capacity in the U.S., and usage is growing rapidly as the technology continues to develop.[34]

Despite the numerous advantages of Li-ion batteries, there are acute hazards regarding the safety and stability of these batteries. Under certain conditions, Li-ion batteries are known to enter thermal runaway, which is the process where the internal self-heating rate of the battery due to an internal failure exceeds the rate of heat loss to the surrounding environment. This causes cells in thermal runaway to reach high internal temperatures, which in turn causes melting, combustion, or expulsion of various components. Thermal runaway can be induced by a variety of sources, including thermal, mechanical or electrical abuse to the cell or battery pack, manufacturing defects that result in the development of an internal short, or from side reactions, such as dendrite formation that develop under aggressive cycling conditions.[35] To avoid safety risks associated with thermal runaway of Li-ion cells, robust thermal management systems and proper cell and battery pack design are crucial.

Packs or modules of lithium-ion batteries can present a multitude of hazards to nearby personnel and equipment. The high voltage and energy density of lithium-ion batteries makes them attractive for many storage applications but also substantially increases their safety risk. Often many cells are strung together in series, which can increase the cumulative voltage of the system into the range of hundreds to thousands of volts. At such potentials, the likelihood of an arc-flash or arc-blast increases substantially. Additionally, while the highly reactive nature of the electrodes and electrolytes in lithium-ion batteries is beneficial for increasing the energy density of the cell, it also makes the materials hazardous if they come into contact with the skin or eyes, or if they are inhaled. Extreme caution and protective equipment should always be used when working with opened cells or any of the active cell components.

Fire or combustion of cell components during a thermal failure event are another primary safety hazard. The electrolyte and other polymer components (e.g. separator, tape, plastic packaging, etc.) are generally the most flammable parts of a lithium-ion cell. Because of the high oxidation

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33 Reddy, T. (2011). Linden's Handbook of Batteries.

34 U.S. Department of Energy. (2017). Energy Storage Systems Overivew of the Technology, Safety Related Issues and Codes/Standards. U.S. Department of Energy.

35 Sandia National Laboratories. (2015). First Responder Safety for Grid Energy Storage. Sandia National Laboratories.

and reduction potentials of lithium-ion batteries, volatile organic electrolytes with fluorinated electrolyte salts are standard. The electrolyte, which is highly flammable under ambient conditions, is commonly vaporized or degraded into gaseous compounds and vented during a thermal failure. While venting of the electrolyte or gaseous products should not occur during safe operation of the battery, it is frequently observed when the cell is overcharged and during thermal runaway. The flammable vented electrolyte may readily ignite on contact with a sufficient ignition source, which can include a spark or even a heated surface.[36] A recent study by Consolidated Edison observed that the mixture of commonly released gases during thermal runaway of a lithium-ion battery are often more flammable than any of the gases on their own. Additionally, the study notes that the majority of the components within the cell are not flammable and that the vented gases and electrolyte are largely responsible for the fire hazard of these devices.[37]

The specific vent gas composition may vary substantially and will depend on multiple factors, including the composition of the cell's active materials and electrolyte, state of charge, and the cause of the cell venting. Vent gases from Li-ion batteries generally consist of organic compounds, such as alkyl-carbonates, methane, ethylene and ethane, hydrogen gas, carbon monoxide, and carbon dioxide. In addition, particle-phase material—including soot and various metal-containing particulates—can be released. Many of these vent gases are highly flammable even in relatively low concentrations. The electrochemical history of the cell also impacts the chemistry of the vent gases. For example, decomposition of the electrolyte may cause new products to form, which can result in different gas compositions during venting. In addition to being highly flammable, vent gases are frequently acutely toxic, highly corrosive, hot, and carcinogenic, which increases their hazard in the event of exposure.[38]

Because the term "lithium-ion" encompasses a multitude of related but distinct chemistries, there are substantial differences in the hazard profile for each specific battery formulation. While it is outside the scope of this work to provide a detailed assessment of each chemistry, it is important to note that differences in the cell's active and inactive materials directly impact the prevalence and severity of each hazard type for that cell. Because most Li-ion cells use a similar carbon-based (i.e. graphite) negative electrode and electrolyte formulations, the main differential in the chemistries of cells with respect to safety is usually the positive electrode. Some positive electrode chemistries—such as $LiFePO_4$, $Li_4Ti_5O_{12}$, and $LiMnPO_4$—are considered by some to be safer alternatives to the more common, energy-dense, nickel- and cobalt-rich layered oxide materials because they have lower operating energy densities, which may form less volatile gases; furthermore, these materials demonstrate below average temperatures during thermal

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36 Exponent, Inc. (2016). Hazard Assessment of Lithium Ion Battery Energy Storage Systems. Bowie, MD: Exponent, Inc.

37 Consolidated Edison. (2017). Considerations for ESS Fire Safety. New York, NY: Consolidated Edison.

38 Energy Storage Association. (2018, October 28). *Energy Storage Association - Energy Storage Technologies*. Retrieved from Energy Storage Association: http://energystorage.org/energy-storage/storage-technology-comparisons.

failures. Extensive work on the safety aspects of various positive and negative electrode and electrolyte chemistries can be found elsewhere.[39,40,41]

The quality of the cell construction is also very important in determining the safety of a Li-ion battery system. It should not be assumed that all batteries, even those with the same chemistry, are fabricated similarly. Small differences in the construction of cells—such as the variation in the active material coatings, size and placement of electrode current collectors and tabs, and the presence of internal safety mechanisms like a positive thermal coefficient (PTC) or current interrupt devices (CID)—can largely determine the safety of the cell. Prior to implementation of any Li-ion battery system, users should be aware of the safety performance and operational restrictions for that particular cell design.

Failures of Li-ion batteries range in character from slow and relatively benign self-discharging to violent and dangerous thermal events. In the former scenario, there may be minimal immediate safety risk to surrounding personnel or equipment because the failure does not rapidly produce heat, ignite or expel any cell components. As a result, little to no fire suppression may be necessary and the primary hazard reduction objective should be removing the damaged cells/pack from the system so additional energy is not loaded onto the failed batteries. The appropriate safety and hazard reduction procedure is substantially different when the lithium-ion batteries undergo thermal runaway. During thermal runaway, the cells and surrounding components may get exceedingly hot and will require active cooling mechanisms. To reduce the severity of the thermal event, good air flow is necessary to carry away any volatile gases that were vented by the cells. Because substantial heat is generated and flammable gases are often ejected from the cell, thermal runaway events can easily spread to multiple cells and/or packs. Restricting the propagation of a Li-ion thermal battery failure requires active monitoring of the cell conditions, satisfactory ventilation, and the presence of thermal management or fire suppression systems.

To minimize the risk of thermal failure and improve personnel safety, understanding the signs of cell failure are important. Common visual signs of failure for Li-ion batteries include bulging or deformation to the cell casing, evolution of any gas or smoke, and fire. Other signs, such as hissing or popping sounds and the smell of either solvents or combustion products are also indicators of cell failure. In the event that any of these failure signals are observed or if alarms are generated from other safety systems (e.g. gas and smoke detection systems) cells should be electrically isolated to prevent any additional energy from being added to them and safely replaced when handling is again possible (i.e. after time or with appropriate engineering controls/PPE).

Fires involving Li-ion cells are largely the result of burning hydrocarbons, such as the electrolyte and separator. These materials require an oxidizing agent, such as air, and have been reported to be extinguished with common fire suppressants, such as water and standard fire extinguishers.

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[39] Nitta, N., Feixiang, W., Lee, J.T., and Yushin, G. (2015). Li-ion battery materials: present and future. *Materials Today, 18 (5), pg 252-264.*

[40] Kim, G., and Dahn, J.R. (2014). ARC Studies of the Effects of Electrolyte Additives on the Reactivity of Delithiated $Li_{1-x}[Ni_{1/3}Mn_{1/3}Co_{1/3}]O_2$ and $Li_{1-x}[Ni_{0.8}Co_{0.15}Al_{0.05}]O_2$ Positive Electrode Materials with Electrolyte. *Journal of the Electrochemical Society*, *161 (9),* pg A1394.

[41] Liu, K., Liu, Y., Lin, D., Pei, A., and Cui, Y., Materials for lithium-ion battery safety, *Science Advances,* 4 (6), 2018, pgs 1-11.

Relatively unique to Li-ion batteries is their ability to reignite well after an initial flame has been extinguished. This is based in their large degree of flammable gas production with intermittent venting, high heat generation in localized areas, and various layers of shielding that make cooling failed batteries inefficient. As a result, the most effective fire suppressants for Li-ion battery fires will also be capable of cooling the system and thus preventing reignition of combustible materials from the cell's hot surfaces.

Fire suppressants that have been demonstrated to extinguish the initial flames of a Li-ion battery fire include inert gas, smothering of flames with carbon dioxide, and various Halon chemicals.[42,43,44] However, these fire suppressants do not significantly cool the failed cells and thus reignition of the affected batteries is common. Historically, water has been shown to be among the most effective ways to extinguish battery fires because of its dual role as a flame suppressant and efficient coolant.[45,46] However, because of the high voltage and electrical nature of BESS, appropriate fire suppressants should ideally be non-conductive, and an increased electrical hazard persists when using water as the fire suppressant method. Because fire suppressants have varying levels of effectiveness depending on the cell chemistry, system design and operational environment, the optimal methods of extinguishing fires and cooling BESS should be evaluated and established before operation of the BESS. When choosing an appropriate fire suppressant, it is critical to fully understand the materials within the BESS, especially for Li-ion batteries that contain highly reactive substances that may not be extinguished through standard methods.

2.6 Lead-Acid and Nickel-Based Battery Technologies and Hazards

Lead-acid and nickel-based (i.e. nickel-cadmium and nickel-metal hydride) batteries are mature battery technologies that have been used in BESS for decades. Because these chemistries use corrosive aqueous electrolytes and heavy metal electrodes, their hazard profiles are similar. Since the introduction of Li-ion and nickel metal hydride batteries, nickel-cadmium systems have lost substantial market share as the battery for consumer electronics, electric vehicles and BESS. According to the Department of Energy statistics, the last BESS to become operational using nickel-cadmium technology for grid storage was in 2003. At the same time, lead-acid batteries have maintained their status as one of the main BESS technologies, primarily due to their familiarity, proven reliability and low cost. As of 2015, lead-acid batteries consisted of about 12% of the grid energy storage capacity in the U.S.[47] However, due to the emergence and development of lithium-ion technology, the market share for lead-acid batteries is in decline, although it remains the BESS of choice for certain applications. Conversely, nickel-metal

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42 Summer SM, "Flammability Assessment of Lithium-Ion and Lithium-Ion Polymer Battery Cells Designated for Aircraft Power Usage," DOT/FAA/AR-09/55, January 2010, http://www.fire.tc.faa.gov/pdf/09-55.pdf.

43 Lain MJ, Teagle DA, Cullen J, Dass V, "Dealing with In-Flight Lithium Battery Fires in Portable Electronic Devices," CAA Paper 2003/4, July 30, 2003.

44 Mikolajczak CJ, Wagner-Jauregg A, "US FAA-Style Flammability Assessment of Lithium Ion Cells and Battery Packs in Aircraft Cargo Holds," Exponent Failure Analysis Associates, Inc., April 2005; PHMSARSPA-2004-19886-0044.

45 Advance Change Notices to NSTM 555VIR12 and NSTM 555V2R11 for Lithium Battery Firefighting Procedures, July 21, 2009.

46 http://www.fire.tc.faa.gov/systems/handheld/handheld.asp, access the link to a video entitled, "Extinguishing In-flight Laptop Computer Fires."

47 U.S. Department of Energy. (2017). Energy Storage Systems Overivew of the Technology, Safety Related Issues and Codes/Standards. U.S. Department of Energy.

hydride batteries were never widely implemented as a BESS due to their high self-discharge rate, low efficiency, poor overcharge stability, and lower energy density than Li-ion systems.[48]

Hydrogen evolution caused by overcharging the cell is a common safety concern for both nickel-based and lead-acid batteries due to the limited stability of water at those potentials. This type of safety hazard has been identified as a main limitation for nickel-metal hydride batteries and has largely prevented their use in BESS. Because hydrogen is colorless, odorless, and tasteless, it can be very difficult to detect, and with a wide flammability range of 4%-74%, it is easy to ignite. As a result, BESS that use either battery technology need to have proper ventilation and gas detection methods to avoid explosive ignition of vented hydrogen gas. The basic potassium hydroxide and acidic sulfuric acid electrolytes used for nickel-based and lead-acid batteries, respectively, are highly corrosive and present a safety hazard if they come into contact with improperly protected personnel.[49] Suppressing a small nickel-based or lead-acid battery fire can be achieved with either an inert gas or powder extinguisher and with water. Larger fires are best extinguished with water because it can more effectively cool the cell and prevent reignition of any combustible cell components or evolved gases. Due to the maturity of these battery systems, extensive information on the hazards, safety protocols, and additional details on the appropriate fire extinguishing methods has already been reported.[50,51] Because of the plethora of safety information, lead acid and nickel-based battery manufacturers should provide a robust safety data sheet for their cells.[52] The most comprehensive information on the safety of these chemistries, the hazards associated with their implementation in a BESS, and the results of safety testing on these systems can be obtained from the cell, pack, and/or system manufacturers.

2.7 Sodium-based Battery Technology and Hazards

Commercially available sodium-based batteries are a unique class of energy storage devices that differ substantially than the other battery chemistries discussed in this report. Here, sodium-based batteries refer mainly to the sodium-sulfur and sodium-metal chloride chemistries. The primary differences in how these chemistries operate compared to more conventional batteries are that the sodium negative electrode is in the liquid state and a solid electrolyte is used to separate the positive and negative electrodes. To maintain molten sodium, these cells operate in a temperature range of ~300-350 °C and intermittently require external heat to be added to the system. Unlike the Li-ion or lead acid technologies previously discussed, a solid ceramic electrolyte (usually β-Al_2O_3 or a similar material) is used in place of the liquid electrolyte and porous solid separator. The most common positive electrode for this class of batteries is a sulfur compound, although various metal chlorides have also been used.[53]

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48 Battery University. (2018, November 8). Battery University – Nickel-based Batteries. https://batteryuniversity.com/index.php/learn/article/Nickel_based_batteries

49 AEG Power Solutions. (2013). Battery Energy Storage System. AEG Power Solutions.

50 U.S. Department of Energy. DOE Fundamentals Lead-Acid Storage Batteries, U.S. Department of Energy.

51 SafeWork SA (2018, November 2). SafeWork SA – Lead acid batteries. Retrieved from SafeWork SA: https://www.safework.sa.gov.au/news/lead-acid-batteries#

52 Batteries Plus, LLC. (2017). Safety Data Sheet (SDS), Lead Acid Battery Wet, Filled With Acid. Batteries Plus, LLC.

53 Energy Storage Association. (2018, October 28). *Energy Storage Association - Energy Storage Technologies*. Retrieved from Energy Storage Association: http://energystorage.org/energy-storage/storage-technology-comparisons

Keeping sodium in the molten state requires a cell design different than what is used for more conventional cells. Typical Li-ion or lead-acid batteries include alternating layers of narrow, densely packed electrodes housed in a thin metal frame. Because this design would be highly inefficient for sodium-based batteries, a different architecture is used, as shown in Figure 2-3. In this cell format, there are no alternating layers of positive and negative electrodes so the sodium, β-Al_2O_3, and sulfur layers can be made thicker, which reduces cell fabrication cost and difficulty. This structure is also advantageous because it concentrates the molten sodium, which is contained within the center of the cell. The main disadvantage of this cell format or any cell that uses thick electrode and electrolyte layers is the reduced power capabilities of the cell because ions have to diffuse a further distance and the surface area of electrochemically active material on each electrode is greatly reduced.

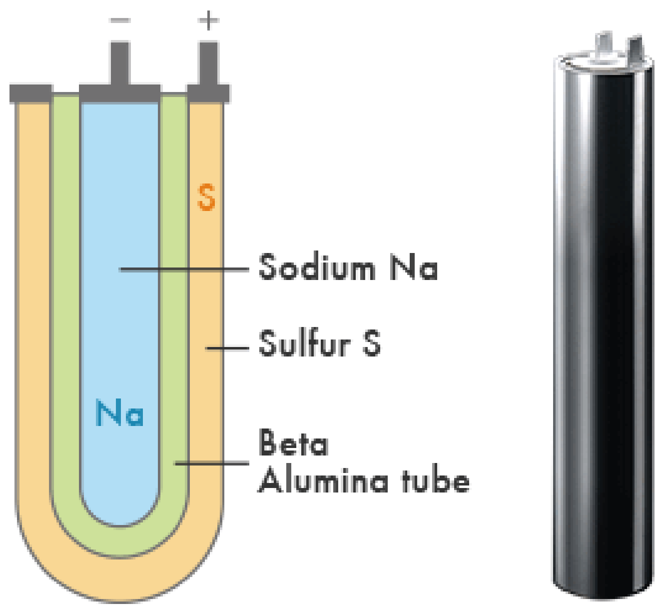

Figure 2-3
Model diagram of a common cell design for sodium-sulfur batteries.[54]

Sodium-based batteries have seen modest commercial success due to their relatively high round-trip efficiency of 90%, low cost, and high energy and power densities. According to a 2017 Department of Energy report, sodium-metal batteries comprised of 13.72% of the BESS power capacity in the U.S. While the low cost and high energy density of sodium-based batteries is attractive for many applications, these systems require special maintenance, particularly related to their safety. Because these systems operate at ~300-350 °C, active cooling mechanisms and shutdown protocols are necessary in case of an incident or system failure.[55] If a sodium-based BESS has a thermal event or a mechanical incident that allows molten sodium to flow out of the cell, the system will become extremely hazardous. Sodium metal is highly reactive, and if ignited, is classified as a Class D fire. As such, it reacts violently with water or Halon

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[54] NGK Insulators, LTD. (2018, November 1). *NAS Sodium Sulfur Battery Energy Storage System.* Retrieved from https://www.ngk.co.jp/nas/specs/

[55] U.S. Department of Energy. (2017). Energy Storage Systems Overivew of the Technology, Safety Related Issues and Codes/Standards. U.S. Department of Energy.

compounds and instead should be extinguished with select dry powder chemicals. Sodium combusts upon exposure to the ambient atmosphere because it reacts with moisture and produces hydrogen gas, which can then be subsequently ignited. Thermal incidents to sodium-based cells may also cause the formation of sulfur or chlorine-based gases, which in addition to being flammable, may also be highly hazardous. Robust air ventilation and gas monitoring systems are required to diffuse any vented gases and alert personnel of the increased hazard.

To minimize heat loss to the surroundings and to prevent mechanical damage to the cell from external sources, sodium-based batteries are enclosed in a thick, double-wall insulated nickel or stainless-steel casing. This protective barrier greatly reduces the risk of external damage to the cell causing a failure that requires an emergency response. In the event of severe mechanical shock to the system, the β-Al_2O_3 electrolyte is likely to crack, enabling the low viscosity molten sodium to readily react with the positive electrode, resulting in a mildly exothermic reaction that produces a nonhazardous solid with a low vapor pressure. The thick thermally insulating enclosure is designed to minimize heat loss to the environment, so even after a sodium battery fire is extinguished, post-fire monitoring is necessary to prevent reignition.

While the degree in which the intrinsic materials of the sodium-based batteries pose a hazard is highly dependent on the system design and operation, it is important to note that many of the reactive components of the cell are hazardous. In particular, sodium, nickel metal, and various metal chlorides are either highly flammable, corrosive or cause acute and chronic health issues if contacted or inhaled. An extensive review of the design of sodium-based cells and their associated hazards can be found in a report by the National Renewable Energy Laboratory. [56]

2.8 Redox Flow Battery Technology and Hazards

Redox flow batteries are attractive as a utility-scale BESS because they can provide high energy storage capabilities at a relatively low cost due to their unique cell architecture. In contrast to conventional batteries in which energy is stored as chemical changes to the positive and negative electrodes, redox flow batteries store energy in two electrolyte solutions. These positive and negative electrolytes—named the catholyte and anolyte, respectively—contain the active materials that can reversibly perform oxidation and reduction reactions, thus enabling the system to store energy. As shown in Figure 2-4, during operation of a redox flow battery, the two electrolytes, which are separately stored in two tanks, are pumped into a reaction cell containing the positive and negative electrodes and an ion permeable membrane.[57] In this cell, ions in each electrolyte are oxidized or reduced at the positive and negative electrodes and the free electrons are used to provide electrical energy. The ion-selective membrane keeps the two electrolytes separate by allowing charge compensation between the two solutions.

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[56] Trickett, D. (1998). Current Status of Health and Safety Issues of Sodium/Metal Chloride (Zebra) Batteries. Golden, CO: National Renewable Energy Laboratory.

[57] U.S. Department of Energy. (2017). Energy Storage Systems Overivew of the Technology, Safety Related Issues adn Codes/Standards. U.S. Department of Energy.

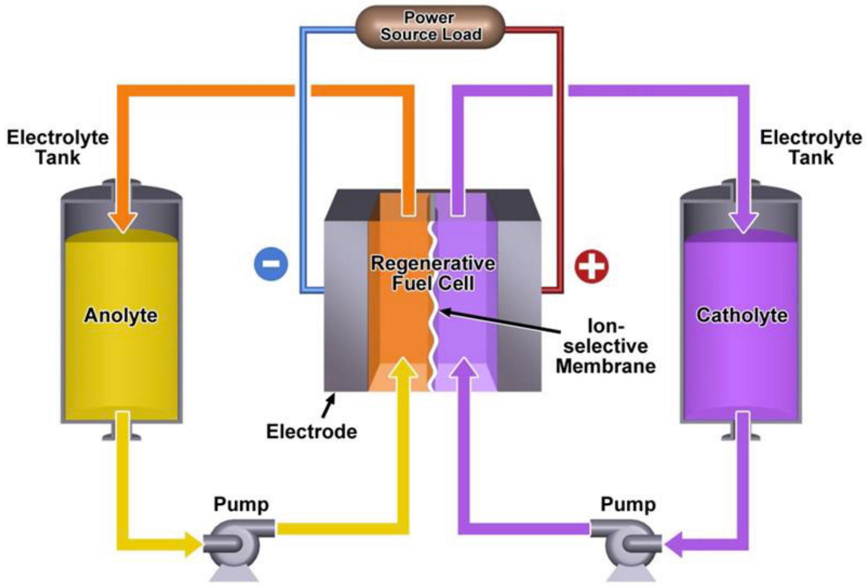

Figure 2-4
Diagram depicting the architecture of a redox flow battery.

Because energy is stored in the electrolytes and not the electrodes, the system's magnitude of the energy storage is directly related to the volume of each solution. As a result, redox flow batteries are scalable up to the hundreds of MWh by increasing the sizes of the tanks holding each electrolyte. Typical cell voltages for redox flow batteries range from 1 to 2.2 V, depending on the reaction chemistry. However, similar to conventional batteries, system voltages can be multiplied by stacking cells in series. The power capabilities of the system are also dependent on the quantity of cells in series, and on the flow rate of the electrolyte solutions through the cells. As more catholyte and anolyte are pumped through the cell, more electrochemically active ions are available for reaction.[58]

The main advantages of redox flow batteries are their ability to be easily scaled to store large amounts of energy and power, wide range of chemistries, and their minimal fire hazard. However, these systems suffer from relatively low efficiencies, small operating temperature range as well as overcharging and cycling stability issues. Redox flow batteries have a below average fire hazard for BESS due to their use of aqueous solutions for both electrolytes and their unique architecture. Because the electrolytes must be pumped into the cell, only a few percent of the total system energy is directly connected to the cell, and thus the total amount of stored chemical energy capable of igniting is substantially lower than other BESS technologies. This is in sharp contrast to conventional battery designs in which all of the stored energy is located within the cell and immediately available for discharge or exothermic reactions during a thermal failure. There are numerous redox flow chemistries in use commercially; each with unique advantages and safety hazards. Because it is not within the scope of this report to provide a detailed assessment of each chemistry, only a brief description of the main chemistries and their

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[58] Barbour, E. (2018, October 30). *Energy Storage Technologies – Flow Batteries*. Retrieved from Energy Storage Sense. http://energystoragesense.com/flow-batteries/

associated hazards is provided. Additional information on each type of flow battery can be found elsewhere.[59,60]

The most prominent flow chemistries used for commercial and utility storage applications are vanadium redox and zinc-bromine flow systems. Vanadium redox flow batteries are "true" redox flow batteries, meaning that all the electrochemically active species are always fully dissolved in solution. The catholyte and anolyte in vanadium redox flow batteries are chemically very similar because they both use vanadium ions dissolved in a sulfuric acid solution, which is advantageous because system storage capacity is not reduced if vanadium ions cross the selective membrane. However, each electrolyte uses a different vanadium redox couple (+4/5 for catholyte and +2/3 for anolyte) and stored electrical energy is lost for that cycle if cross contamination of the electrolytes occurs. Vanadium redox flow batteries are generally limited by a narrow operating temperature range of ~10-40 °C, and thus temperature management systems may be required. As the temperature begins to exceed 40-45 °C, vanadium compounds irreversibly precipitate out of the electrolytes, permanently lowering the system storage capacity and changing the chemical composition of the electrolytes.

Unlike the vanadium-based chemistry, zinc-bromine flow batteries are considered hybrid flow systems, where energy is partially stored in plated zinc metal as well as in the electrolyte. Also different from the vanadium redox system, two chemically different electrolytes are used in zinc-bromine flow batteries. A water-based electrolyte containing zinc is used for the negative electrode, while the positive electrode uses an organic amine solvent to transport the bromine. The zinc-bromine chemistry has among the highest cell voltages and capacities for flow batteries, but suffers from relatively low efficiency (65-75%), poor cell lifetime, and requires active maintenance. Additional hazards are also present for zinc-bromine flow batteries due to the high toxicity of bromine, flammability of the organic amine solvent, and dendrite formation that occurs with repeatedly plated zinc metal.

Other flow chemistries—such as iron-chrome, and zinc-chlorine, and zinc-iron—have been demonstrated but are not widely used. Some of these chemistries, particularly zinc-iron, are still being actively developed, so a full evaluation of the potential hazards has not been completed. Like the vanadium redox chemistry, these systems aim to use only aqueous electrolytes, thus reducing the potential flammability of the system. Furthermore, these chemistries target the use of non-toxic and environmentally benign materials, which would minimize the chemical safety hazard to workers and first responders in a failure.[61]

While each flow chemistry has its own flammability risk and hazard profile, they share some broad safety concerns. Flow cells that use aqueous electrolytes have an inherently lower flammability risk, and if a fire does occur, a water-based suppression is likely effective. However, these same systems likely produce hydrogen gas if overcharged, due to the redox stability of the water-based electrolytes. If evolved in substantial quantities, hydrogen gas can be explosive and create serious hazards to personnel and equipment. Gas monitoring systems and adequate air ventilation are required for safe operation of these systems. Additionally, the

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[59] Energy Storage Association. (2018, October 28). *Energy Storage Association - Energy Storage Technologies*. Retrieved from Energy Storage Association: http://energystorage.org/energy-storage/storage-technology-comparisons

[60] Sandia National Laboratories. (2015). *First Responder Safety for Grid Energy Storage*. Sandia National Laboratories.

[61] ViZn Energy. (2018, October 28). *ViZn Energy - Technology*. Retrieved from ViZn Energy: https://www.viznenergy.com

electrolytes used in flow batteries are often acidic and may be corrosive or toxic; thus, they pose a serious hazard in the event the electrolyte leaks or spills.

2.9 Metal-Air Battery Technology and Hazards

Metal-air batteries have recently overcome many technical hurdles and are now beginning to enter the commercial market. These systems differ from conventional battery technologies because one of the major reactants (oxygen) is derived from air and is not physically contained within the cell. As a result, metal-air batteries generally possess high volumetric and gravimetric energy densities. Presently, zinc-air batteries are the most developed technology in this class and are beginning to be commercially implemented with three utility-scale BESS projects already announced in the U.S.[62] This technology has also been implemented in various smaller scale energy storage projects, including providing power to communications towers and to remote villages in Africa and Asia.[63]

Zinc-air batteries can be discharged by allowing oxygen (from air) to enter the cell and react with water on the positive electrode, which is usually a high surface area carbon material. Together the oxygen and water molecules form hydroxide ions, which then diffuse to and react with the zinc metal anode, producing two free electrons per zinc atom. In addition to its relatively high energy density, the chemistry of this battery is advantageous because it uses low cost, safe and environmentally benign materials. The primary advantages of zinc-air batteries are their low cost, which is claimed to be below $100 per kWh, and relatively non-hazardous properties. Zinc-air batteries are not expected to be a substantial fire hazard because they utilize an aqueous electrolyte and because zinc metal is not very flammable. In the event a zinc-air battery does catch fire or has a thermal incident, a water-based suppression system should be able to be safely used. The expected less hazardous nature of zinc-air batteries is also attributed to the relatively low toxicity of the electrodes and electrolyte. Because this technology is still actively being developed and has yet to be demonstrated in large-scale facilities, a complete understanding of all the fire safety and personnel hazards of a zinc-air BESS are not fully established.[64]

2.10 Additional Battery Considerations

Recycled Batteries for Use in BESS

With the recent increase in the use of electric vehicles (EVs), there has also been a growing market for used EV batteries. As EVs are used, the capacity of the battery decreases over time. The reduced capacity of the aging battery shortens the range the car can travel, eventually making the battery impractical for further use in a vehicle. These batteries are typically replaced once their capacity decreases below 80% of the original capacity of the battery.[65] However, the batteries can still effectively store and transmit energy, even at reduced capacity, making them attractive for many different systems, including BESSs, which have more lenient power and capacity requirements. The economics of repurposing of EV batteries for BESSs is still currently

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[62] U.S. Department of Energy. (2018, October 28). *DOE Global Energy Storage Database*. Retrieved from DOE Global Energy Storage Database: https://www.energystorageexchange.org

[63] Bussewitz, C. (2018). *Zinc-Air Batteries Provide Power in Remote Areas*. Associated Press.

[64] NantEnergy. (2018, October 30). *NantEnergy - Technology*. Retrieved from NantEnergy: https://nantenergy.com/technology/

[65] G. Reid, J. Julve, *Second Life-Batteries As Flexible Storage For Renewable Energies*. BEE (2016).

debated in industry. Despite some sources quoting the cost of a new battery as much as six times the cost of a repurposing a used EV battery, the lack of certainty of the repurposed battery's capability and lack of warranty have slowed widespread adoption of repurposing used EV batteries.[66] In October 2018, UL1974: *Standard for Evaluation for Repurposing Batteries* was published to establish sorting and grading processes of repurposing batteries and electrochemical capacitors for other applications, including energy storage systems.[67,68]

BESSs composed of used EV batteries, as compared to ones using new batteries, requires additional safety and considerations. While limited data are currently available on performance characteristics of aged batteries, there has been work showing that Li-ion batteries, such as those commonly used in EVs, display higher rates of self-heating than un-aged batteries and will vent electrolyte at lower temperatures (~145 °C instead of 165 °C).[69] Additionally, larger increased rates of self-heating can occur if the aged battery has been subjected to cold environmental conditions, which may be the case for batteries from EVs used in colder climates. The increased rates of self-heating and electrolyte venting at lower temperatures increases the risk for thermal runaway, which is the main fire and explosion hazard associated with batteries. Therefore, operating temperature ranges for BESSs determined from manufacturer data from new (i.e. un-aged) batteries may tend to overpredict the safe upper temperature limit. These uncertainties related to second-life battery use are also increased by the different battery chemistries, manufacturing processes, and first-life use conditions.

Besides the issues of using aged batteries listed above, BESS utilizing recycled EV batteries also create a need for more advanced control of the BESS. Most research on BESS focuses on systems using new batteries of the same type, resulting in limited variation in chemistry, voltage, and state-of-charge (SOC) between the different cells; therefore, these systems can be controlled simply by using an active or passive balancing circuit. In systems utilizing second-life batteries, there is a wider variance in cell capacity, voltage, and initial state of charge due to their different first-life operations. As battery technologies continue to advance, so will the chemistry and performance of batteries. Additionally, variation of battery performance can be a result of different manufacturing processes. For these hybrid systems that may utilize a variety of battery types, more advanced BESS controls are needed to ensure that the battery system remains balanced and that no hazardous conditions are created within the system.[70]

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66 Lieberich, M. and McCrone, A. *Electric Vehicles-It's not just about the car*. Bloomberg News (2016).

67 Underwriters Laboratory. "The Afterlife of Electric Vehicle Batteries." *Inside UL*, 2015.

68 UL 1974, Standard for Evaluation for Repurposing Batteries, edition 1, October 25, 2018.

69 Fleischhammer, M. Interaction of cyclic ageing at high-rate and low temperatures and safety in lithium-ion batteries. J. of Power Sources, (2015).

70 Mukherjee, N. and Strickland, D. Control of second-life hybrid battery energy storage systems based on modular boost-multilevel buck converter. IEEE Transactions on Industrial Electronics, 2015.

3
BESS INSTALLATION AND OPERATION SAFETY PRACTICES

BESS installation and operational safety practices were collected from codes, standards and regulations put forth by the International Fire Code (IFC), the National Fire Protection Association (NFPA), and the Occupational Safety and Health Administration (OSHA). Specific operational safety practices discussed include signage, air monitoring systems, ventilation, fire suppression systems, alarms and shut-off systems, and containment.

3.1 Codes, Standards, and Regulations

With the significant growth of the BESS industry in the past decade, codes, standards, and regulations are developing to keep up with the pace of the BESS industry as well as the technology advancement to ensure safe deployment of BESS.[71] Current codes, standards, and regulations are in the process of development to incorporate more specific and uniform requirements for BESS. This section outlines briefly current codes, standards, and regulations pertaining to BESS installation and operation safety practices, including:

- 2018 International Fire Code (IFC)
- National Fire Protection Association 1, *Fire Code*, 2018 edition (NFPA 1)
- National Fire Protection Association 855, Standard for Installation of Energy Storage Systems, proposed 2nd draft edition[72]
- CFR Title 29 Volume 8 § 1926.441, *Batteries and Battery Charging*
- CFR Title 29 Volume 5 § 1910.178, *Powered Industrial Trucks*

The IFC, published by the International Code Council, is a model fire code that is widely adopted in the United States by states and local jurisdictions. NFPA 1, published by the National Fire Protection Association (NFPA), is another model fire code that is adopted by many jurisdictions in the United States. When adopted by states or local jurisdictions, the IFC and NFPA 1 mandate prescriptive fire safety requirements for new and existing buildings. Both IFC and NFPA 1 contain requirements governing building and equipment design features including BESS installation.

NFPA 855, currently in its development process and expected to be published in 2019, addresses design, construction, installation, commissioning, operation, maintenance, and decommissioning of BESS. [73] It is expected that NFPA 855, once officially published, will be adopted and/or referenced by the model codes.

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[71] EPRI, Energy Storage Safety: 2016, Guidelines Developed by the Energy Storage Integration Council for Distribution-Connected Systems, Technical Update, June 2016.

[72] NFPA 855, Second Draft Report, November 1, 2018.

[73] NFPA 855, Second Draft Report, November 1, 2018

The Code of Federal Regulations (CFR) contain specific requirements provided by the U.S. Occupational Safety and Health Administration (OSHA). These requirements are specific to batteries, battery charging, and powered industrial trucks associated with changing and charging storage batteries.[74,75] These requirements include facility safety measures, personal protection equipment (PPE), and vehicle requirements.

Although not directly related to BESS installation and operational safety practices, UL 9540: *Standard for Energy Storage System and Equipment* includes requirements to address the construction, design, and performance of the BESS as well as the interface of the BESS with the infrastructure. UL 9540 outlines construction and design criteria for BESS including requirements for enclosure and electrical insulation materials, enclosure ratings and construction, general electrical safety, electrical connections and components, remote controls and communication, safety analysis, containment of hazardous spill and moving parts, combustible concentrations, requirements for fire risk assessments to determine if fire detection and suppression is necessary, nameplate markings, and instructions for BESS installation, operating and maintenance.[76] The details of UL 9540 are outside the scope of this report and are not reviewed.

3.2 BESS Installation

The IFC and NFPA 1 contain similar BESS installation requirements. Both IFC and NFPA 1 cover BESS based on the battery capacity threshold and technology.[77] Maximum allowable quantities per control area (MAQ), which refers to the maximum amounts of hazardous material allowed to be stored or used within a control area inside a building or an outdoor control area[78], are also mandated in both codes based on the battery total capacity and technology.[79] When a facility exceeds the MAQ, such a facility will be classified as a high-hazard occupancy and be subjected to more stringent requirements for construction, protection measures and operations. Both IFC and NFPA 1 also mandate location requirements, with some exceptions, in prohibiting BESS installation more than 75 feet above street level and more than 30 feet below the lowest finished floor access point.[80] Furthermore, BESS must be provided with a minimum of 3 feet separation distance from walls, equipment, or other obstruction when installed indoor and 5 feet from lot lines, public ways, buildings, stored combustible materials, hazardous materials, high-piled stock, and other exposure hazards when installed outdoors per the IFC and NFPA 1.[81] Both fire codes require that rooms containing capacitor BESS be separated by fire barriers or horizontal assemblies with up to 2-hour fire resistance-rated construction based on the occupancy types.[82] Details regarding construction safety distances can be sourced directly from IFC and NFPA 1.

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74 Occupational Safety and Health Administration (OSHA), CFR 2011 Title 29 Volume 8 §1926.441.

75 Occupational Safety and Health Administration (OSHA), CFR 2007 Title 29 Volume 5 §1910.178.

76 UL 9540, Standard for Energy Storage System and Equipment, edition 1, November 21, 2016.

77 2018 IFC §1206.2 and NFPA 1 -2018 §52.1

78 2018 IFC §202 and NFPA 1 -2018 §3.3.181

79 2018 IFC §1206.2.9 and NFPA 1 -2018 §52.3.2.2

80 2018 IFC §1206.2.8 and NFPA 1 -2018 §52.3.2.1.2.1

81 2018 IFC §1206.2.8.2 & 1206.2.8.7.1 and NFPA 1 -2018 §52.3.2.1.4.2 & 52.3.2.1.4.3

82 2018 IFC §1206.3.2.2 and NFPA 1 -2018 §52.3.3.2

NFPA 855, in general, contains similar BESS installation requirements as outlined in both IFC and NFPA 1. NFPA 855 draft language contains a more restrictive separation distance of 10 feet for BESS installed outdoors, but also allows for a 3-foot separation distance when outdoor BESS installations are protected with a 1-hour freestanding fire barrier suitable for exterior use.

3.3 Signage

Signage can provide critical information for firefighters and emergency first responders who respond to a fire involving BESS in a building or facility. The critical information includes:

- The presence and location of disconnect switches that can be used to de-energize and isolate portions of the electrical system.
- The location of BESS rooms and areas and the types of BESS.
- Significant hazards associated with the BESS technology present.

IFC and NFPA 1 provide requirements on proper signage for BESS. To provide proper warnings, approved signs are to be provided on doors and in locations near the entrance to a room housing the BESS. The signage must identify that the room contains an energized battery system, energized electrical circuits, and any additional required marking based on the specific battery system contained in the room.[83] When a battery storage cabinet is in an occupied work center, the exterior of the cabinet is required to have the appropriate labels and warnings, including warnings identifying the presence of a battery systems and labels that identify the manufacturer, model number, and electrical rating of the contained battery system. Inside the cabinet, signs indicating relevant chemical and electrical hazards of the contained system are required to be provided.[84] In addition to signs warning of the presence of the battery systems, placards and signs must be in place identifying the location of the main disconnects if they are not within sight of the battery system disconnects.[85]

3.4 Air Monitoring Systems

As reviewed in the descriptions of the different BESS battery chemistries, gases can be vented from batteries during routine usage, such as charging and during battery abuse and failure. Air monitoring systems are used to track the emission and to detect hazardous concentrations of these gases in enclosures containing batteries. There are two main aspects of hazard management considered for both personnel and equipment: personal injury or harm, and physical risk to the facility.

Within personal injury, there are two further categories of concern: exposure to physically-acting agents such as asphyxiants or corrosives, and health-acting agents, such as toxics. The action of physical agents may include explosive atmospheres (such as with H_2) and displacement of sufficiently life-supporting air with other gases (such as with CO; however, in the case of CO,

[83] 2018 IFC §1206.2.8.6 and NFPA 1 -2018 §52.3.2.6.5

[84] 2018 IFC §1206.2.8.6.2 and NFPA 1 -2018 §52.3.2.6.5.5

[85] 2018 IFC § 1206.2.8.6.1 and NFPA 1 -2018 §52.3.3.9.1

there is both the displacement concern as well as a toxic dimension that includes CO binding to hemoglobin and preventing proper oxygen delivery to cells).

The physical agent class of exposure agents requires a less sensitive detection system because the concentrations that produce an impact are generally higher. For example, CO concentrations are measured in parts-per-million-by-volume (ppmv) and lower explosive limits (LEL) are often measured in percent concentration range. Therefore, lower-cost sensors for these specific targets are available.

The health-acting agents refer to toxic chemicals that may or may not produce immediate symptoms, but that typically are avoided for personal protection. These can be categorized into those that cause acute symptoms and those that cause chronic symptoms (such as carcinogens). The range of toxics of concern are generally larger, but the active concentrations are frequently much lower. Therefore, detection systems are more complicated in this instance because of both the higher number of toxics and the lower concentrations that cause harm, although simplifications are used to detect a whole class of compounds (such as with organic vapors).

Two types of measurement technologies can be deployed: fixed and portable systems. Fixed systems provide continuous coverage for the more commonly found substances and may be less sensitive or more restricted in the types of compounds detected. These are mostly appropriate for infrastructure or facility safety considerations. On the other hand, portable detection systems are usually more sensitive and have a broader range of detectability; as a result, they are often used in personal safety protection for first responders.

Standard measurement protocols that are recommended for both of these types of detection systems include: (1) appropriate selection of specifications to allow for adequate concentration and time responses, both in concentration and time, and avoidance of cross-sensitivity, which is a frequent problem with lower-cost sensors; (2) initial calibration (often performed by the factory) and periodic checks of both operation and calibration; (3) correct siting (sensor placement); and (4) sufficiently responsive alarming systems for rapid and complete communication of exceedance of target concentration.

It is recommended that for any installation, a qualified safety engineer or industrial hygienist review the plans for appropriate attention to these potential impacts.

3.5 Ventilation

Because the emission of hazardous gases from BESS is a concern, NFPA 1 and the IFC include ventilation requirements for energy storage systems. The need for a ventilation system is dependent on the type of battery storage system, specifically the types of gases expected to be emitted and the corresponding acceptable gas concentrations. If a ventilation system is required, the design and installation is guided by the applicable mechanical code and recommended either to limit the concentration of flammable gas to 25% of the lower flammability limit (LFL), or to use continuous ventilation provided at a rate not less than 1 ft^3/min per square foot of the total floor area of the room or cabinet. If hydrogen gas is expected to be emitted, the ventilation is restricted to limit concentration to 1% of the total room volume.[86] NFPA 855 includes similar

[86] 2018 IFC §1206.2.11.3 and NFPA 1 -2018 §52.2.2.6

ventilation requirements to those listed in NFPA 1 and the IFC.[87] The standard allows for use of either continuous ventilation or a system activated by a gas detection system.[88] In addition to the design requirements, the standard states that the mechanical system is to be supervised in accordance with NFPA 72 or should initiate an audio/visual signal at an approved on-site location that is constantly attended.[89]

3.6 Fire Control and Suppression Systems

BESS can present fire and explosion hazards to facility personnel as well as create a higher risk of property damage due to fire. Fire control and suppression systems can be provided to manage the impact of fire involving BESS. NFPA 855 describes types and requirements for fire control and suppression systems for BESS, including automatic sprinkler systems and fixed suppression systems.

3.6.1 Automatic Sprinkler Systems

NFPA 855 proposes requirements that an automatic sprinkler system for protecting BESS be installed in accordance with NFPA 13, *Standard for the Installation of Sprinkler Systems*. For BESS fires, NFPA 855 requires that the sprinkler system be designed to deliver a minimum amount of water (i.e. design density) of 0.3 gpm/ft^2 (12.2 mm/min) when activated based on the area of the room or 2500 ft^2 (230 m^2) design area, whichever is smaller. As a point of reference, this design density of 0.3 gpm/ft^2 over 2500 ft^2 is similar to the design density that is required per NFPA 13 for the Extra Hazard Occupancy Group 1, which includes those occupancies with hydraulic machinery or systems with flammable or combustible hydraulic fluids under pressure.[90] Alternatively, the design density can be based on large-scale fire testing of a representative BESS in accordance with UL 9540A, *Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems*.[91]

3.6.2 Fixed Suppression Systems

There are various types of fixed suppression systems, including water-based fire suppression systems and inert gas-based fire suppression systems, among others. Fixed fire suppression systems consist of discharge nozzles, a control panel, detection devices, warning alarms, manual discharge station, and storage containers with the selected extinguishing agent.

Water-based systems use water either in direct application or via the deluge method to cool the environment and halt thermal runaway. Water-based systems can be effective but may also be insufficient in reaching inaccessible areas, such as inside cabinets.

When an inert-gas fire suppression system is used, the main objective is to displace or lower the oxygen levels in an enclosed area to a level below 16%, the level needed for combustion and to maintain burning. For such inert-gas fire suppression systems, an additional pre-action disconnect switch is typically installed to halt suppression measures in the event personnel safety

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[87] NFPA 855, Second Draft Report, §4.9.2 & §4.9.3

[88] NFPA 855, Second Draft Report, §4.9.3.1

[89] NFPA 855, Second Draft Report, §4.9.3.3

[90] NFPA 13-2016, §11.2.3.1.1

[91] NFPA 855, Second Draft Report, §4.11.2, and 4.1.5

is jeopardized with the introduction of inert gas. Per NFPA 855, a gaseous agent fire suppression system is to be designed based on factors including the required concentration of agent for the combustible material involved and the specific configuration of the equipment and area.[92] When a total flooding system is used, it should be designed such that it maintains the design concentration in the enclosed area for a time long enough for the fire to be extinguished and the temperature of the BESS to cool below the autoignition temperature of the combustible material and the temperature that causes thermal runaway.[93]

3.7 Alarm and Shut-Off Systems

Most air monitoring systems and fire suppression systems can be connected to a central alarm system that can alarm internally and/or externally to local fire departments. Typically, an alarm from the air monitoring system can trigger the activation of the fire suppression system. Each of these systems also typically has emergency disconnect switches to manually override alarms and prevent undesired suppression measures.

Emergency power-off systems can be installed to isolate individual racks, sections, or the whole BESS. The main emergency power-off system is typically positioned at a distance from the batteries, either outside of the battery room or at a safe distance from external enclosures. This distance allows for safe emergency shut-off during an incident.

3.8 Containment

NFPA 855 proposes requirements that rooms, buildings, or areas containing BESS with free-flowing liquid electrolyte in an individual vessel having a capacity of more than 55 gal (208 L) or multiple vessels having an aggregate capacity exceeding 1000 gal (3785 L) must be provided with spill control to prevent the flow of liquids to adjoining areas. The method and materials used for the spill control must be capable of controlling a spill from the single largest vessel.[94] For sealed valve-regulated lead-acid (VRLA) batteries and other BESS equipment with immobilized electrolyte or immobilized hazardous liquids, these systems are not required to be provided with spill control per NFPA 855.[95]

NFPA 855 recommends the following method for spill control:

- Liquid-tight sloped or recessed floors in indoor locations or similar areas in outdoor locations.
- Liquid-tight floors in indoor locations or similar areas in outdoor locations provided with liquid-tight raised or recessed sills or dikes.
- Sumps and collection systems.

When rooms, buildings or areas containing BESS are protected by water-based fire protection systems, NFPA 855 states that the capacity of spill control must also accommodate the capacity of the expected fire protection system water discharge for a period of 10 minutes, except for

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92 NFPA 855, Second Draft Report, §4.11.2.1.2.1

93 NFPA 855, Second Draft Report, §4.11.2.1.2.2

94 NFPA 855, Second Draft Report, § 4.14.1 and 4.14.2

95 NFPA 855, Second Draft Report, § 4.14.5

when the spill control is an integral part of BESS and is shielded from the fire protection water discharge.[96]

Furthermore, NFPA 855 proposes that a method to neutralize spills from BESS be provided. The neutralization method must be capable of neutralizing a spill of free-flowing electrolyte from the largest battery or a vessel in BESS to a pH level between 5.0 and 9.0. NFPA 855 also refers to UL 2436, *Outline of Investigation for Spill Containment for Stationary Lead Acid Battery Systems*, for the compliance of pH neutralization capability.[97]

3.9 Occupational Safety and Health

As described in previous sections, the hazards for workers at BESS primarily consist of fire, explosion, electrical hazards, and associated chemical hazards. In addition to the system safety precautions for first responders in the event of an emergency incident, several routine precautions can be taken to protect BESS workers. These safety elements include fire extinguishers, eyewash stations, chemical spill kits, personal protective equipment (PPE) for handling battery acid and electrolyte (rubber gloves, face shield, and apron), appropriate equipment for disposal of battery acid and electrolyte, and appropriate signage indicating fire, explosion, and electrical hazards. The U.S. Occupational Safety and Health Administration (OSHA) provides specific requirements for batteries and battery charging, as follows:[98]

- Batteries of the unsealed type are recommended to be located in enclosures with outside vents or in well ventilated rooms and are recommended to be arranged so as to prevent the escape of fumes, gases, or electrolyte spray into other areas.
- Ventilation is recommended to be provided to ensure diffusion of the gases from the battery and to prevent the accumulation of an explosive mixture.
- Racks and trays are recommended to be substantial and be treated to make them resistant to the electrolyte.
- Floors are recommended to be of acid resistant construction unless protected from acid accumulations.
- Face shields, aprons, and rubber gloves are recommended to be provided for workers handling acids or batteries.
- Facilities for quick drenching of the eyes and body are recommended to be provided within 25 feet (7.62 m) of battery handling areas.
- Facilities are recommended to be provided for flushing and neutralizing spilled electrolyte and for fire protection.
- Battery charging installations are recommended to be located in areas designated for that purpose.
- Charging apparatuses are recommended to be protected from damage by trucks.

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96 NFPA 855, Second Draft Report, § 4.14.3 and 4.14.4

97 NFPA 855, Second Draft Report, § 4.15 and A4.15.1

98 Occupational Safety and Health Administration (OSHA), CFR 2011 Title 29 Volume 8 §1926.441.

- When batteries are being charged, the vent caps are recommended to be kept in place to avoid electrolyte spray. Vent caps shall be maintained in functioning condition.

OSHA also provides requirements specific to powered industrial trucks associated with changing and charging storage batteries, as follows:[99]

- Battery charging installations are recommended to be located in areas designated for that purpose.
- Facilities are recommended to be provided for flushing and neutralizing spilled electrolyte, for fire protection, for protecting charging apparatus from damage by trucks, and for adequate ventilation for dispersal of fumes from gassing batteries.
- A conveyor, overhead hoist, or equivalent material handling equipment are recommended to be provided for handling batteries.
- Reinstalled batteries are recommended to be properly positioned and secured in the truck.
- A carboy tilter or siphon is recommended to be provided for handling electrolyte.
- When charging batteries, acid is recommended to be poured into water; water is not recommended to be poured into acid.
- Trucks are recommended to be properly positioned and brake applied before attempting to change or charge batteries.
- Care is recommended to assure that vent caps are functioning. The battery (or compartment) cover(s) is recommended to be open to dissipate heat.
- Smoking are recommended to be prohibited in the charging area.
- Precautions is recommended to prevent open flames, sparks, or electric arcs in battery charging areas.
- Tools and other metallic objects are recommended to be kept away from the top of uncovered batteries.
- Additional requirements such as truck operation and training are described in the main body of the regulation.

The precautions described above are general in nature and each specific facility is recommended to be thoroughly evaluated to determine any additional safety requirements that may be needed. Additional state and local requirements may apply.

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[99] Occupational Safety and Health Administration (OSHA), CFR 2007 Title 29 Volume 5 §1910.178.

4
EMERGENCY FIRST-RESPONDER SAFETY PRACTICES

BESS-related emergency first responder safety practices were collected through NFPA training material and interviews conducted with members of fire departments in California and Maryland. The practices will be discussed in three main categories: pre-incident planning, hazard mitigation, and emergency response. Pre-incident planning is the systematic method of gathering general and detailed data regarding a specific site. This is intended to be performed in advance of any incident. Hazard mitigation involves determining the present hazards and executing the best practices for addressing those hazards. Emergency response involves the common scenarios in which first responders are called onto a scene and what best practices are currently performed in those scenarios.

4.1 Energy Storage Systems Safety Online Training

The NFPA provides a self-paced online course on battery energy storage systems, titled *Energy Storage Systems Safety Online Training, Fire Service Edition*. This course educates the fire service on how to respond safely to emergency situations involving high-voltage commercial and residential energy storage systems, and provides recommended mitigation and emergency responses.[100] The recommendations include general protocols for initial action upon scene arrival, hazard mitigation, and handling BESS-specific incidents, such as electrolyte release, overheated batteries, and BESS fires. The details of these recommendations, supplemented by the input from local fire departments, are discussed in the following sections. In addition, Annex C of NFPA 855, *Fire-fighting Considerations (Operations)*,[101] was reviewed; this document outlines recommendations for emergency first-responders to effectively respond to events involving BESS.

4.2 Interviews with Local Fire Departments

Interviews with local first responders were conducted to gather current safety practices during emergency responses involving BESS facilities and other battery-related incidents. Fire marshals, captains, battalion chiefs, and fire chiefs were interviewed from fire departments in California and Maryland. While some the fire department members who were interviewed had limited experience with BESS fires, the interviews provided insight into first responder familiarity with batteries and the standard emergency response protocols developed at the local stations.

The typical emergency response practices from first responders to BESS or other battery-related fires appear to follow a systematic approach similar to the following:

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[100] National Fire Protection Association. "Energy Storage Systems Safety Online Training, Fire Service Edition," taken 2018.

[101] NFPA 855, Second Draft Report, Annex C Fire-Fighting Considerations (Operations).

- Evaluate the scene ("size-up") upon arrival based on emergency call information and visual assessments.
- Assess the scene with input from pre-incident plans, SDS documentation, and guidance from knowledgeable BESS and building personnel.
- Prioritize civilian and responder lives while containing the incident to minimize property and environmental damage; this can include evacuation procedures for nearby structures and facilities
- Isolate BESS power through battery disconnects and main service breakers.
- In the event of a fire, extinguish with copious amounts of water (unless explicitly discouraged in SDS documentation).
- In the event of an incident other than a fire, contain chemicals releases and contact a qualified hazardous materials (HAZMAT) team.
- Monitor the incident with thermal imaging cameras and air-sampling gas meters both after extinguishment and during fire watch follow-up visit(s).
- Document the incident and record lessons learned for potential updates to pre-incident plans.
- Maintain open communication with BESS personnel to keep up with changes in the facility.

The members of the fire departments who were interviewed repeatedly emphasized that emergency response strategies are highly dependent on the information immediately available to the incident commander in charge of the scene and to the crew members carrying out the fire-attack strategies. Each emergency situation is approached methodically because the details of the situation frequently change the order of emergency operations.

The execution of emergency operations and protocols exercised by local fire departments are prescribed by guidelines put forth by the International Fire Code (IFC). Additional training and information (such as training provided by the NFPA) are adapted by the fire departments depending on the specific needs that are expected within the service's jurisdiction. For example, many fire departments in California are being trained to respond to emergencies involving electric vehicles (EV) due to the increasing EV prevalence in certain areas of California. This voluntary training is available through the NFPA and certain EV manufacturers. However, other fire departments in areas with a small EV presence may not invest in such training because the likelihood of responding to an EV emergency is minimal.

In the absence of formal training in any particular emergency response, exercised protocols can be developed locally within each fire department based on related protocols and the collective anecdotal experience of that individual fire service. For example, an interviewed fire service representative did not have any direct training with BESS fires. When asked what strategies would be taken if faced with a BESS fire without training, he followed a systematic approach to assessing and attacking the fire (in a manner similar to the approach listed above), while asking questions regarding potential hazards. The hypothetical fire attack strategy was adapted to the new information he learned about BESS and battery hazards, borrowing from existing protocols exercised by his fire department. The fire serviceman's strategy initially involved treating batteries as hazardous waste materials and contacting the local hazardous material (HAZMAT) team. When told that BESS can include high-voltage components, the strategy referred to protocols for checking high voltage and handling fires near high-voltage lines. When told that some batteries can enter thermal runaway and vent violently, the updated strategy involved protocols for ammunition fires. Finally, when told that batteries have been known to reignite materials hours and days later, the final strategy included fire watch follow-up visits typically exercised in wildland fires and in structure fires known to rekindle (such as those involving cellulose-based insulation). By the end of the discussion, the hypothetical fire attack strategy closely resembled the practices recommended in the NFPA online energy storage system safety training.

4.3 Pre-Incident Planning

Pre-incident planning is the systematic method of gathering general and detailed data that are used by responding personnel in effectively managing emergencies for protection of occupants, participants, responding personnel, property, and the environment.[102] This allows emergency first responders to be well-informed and prepared to respond to foreseeable incidents at a BESS. The development of a pre-incident plan is recommended to be a cooperative effort between the first responders and BESS facility management and operations staff. This can be one of the most effective steps in prioritizing the safety of first responders who arrive at a BESS incident.

While each authority having jurisdiction (AHJ) responsible for a BESS may have pre-existing recommendations for pre-incident planning, NFPA 1620 recommends the following items be considered during the pre-incident planning process:

- Potential life safety hazard, including emergency responder safety.
- Structure size and operation complexity.
- Economic impact.
- Importance to the community.
- Location and seasonal variations.
- Presence of hazardous materials.
- Susceptibility to natural disasters.

Specific to BESS, this may include:

- Technical specifications, construction, and layout of the BESS.
- Clear identification of the hazards associated with BESS, batteries, and other aspects of the BESS.
- Standard operating procedures (SOP) development for BESS operation, maintenance, emergency response, and pre-incident plan upkeep.
- Clear signage for locations of batteries, battery chemistries and hazards, locations of SDS and emergency disconnect switches
- An updated and maintained system of SDSs specific to the battery chemistry, chemicals used by fire suppression system, and foreseeable chemicals produced during battery failure; SDSs should include chemistry, health hazard, and firefighting measures.

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[102] National Fire Protection Agency (NFPA) 1620: Standard for Pre-Incident Planning, 2015.

- Clear procedures for shutting down and de-energizing or isolating equipment to reduce the risk of fire, electric shock, and personal injury hazards.
- Clear description of existing safety measures, including ventilation, fixed suppression systems, air monitoring systems, and battery management system.
- Emergency contact for building representatives and crucial BESS operators.
- Walk-through of the BESS involving both first responders and BESS representatives.
- Clear procedures for handling damaged BESS equipment in a post-fire incident, including recognizing the potential for re-ignition of fire-damaged BESS after initial extinguishment and contacting personnel qualified to safely remove damaged BESS.

The details and format of the pre-incident plans will vary based on the BESS, AHJ, and fire department. It has been stressed by multiple fire services that open communication between first responders and BESS representatives early in the design phase of the BESS is crucial as pre-incident planning may guide design to prioritize first responder safety. According to active first responders, there are many cases in which discussions with the fire service does not begin until the end of the building permitting process when most building designs and construction plans have been finalized.

The development of the pre-incident plan requires hours of preparation and relies heavily on the preparedness of the BESS facilities. In speaking with members of fire departments, the quality of information available to incident command about the incident and the incident facility is one of the most important factors that determines the effectiveness and efficiency of an emergency response. This is not only true for BESS incidents, but nearly all emergency response. However, for BESS facilities where the hazards are abundant but not always known, the information provided by the pre-incident plans, SDS documentation, and guidance from knowledgeable BESS personnel is crucial to effective emergency response and prioritized first-responder safety.

Once the pre-incident plan is developed, it is recommended that copies are distributed among the relevant parties, training is provided by BESS operations and first responders, and the pre-incident plan is reviewed and modified as changes to the BESS are implemented and if incidents occur. First responders have emphasized the need to update pre-incident plans after each incident or training to ensure more effective execution if any subsequent incident occurs.

4.4 Hazard Mitigation and Emergency Response

In discussions with local fire departments, there are typical emergency response situations foreseeable in BESS facilities. Responses to BESS incidents should consider the range of possible conditions and associated hazards described in previous sections. The response should include commonly accepted practices with any HAZMAT response, including isolating the area to all personnel, confirming location and type of alarm, performing air monitoring, managing ventilation/exhaust, and suppressing fires. The procedures covered in these sections are compiled from the NFPA Energy Storage System Safety Training Program for the Fire Services, Annex C of NFPA 855, and from discussion with local fire departments.

4.4.1 Initial Actions

NFPA recommends that first responders use an organized process to identify and mitigate hazards. The recommended best practice is summarized as "identify, shutdown, and watch out."[103]

"Identify" involves identifying the location and type of BESS as part of continued assessment upon scene arrival. Pre-incident plans and accessible signage on site are extremely helpful for first responders to navigate the BESS facility. In the absence of signage, first responders will look for physical racks to identify the location of the BESS. First responders will also look for battery disconnect switches and SDS documentation. If these steps are outlined in the pre-incident plan, the emergency response will be much more rapid and effective, potentially containing the incident sooner and minimizing damage and spread.

"Shutdown" involves securing the appropriate level of power in response to an incident. First responders are trained to identify the critical loads that must be maintained (i.e. ventilation circuits, backup power, life-supporting systems) and ensure that power is not disconnected unless necessary for containment. All other nonessential power will be secured. If the locations of the disconnect switches are in the pre-incident plan and all switches are appropriated signed at the facility, this procedure can be done efficiently. First responders are trained to disconnect smaller breakers before larger breakers to protect against arc flash. Full PPE, including the standard fire protection turnout, is required for disengaging disconnect switches. Self-contained breathing apparatus (SCBA) face protection may be insufficient to protect against arc flashes, so first responders are recommended to look away when throwing disconnects.

"Watch out" involves remaining vigilant for remaining hazards, such as "stranded energy," reignition, air quality, and electrolyte leakage. Because batteries serve has an additional source of power, disconnecting the emergency power does not discharge the batteries. The batteries retain charge, or "stranded energy," and caution must be used when handling batteries, especially the bus bars and any exposed terminals. The "stranded energy" of the batteries can also manifest into reignition of combustibles after initial extinguishment has occurred. Reignition is known to occur hours and even days after extinguishment. Thermal imaging cameras and fire watch follow-up visits are recommended. Many fire departments have protocols in place for fire watch follow-up, especially for wildland fires and structure fires involving cellulose-based insulation. Schedules are put in place in which an engine will purposefully make additional visits to the site to assess the potential reignition. Similar procedures are encouraged to be enforced for BESS.

4.4.2 Air Monitoring and Ventilation

Due to the gases known to be released from batteries during abuse conditions and failures, it is crucial for workers and first responders that enclosures with batteries are adequately ventilated and that in addition to the fixed air monitoring system, portable standard 4-gas meters are available for personnel to constantly monitor their surroundings. First responders typically carry the standard portable 4-gas meter for local air monitoring. This portable gas meter measures for oxygen (O_2), lower explosive limit for flammable gases (LEL), carbon monoxide (CO), and

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[103] National Fire Protection Agency (NFPA). Energy Storage System Safety Training Program, Fire Service Edition, June 2018.

hydrogen sulfide (H_2S). Additional specialized monitors may be required depending on the specific battery chemistry.

Specific considerations need to be taken when reading the standard 4-gas meter. Oxygen levels are to the noted first because decreased oxygen levels can indicate an immediate health hazard. Decreased oxygen levels can also affect the readings for other gases depending on the gas meter operation. Additionally, CO and hydrogen gas (a flammable gas) are known to have cross-sensitivity. Adjustments can be for these interferences per the gas meter manufacturer recommendations.

Adequate ventilation is crucial to ensure that flammable gases do not accumulate in an enclosure. Flammable gases, such as hydrogen, have LEL as low as 4% by volume in air.[104] The design of the ventilation system typically considers the following: the system's ability to safely evacuate flammable gases, the use of positive or negative pressure ventilation, the ability to maintain power to ventilation as nonessential power is secured, and the direction of ventilation to prevent nearby contamination. In the event of ventilation system shutdown or failure, external ventilation, such as air movers and fans, are alternative options.

4.4.3 Investigations

Alarm activation in BESS facilities can be triggered by smoke detectors, fixed suppression systems, or gas detector systems. In some cases, there may not be an incident or the incident may have been resolved by the time first responders arrive on scene. In these cases, first responders are trained to investigate the situation. By default, first responders will reference the pre-incident plan developed for investigations. It is extremely helpful to first responders if knowledgeable building personnel are present to relay any pertinent information, including status of the BESS, to the incident commander. During an investigation, first responders can be expected to use handheld gas meters to sample air locally and to use thermal imaging cameras to check for heated components. Because thermal imaging requires direct line of sight, more direct access to batteries may be required. Knowledgeable BESS personnel can expedite the investigations.

4.4.4 Electrolyte Releases

Electrolyte release or leakage can potentially lead to a HAZMAT operation. Depending on battery chemistry, electrolyte can be neutral, acidic, or basic. When in doubt, first responders are trained to assume liquid leakage is caustic. In many situations, this leads to calling in a local HAZMAT team, whether the team is internal to the BESS facility or an external service. In the case of an external HAZMAT team, significant delays may occur due to rigorous clean-up.

A well-documented pre-incident plan and knowledgeable personnel on staff at the BESS facility can minimize delays due to electrolyte release clean-up. With proper understanding of the chemical hazards that exist in the battery, SOPs can be developed to respond to electrolyte leakage in a manner similar to HAZMAT operation. Actions to consider include:

- Early establishment of "hot," "warm," and "cold" zones as guided by HAZMAT operation.
- Identification of chemicals with SDS documentation and knowledgeable staff.

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[104] Hurley, M.J. SFPE Handbook of Fire Protection Engineering, 5th edition, 2016.

- If safe to do so, lockout/tagout isolation of the batteries or modules affected.
- Ventilation and continued air monitoring.
- Treatment of the spill by qualified personnel.
- Selection of appropriate PPE because traditional PPE and SCBA may offer limited protection to chemicals.
- Proper decontamination and inspection of all used PPE after the incident.
- Update of the pre-incident plan based on lessons learned after the incident.

4.4.5 Overheated Batteries

Overheated batteries may be a precursor to an eventual BESS fire, but if alerts occur before any dramatic event, certain actions can be taken to arrest the incident before it proceeds. Depending on the specific battery chemistry and form factor, the battery cells behave differently when overheating. For example, lead-acid batteries may show signs of bulging and lithium-ion batteries may show wisps of white smoke emitting from the enclosure. Either scenario can lead to rapid off-gassing and potential fire, which would require a qualified HAZMAT team or fire departments to respond. In these cases, extreme caution must be taken to ensure the safety of personnel responding to the incident.

It is recommended that procedures for handling overheated batteries be included in the pre-incident plan. Consulting SDS documentation and knowledgeable building personnel is a key first step in understanding the nature of the overheating battery. If safe to do so, carbon dioxide or dry chemical fire extinguishers can be used to locally cool the overheating battery. Direct access to the batteries may require opening enclosures with the help of knowledgeable personnel. If direct access is available, thermal imaging cameras can help monitor battery surface temperatures. The battery should also be isolated electrically with the battery management system (BMS). Constant ventilation and air monitoring is recommended as long as it is safe to do so.

The NFPA 855 draft summarizes the procedures in response to an overheated battery as:[105]

- Isolate the area of all nonessential personnel.
- Review the status of both the building and ESS alarm system with available data.
- Review the status of any fire protection system activation.
- Perform air monitoring of all connected spaces.
- Identify the location of the overheated battery.
- Isolate affected battery, string, or entire system based on the extent of damage by opening battery disconnect switches, where provided.
- Contact person or company responsible for operation and maintenance of the system.
- Continue temperature monitoring to ensure mitigation of the overheating condition.

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[105] NFPA 855, Second Draft Report, Annex C.4.1

4.4.6 BESS Fires

Battery fires are difficult to control due to the intense nature of the fires, the ability of latent reignition after extinguishment, and the potential chemical hazards present during the fire. Two major BESS fires in the United States in the past decade are the Port Angeles Mall fire in Port Angeles, WA in 2013 and the Kahuku wind energy storage farm in Oahu, HI in 2012.

On July 3, 2013, at Landing Mall in Port Angeles, Washington, a fire was detected in the battery room located in the north east corner of the mall on the Landing property. The batteries were used to receive and store excess power during low energy days and used as supplemental energy sources when needed. The room had its own fire suppression system, which allowed the fire to be contained in the battery room; however, the smoke spread and forced the evacuation of the mall. The fire was extinguished, but the building remained closed. On July 8, 2013, it was reported that there was another small fire in the battery room. A single battery that survived the original fire had enough energy remaining to ignite and melt surrounding plastic. The second fire was also isolated from the rest of the building.[106,107]

On August 3, 2012, the Kahuku wind energy storage farm in Oahu, Hawaii experienced a large fire. The wind farm was a 12 turbine, 30 MW facility that included around 12,000 "chemical capacitor" batteries. Early in the morning, the smoke alarm alerted personnel of the fire, but due to the possible toxicity of the batteries, firefighters did not enter the building for over 7 hours. It is suspected the fire started in or near the battery banks and continued to spread. The building had previously been on fire in 2011 but it was able to self-extinguish. In this case, the fire continued to grow, and the fire departments were unable to extinguish the fire with their supply of dry chemical. Hawaiian Electric Company assisted the efforts and provided a truck that contained 1000 pounds of fire-extinguishing dry chemicals. The fire burned for several days before it was fully extinguished.[108,109,110]

Both these incidents demonstrate a few areas of difficulty in extinguishing battery fires. For one, due to batteries having their own internal electrochemical source of power, batteries can reignite hours or days after the initial extinguishment. Several similar claims have been made with accidents and fires involving battery-powered electric vehicles. In March 2018, a Tesla vehicle was involved in an accident that severely damaged the battery pack. Because the fire department used copious amounts of water to extinguish and cool the pack, occasional reignition was

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106 Rice, A. "BREAKING NEWS: Fire at The Landing centered on power storage room below restaurant." Peninsula Daily News, 3 July 2013. <http://www.peninsuladailynews.com/news/breaking-news-fire-at-the-landing-centered-on-power-storage-room-below-restaurant/>.

107 Rice, A. "Fire erupts again in Landing battery room." Peninsula Daily News, 9 July 2013. <http://www.peninsuladailynews.com/news/fire-erupts-again-in-landing-battery-room/>.

108 Wesoff, E. "Battery Room Fire at Kahuku Wind-Energy Storage Farm." Greentech Media, 3 August 2012. <https://www.greentechmedia.com/articles/read/battery-room-fire-at-kahuku-wind-energy-storage-farm#gs.=WzC94w>.

109 "Fire at Kahuku wind farm destroys crucial building." Hawaii News Now, 1 August 2012. <http://www.hawaiinewsnow.com/story/19173811/hfd-battling-kahuku-wind-farm-blaze/>,

110 Shikina, R. "Stubborn fire destroys battery building at Kahuku wind farm." Star Advertiser, 2 August 2012. <http://www.staradvertiser.com/2012/08/02/breaking-news/stubborn-fire-destroys-battery-building-at-kahuku-wind-farm/>,

observed on the scene. The vehicle also reportedly reignited while in storage days after the incident.[111]

In responding to BESS fires, the initial actions involved follow a systematic approach. Upon scene arrival, the incident commander will assess the incident, relying on pre-incident plans, available SDS, and knowledgeable BESS personnel. In full PPE and SCBA, first responders will prioritize rescuing persons in the building while securing power and containing the fire from outside the building. "Copious amounts of water" is a terminology frequently used by fire service to describe water application to contain and extinguish battery fires. This is the default action by first responders in the absence of guidance specific to the battery system and the facility. As one member stated, the priority is fire suppression to extinguish the fire and minimize property damage.

Before entering the building, first responders confirm that they have secured power. If disconnect switches are inaccessible, first responders typically rely on utilities to disable power from the farther upstream. This typically requires knowledgeable personnel with a detailed pre-incident plan to execute. After the fire, first responders typically enter the building in full SCBA. Thermal imaging cameras and gas meters are used to evaluate the scene.

The NFPA 855 draft summarizes the procedures in response to BESS fires as:[112]

- System isolation and shutdown.
- Hazard confinement and exposure protection.
- Fire suppression.
- Ventilation.

4.4.7 Environmental Events

Although not as common, environmental events such as seismic activity and floods can damage batteries in BESS. In the event of flooding, personnel are advised to evaluate whether it is safe to approach the battery disconnect switch. Standing water is an electrical hazard for AC power, and while DC power requires a connection to both positive and negative terminals of the batteries, excessive water damage may provide a current path unseen by personnel. It is always recommended to wait for a qualified service technician to assess the scene.

Seismic activity can mechanically abuse batteries and energize metal enclosures. Open communication with the BESS manufacturer is recommended to become familiarized with the different potential failure modes of the batteries, racks, cabinets, and enclosures.

Prior to releasing the scene after any environmental event, incident command typically looks to qualified individuals, such as BESS personnel, to confirm that the BESS does not continue to present a hazard.

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[111] National Transportation Safety Board Office of Public Affairs. "NTSB News Release: Preliminary Report Issued for Investigation of Fatal, Mountain View, California, Tesla Crash." 7 Jun 2018.

[112] NFPA 855, Second Draft Report, Annex C.4.2

5
GAP ANALYSIS AND CONSIDERATIONS FOR FUTURE WORK

A comparison of the information gathered from published literature, current and upcoming codes, standards, and regulations, and first responder safety practices shows that there are gaps in the current knowledge base of worker and first responder safety practices. These gaps and associated considerations include assessing new battery technology and associated hazards, understanding BESS fire behavior, establishing post-incident activities, and increasing awareness of existing education and training for BESS safety.

5.1 Battery Technologies and Associated Hazards

Battery technology is a rapidly growing field with cutting-edge research focused on creating new battery chemistries and improving currently existing chemistries. While the hazards associated with new battery chemistries are expected to be rigorous assessed, the new hazards that can arise from subtle changes in existing battery chemistries may not be as obvious. For example, advances in Li-ion active material are exploring the introduction of trace amounts of lithium metal. Currently, lithium-ion batteries are not considered Class D materials in fire suppression classification because the lithium remains in ionic form in current technologies.[113] However, it is possible that lithium metal can be introduced into Li-ion batteries in amounts sufficient to require different fire suppression strategies, despite the battery chemistry still being classified as lithium-ion. In such cases, it is important to reassess the change in Li-ion battery technology for changes in the thermal, electrical, mechanical, and chemical hazards. Updated SDS documentation is crucial for conveying new information to workers and first responders.

In addition, the extent of worker and first responder exposure to chemicals released from batteries and to products of combustion during battery fires is still being studied. This includes health effects of the less common chemicals released by batteries and of the particulates released in air during and after a battery fire. While battery chemistries may have fully descriptive SDS documentation, the combustion of compounds in different battery chemistries may produce chemicals not listed in SDS documentation or chemicals without known hazard levels. These new chemicals may present additional hazards not initially considered in pre-incident planning and emergency response.

It is important to have a full understanding of the different thermal, electrical, mechanical, and chemical hazards associated with the battery chemistry and construction of the battery, module, and facility. SDS documentation is crucial for conveying this information to workers and first responders. Additional documentation from the BESS manufacturer and safety assessments performed on the specific BESS facility are also helpful.

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113 National Fire Protection Agency (NFPA). Energy Storage System Safety Training Program, Fire Service Edition, June 2018.

5.2 Fire Behavior

Effective firefighting techniques for containing and extinguishing large BESS fires are still in development. Current fire attack strategies are borrowed from strategies used for electric fires, chemical fires, and ammunition fires, most of which involve using copious amounts of water until the fire is extinguished. Battery fires are expected to present unique fire behaviors due to the batteries' supply of chemical energy, DC power output, and reignition capabilities. The combination of these characteristics may require more aggressive fire suppression strategies compared to those used for electric fires, chemical fires, and ammunition fires individually.

The NFPA and the Fire Protection Research Foundation (FPRF) have funded research into assessing fire hazards associated with Li-ion battery energy storage systems in the past few years. Current research involves burn tests involving BESS.[114] Additional scientific research into the fire behavior of fully-involved BESS, fire development and propagation across multiple BESS, and the behavior of BESS structures during a fire will likely improve the effectiveness of current firefighting techniques used for BESS fires. Joint research initiatives with fire departments can improve the relevancy and usefulness of the research results.

5.3 Post-Incident Activities

Post-incident activities by first responders—including overhaul of BESS facilities, fire watch, and incident reporting—are being developed independently by individual fire departments. These procedures are frequently practiced by a fire service based on the collective anecdotal experience of that individual fire service. The development of guidelines and best practices agreed upon by a larger population of the fire service can help create more consistent protocols for post-incident activities specific to BESS and battery-related incidents.

Procedures for handling and storing post-incident batteries are also not well established. The mechanisms behind latent battery failures and methods to predict these latent failures are being developed. Workers and first responders develop their own procedures at times based on anecdotal evidence as opposed to scientific research. Systematic research to investigate the mechanisms and predictors of latent battery failure can provide data-driven guidelines to develop safe procedures for handling post-incident batteries.

5.4 Education

Communications with first responders indicate they are not informed of battery hazards and not formally trained in handling large-scale battery fires. Training tools are available from agencies like the NFPA for fire departments, so there appears to be a need for increased awareness. Increased awareness regarding the availability of educational tools can prepare more fire departments for BESS and battery-related incidents.

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[114] Blum, A.F. and Long, R.T. "Hazard Assessment of Lithium Ion Battery Energy Storage Systems" Fire Protection Research Foundation, Feb 2016.

6
CLOSING

Worker and first responder safety concerns related to large-scale battery energy storage systems (BESS) facilities for power utility application were reviewed through published literature, current and upcoming codes, standards, and regulations, select first responder interviews, and gap analysis related to BESS technology, hazards, and related safety measures.

A review of the scientific literature showed that batteries used in BESS present potential thermal, electrical, and mechanical hazards to workers and first responders. Additional chemistry-specific hazards are present for the different rechargeable battery chemistries used in BESS facilities. The common rechargeable battery chemistries reviewed include lithium-ion (Li-ion), lead-acid, nickel-based, sodium-based, redox-flow, and metal-air chemistries. Each of these battery chemistries has unique susceptibilities and reactions to abuse scenarios.

This review identified codes, standards, and regulations that are being developed to guide safety practices that address known BESS and battery hazards. These safety practices include proper signage, air monitoring systems, fire suppression systems, central alarm systems, and emergency shut-off systems. Training material for an online BESS safety course provided by the National Fire Protection Agency (NFPA) was reviewed, local fire departments were interviewed to gain first-hand accounts of the safety practices currently being implemented during emergency response to BESS facilities and other battery-related incidents. These safety practices include pre-incident planning with the BESS facility, hazard mitigation upon arrival to an incident, and emergency response to electrolyte release, overheated batteries, BESS fires, and environmental events, such as seismic activity and flooding.

A comparison of the information gathered from published literature, current and upcoming codes, standards, and regulations, and first responder safety practices shows that there are gaps in the current knowledge base of worker and first responder safety practices. These gaps include knowledge of battery technologies and associated hazards, BESS and battery fire behavior, post-incident activities, and awareness of available education and training.

This research serves as an initial step towards the larger pursuit of research in worker and first responder safety. The information and results obtained from this review can be coupled with research testing to develop guidelines for handling BESS safety and fires and to improve first responder best practices.

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