ENERGY STORAGE SAFETY STRATEGIC PLAN

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Acronyms

AHJ	Authorities Having Jurisdiction
ASSB	All-solid-state Battery
BESS	Battery Energy Storage System
BMS	Battery Management System
Br	Bromine
BTM	Behind-the-meter
CAES	Compressed Air Energy Storage
CSA	Canadian Standards Association
CSR	Codes, Standards, and Regulations
DOD	Depth of Discharge
EOL	End-of-life
EPRI	Electric Power Research Institute
ERP	Emergency Response Plan
ESS	Energy Storage System
EV	Electric Vehicle
FACP	Fire Alarm Control Panel
FEMA	Federal Emergency Management Agency
FMEA	Failure Mode and Effects Analysis
GADS	Generator Availability Data System
GW/GWh	Gigawatt/Gigawatt Hour
HMA	Hazard Mitigation Analysis
HVAC	Heating, Ventilation, and Air Conditioning
IAFC	International Association of Fire Chiefs
ICC	International Code Council
IEC	International Electrical and Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
kW/kWh	Kilowatt/Kilowatt Hour
LCO	LiCoO2
LFP	$LiFePO_4$
Li	Lithium
LMFP	$LiMn_xFe_{1-x}PO_4$
LMO	$LiMn_2O_4$
MW/MWh	Megawatt/Megawatt Hour
NaS	Sodium-sulfur
NCA	$LiNi_xCo_yAl_{1-x-y}O_2$
NEC	National Electric Code
NERC	North American Electric Reliability Corporation
NERIS	National Emergency Response Information System

NFIRS	National Fire Incident Reporting System
NFPA	National Fire Protection Association
Ni	Nickel
NMC	$LiNi_xMn_yCo_{1-x-y}O_2$
O&M	Operations and Maintenance
Pb	Lead
PCS	Power Conversion System
PNNL	Pacific Northwest National Laboratory
PPE	Personal Protective Equipment
RFB	Redox Flow Battery
RFP	Request for Proposal
SDO	Standard Development Organization
SEI	Solid Electrolyte Interphase
SNL	Sandia National Laboratories
SOP	Standard Operating Procedure
SSB	Solid-state Battery
TW/TWh	Terawatt/Terawatt Hour
UL	Underwriters Labs
UPS	Uninterruptible Power Supply
V	Volt
VLA	Vented lead-acid
VRLA	Valve-regulated lead-acid
Zn	Zinc

Executive Summary

Energy storage has emerged as an integral component of a resilient and efficient electric grid, with a diverse array of applications. The widespread deployment of energy storage requires confidence across stakeholder groups (e.g., manufacturers, regulators, insurers, and consumers) in the safety and reliability of the technology. Since the publication of the first Energy Storage Safety Strategic Plan in 2014, there have been introductions of new technologies, new use cases, and new codes, standards, regulations, and testing methods. Additionally, failures in deployed energy storage systems (ESS) have led to new emergency response best practices. The goal of this revision is to review the current state of energy storage safety and identify priorities to advance the field.

The report begins with an overview of the status and known safety concerns associated with major electrochemical and non-electrochemical energy storage technologies. Then, we highlight safety considerations during energy storage deployment in the US, spanning codes and standards, permitting, insurance, and all phases of project execution.

Lithium-ion (Li-ion) batteries currently form the bulk of new energy storage deployments, and they will likely retain this position for the next several years. Thus, this report emphasizes advances in incident response and safety research and development for Li-ion batteries. A framework is provided for evaluating issues in emerging electrochemical energy storage technologies.

The report concludes with the identification of priorities for advancement of the three pillars of energy storage safety: 1) science-based safety validation, 2) incident preparedness and response, 3) codes and standards.

Priorities for science-based safety validation include improved: containment of Li-ion cell failure, operations and maintenance guidance, end-of-life guidance for Li-ion systems, system-level fire modeling of Li-ion, identification of safety and degradation issues for non-Li technologies, assessment of risks of energy storage in new applications, and standardization of testing and reporting.

Priorities for advancement of incident response and preparedness include improved: inclusion of energy storage data in responder guidebooks, emergency response coordination, incident data reporting, physical status indicators, assessment of the impact of toxic emissions, guidance for decommissioning and dealing with stranded energy, and tools for the fire service.

Priorities for codes and standards include addition of guidance for: electrical worker safety, grounding, electrical retesting of a system over time, explosion protection, toxic emissions, and performance and reliability data collection.

1. Introduction

Grid energy storage systems are “enabling technologies”; they do not generate electricity, but they do enable critical advances to modernize and stabilize the electric grid. Numerous studies have highlighted the value of grid energy storage for supporting the integration of variable renewable resources, demand charge management, mitigating losses from outages, improving power quality, transmission and distribution upgrade deferral, and off-grid applications. The variety of deployment environments and application spaces, and the increasing variety in storage technologies, has increased the challenge of developing a single set of protocols for evaluating and improving the safety of grid storage technologies.

Much has changed since the first Energy Storage Safety Strategic Plan was published in 2014. In 2013, the cumulative energy storage deployment in the US was 24.6 GW, with pumped hydro representing 95% of deployments.[1] Utility-scale battery storage was about 200 MW at the end of 2013, about 9 GW at the end of 2022, and is expected to reach 30 GW by the end of 2025 (Figure 1).[2] Most new energy storage deployments are now Li-ion batteries. However, there is an increasing call for other technologies given the broad need for energy storage (especially long duration energy storage), the competition for Li-ion batteries from the electric vehicle (EV) sector, and safety concerns with Li-ion batteries.

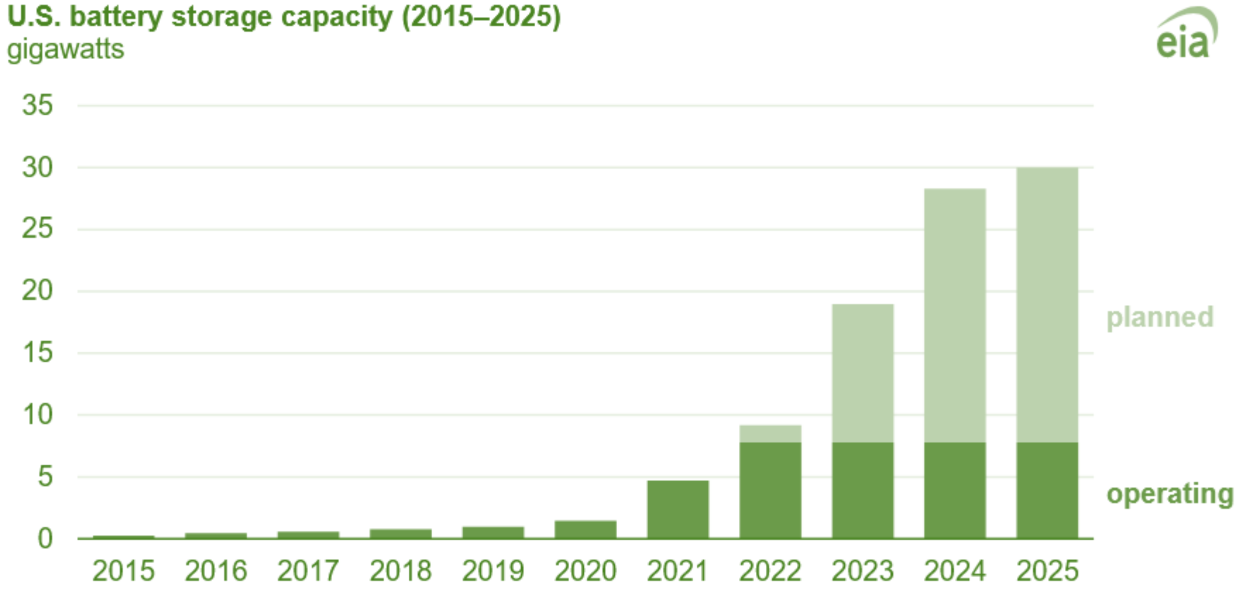

Figure 1. U.S. battery storage capacity through 2025. Source: U.S. Energy Information Administration.

Major advances in safety codes & standards since 2014 include the development of an installation standard for stationary ESS by the National Fire Protection Association (NFPA 855) as well as a product safety standard in UL 9540. Both of these will be discussed in Chapter 4. With the rapid deployment of ESS in the US, there have been a number of opportunities to learn from system failures and incorporate those lessons learned into updates to the codes & standards. While the lithium-ion family of chemistries

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[1] https://www.energy.gov/sites/prod/files/2013/12/f5/Grid%20Energy%20Storage%20December%202013.pdf

[2] https://www.eia.gov/todayinenergy/detail.php?id=54939

remains the primary technology being deployed, there have been significant advancements in Li-ion anode and cathode materials as well as flow battery, Zinc, and Sodium-based technologies. These new batteries are setting the stage for more flexibility in cost, supply chain resources, and applications.

The discussion within this document explores the current landscape of energy storage deployments and technologies, with an emphasis on Li-ion batteries. At the end, we identify general gaps and outstanding questions for energy storage safety, focusing on the three pillars of energy storage safety previously mentioned: 1) science-based safety validation, 2) incident preparedness and response, 3) codes and standards. These three areas are all equally important for instilling confidence in the community of stakeholders who interact with energy storage technologies. Ultimately, it is the goal of this strategic plan to lay the groundwork necessary to ensure that safety concerns do not serve as a barrier to deployment of grid energy storage to support an efficient, reliable, and resilient electric grid.

2. Current State of Grid-Scale Electrochemical Energy Storage

Electrochemical energy storage includes various types of batteries that convert chemical energy into electrical energy by reversible oxidation-reduction reactions. Batteries are currently the most common form of new energy storage deployed because they are modular and scalable across diverse applications and geographic locations. This section covers Li-ion, lead acid, flow, Zn-based, and high temperature batteries. Li-ion and lead acid batteries are considered commercially mature technologies. The other listed battery technologies are being explored by academia and industry as alternatives to Li-ion due to concerns about safety, cost, and material availability. Table 1 summarizes the primary safety concerns and upcoming developments for each technology.

Table 1. Summary of electrochemical energy storage deployments.

TECHNOLOGY	MATURITY	PRIMARY SAFETY CONCERNS	FUTURE DEVELOPMENTS
Li-ion batteries	Nearly 10 GW ESS deployed	Thermal runaway leading to fire or explosion	- More stringent codes & standards - Materials: Emphasis on LFP, solid electrolyte, Na-ion
Lead-acid batteries	Decades of use in standby applications	- Thermal runaway less common and severe than Li-ion - Vented lead acid cell spills	- Increased cycle volume and DOD with activated carbon - Bipolar plate to increase cycle count/reduce footprint
Flow batteries	< 1 GW deployed	- H2 gas (or toxic gas) generation - Strong acid/base electrolyte spill if containment breach	- Redox active materials other than vanadium
Zn batteries	< 100 MW deployed	- H2 gas generation - Spill of acidic/basic electrolyte if breached	- Making alkaline batteries rechargeable - Few major deployments, focus on increasing cycling lifetime
High-temperature batteries (e.g., NaS, NaNiCl2, liquid metal)	~700 MW deployed globally	- NaS: exothermic reaction of molten sodium	- Demonstrating new liquid metal technologies (e.g., Ca-based) - Reducing operating temperatures
Hybrid systems	Few deployed projects	- Known issues associated with the individual technologies - Mismanagement of controls for the different technologies	- Developing standard procedures for integrating and controlling different entities

2.1 Li-ion Batteries

Li-ion batteries are the dominant electrochemical grid energy storage technology. Characteristics such as high energy density, high power, high efficiency, and low self-discharge have made them attractive for many grid applications. The ability to significantly modify materials properties of the electrodes and electrolytes has made it possible to tailor Li-ion batteries for many different operating conditions and applications.

Li-ion batteries are most often distinguished by their positive electrodes, or cathodes. The classification of cathodes is based on the crystal structure of the compound: layered, spinel, and olivine. Cathodes with a layered structure, such as LCO ($LiCoO_2$), NCA ($LiNi_xCo_yAl_{1-x-y}O_2$), and NMC ($LiNi_xMn_yCo_{1-x-y}O_2$), have been the most popular material for Li-ion batteries since the commercialization of LCO in the early 1990s. This structure has a good energy density and a sloping voltage profile which makes assessment of battery state-of-charge easier. Spinel electrodes such as LMO ($LiMn_2O_4$) are of interest due to their high average potential and specific energy, but their low theoretical capacity and material instability currently prevent them from being used independently. LMO is often used in a blended cathode with the layered NMC and olivines. The most common olivine electrode, LFP ($LiFePO_4$), has a lower average potential than other popular commercial cathodes, and a correspondingly lower energy density. This initially limited the use of LFP in EV applications, where energy density is prioritized. However, low cost and good thermal stability have fueled its broad adoption in grid energy storage applications.

The primary safety concern for Li-ion batteries is thermal runaway, a phenomenon wherein an accelerating release of heat inside a cell, due to a series of exothermic reactions, manifests as an exponential, uncontrollable, increase in cell temperature. Thermal runaway can be initiated when a battery experiences electrical, mechanical, or thermal abuse; a Li-ion battery possesses all the components required for combustion or even explosion once thermal runaway occurs—fuel (liquid electrolyte), oxygen (released from metal oxide cathodes), and an ignition source (heat from the thermal runaway reactions). LFP is more thermally stable because the phosphorus-oxygen bond is stronger than the metal-oxide bond in most other positive electrodes.

Nearly 10 GW of Li-based utility-scale energy storage is currently deployed in the US, from Alaska to Puerto Rico, for power and energy applications including frequency regulation, peak shaving, load management, and backup power.[3] Li-ion batteries will likely dominate the electrochemical energy storage market for the next several years, despite safety concerns from recent system fires. These safety concerns are encouraging more stringent codes and standards, leading to evolving system designs. However, batteries are likely to retain the same fundamental characteristics with materials modifications to achieve higher lifetime, energy density, and safety.

All solid-state batteries (ASSBs) are an emerging type of Li-ion technology that holds the promise of increased energy density and safety. In an ASSB, the liquid electrolyte and polymer separator is replaced with a solid electrolyte. The liquid electrolyte typically contains a volatile and flammable solvent that, in the event of failure, is largely responsible for the buildup of internal pressure and, especially when aerosolized on venting from the cell, deflagration events. A solid-state battery (SSB) still uses a solid electrolyte, but a small amount of liquid is added to the cathode to minimize interfacial resistance. It is expected that a solid electrolyte will enable the use of a Li-metal anode, which is key to achieving high energy densities. Many existing electric vehicle companies are investing millions into ASSB and SSB start-ups, although none have yet produced commercial products. Target dates as aggressive as 2027 have been announced for mass production of SSBs and implementation into EV battery packs. It is possible that this technology will eventually be implemented in grid-scale systems, but likely not until the end of the decade.

2.2 Lead-acid Batteries

Lead-acid batteries are one of the oldest and safest battery technologies available for use in both stationary standby and regularly cycling energy storage applications. There are two fundamental types of lead-acid batteries: vented lead-acid (VLA) cells and valve regulated lead-acid (VRLA) cells. The VLA

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[3] https://www.eia.gov/todayinenergy/detail.php?id=54939

cells can be classified as lead-antimony, lead-calcium, or lead-selenium/low-antimony cells. There are two types of VRLA cells: an absorbed glass mat cell that utilizes a “starved electrolyte” topology and a gelled electrolyte that is more of a hybrid VLA/VRLA topology.[4]

The primary advantages of a lead-acid cell are: its long history of use with over a million batteries installed worldwide (enjoying a now accepted safe history); its relative ease of installation with simple infrastructure requirements; its environmental sustainability – the lead-acid battery is >98% recyclable and the spent lead can be processed and reused comfortably. The two major disadvantages of a Pb battery are (1) its lower power density, i.e., its weight and footprint requirements, and (2) the need for complete recharging on a regular basis when used in partial charge/discharge applications. Ideally, the lead-acid battery needs to function in the discharge range of 10% to 50% depth of discharge (DOD) when used in a cycling energy storage application. This does impact round-trip efficiency and capacity. However, for traditional UPS (uninterruptible power supply) and other standby backup applications, the lead-acid battery is an extremely reliable and cost-effective alternative.

Thermal runaway was first observed in VRLA batteries, due to uncontrolled recombination of charge gas (hydrogen and oxygen), deforming the primary containment and even causing fires. However, these events are typically less severe than in Li-ion batteries. There have been successful efforts to reduce the likelihood of thermal runaway in VRLA batteries, for example, by temperature compensation of the battery charger output and by incorporating a catalyst device in the headspace of larger cells.

For VLA cells with liquid electrolyte visible, safety mitigation efforts include following proper maintenance (watering) procedures and incorporating spill containment.

There are several advances being made with advanced lead-acid batteries. These include improvements in the grid structure with the use of black and/or activated carbon, barium sulfate and lignocellulose expander materials. This aids in increasing cycle volume and enlarging the DOD range. Improvements to 3,000 to 5,000 cycle counts at 80% DOD have been reported. The recent ability to utilize a bipolar plate is showing promise of major cycle count improvement, while reducing footprint requirements.

2.3 Flow Batteries

Redox-flow batteries (RFBs) are a system that operates by dissolving active species into electrolytes which are then stored in containers away from the cell’s electrodes. During operation electrolyte is moved from the storage tanks to a cell stack where charge and discharge can occur.

The dominant flow battery chemistries are currently all vanadium and hybrid Zn-Br batteries. There are several companies that have been developing these chemistries for over a decade. Their prospects have improved over the last few years with the need for long duration energy storage for grid resilience. Other types of flow batteries that are being considered are Fe-flow, slurry flow, and various systems with organic charge carriers. In 2020, the total deployed capacity of RFBs globally was estimated to be 340 MW/1200 MWh. In September 2022, the largest flow battery in the world commenced operation, with a capacity of 100 MW/400 MWh (to be expanded to 200 MW/800 MWh in the future).[5]

Gas generation is a ubiquitous issue in aqueous redox flow batteries. The stable voltage window of water is a relatively small 1.2 V that shifts with pH. Outside of this window, H_2 and O_2 can evolve along with toxic gases depending on the system chemistry. Since a system’s power scales directly with increased

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[4] Thomas B. Reddy. Linden's Handbook of Batteries, Fourth Edition. Fourth. McGraw-Hill Education.

[5] https://www.pv-magazine.com/2022/09/29/china-connects-worlds-largest-redox-flow-battery-system-to-grid/, Accessed August 1, 2023.

nominal voltage, batteries typically operate at or just outside of the voltage window where gas can be generated. Often, the generated oxygen and hydrogen can be recombined into water to refill the battery or simply vented via an engineered exhaust system. For toxic gases, other mitigation and prevention efforts may be required to address the hazard adequately.

Additionally, RFB electrolytes are often strong acids and bases carrying high concentrations of metal ions. Hazard mitigation typically involves additional containment for any electrolyte that spills out of the primary system containment.

2.4 Zinc Batteries

Zinc-based batteries have a long history in a variety of applications on smaller scales. Single use Zn-MnO_2 alkaline systems with low relative energy and power density are used in consumer electronics, Zn-air batteries are used in hearing aids, and Ni-Zn systems have been used in UPS applications. Recently, several firms have been working on developing Zn-based batteries for different applications on the grid. Several are working on Zn-air systems for long duration energy storage on the grid (100 h discharge). Others are working on updating the Zn-MnO_2 system to make it rechargeable, more energy dense and able to work in mobility applications and daily operation in front of and behind-the-meter (BTM). Finally, companies are developing Zn intercalation cells that could significantly increase the energy density and power of the cell. These companies are all at different stages of production, some with commercial products and others in the prototype phase.

19 MW/300 MWh of Zn-based systems are currently used in grid operations, although there are many Zn-based deployments planned in the near future. These deployments range from a 20 MWh system in California to residential deployments in 200,000 planned homes via a partnership with a sustainable home builder.[6]

Emerging Zn-based batteries are roughly the same size as lead-acid batteries and have similar safety concerns (H_2 gas generation and spill of basic/acidic electrolyte).

2.5 High-temperature Batteries

High temperature batteries, which we define here as having a *target* operating temperature significantly above ambient temperatures and typically above 250 °C, are emerging as potentially effective energy storage systems, particularly for stationary storage. At present, there are three technologies that are in significant commercial development and deployment: Sodium-Sulfur (NaS), Sodium-Nickel Chloride Molten Salt, and Liquid Metal (Molten Calcium) Batteries. These batteries employ highly durable inorganic components that lead to long expected lifetimes. They are fully-sealed with no emissions, and they require significantly less operational maintenance (little to none for the sealed cells) compared with other batteries. The high temperature design and operation of these batteries makes them much less sensitive to external ambient temperature variability, allowing for operation in both cold and hot environments. They are, however, designed and insulated to be cycled regularly, as heat generated during cycling (for example, from resistive heating) provides sufficient energy to maintain the battery at high temperature. When batteries are left dormant for extended periods of time, the absence of this internal heating requires an additional source of heat, which decreases the overall storage/cost-benefit of the storage system.

NaS and Liquid Metal batteries are primarily developed for stationary applications. NaS batteries have been deployed in over 250 projects globally (700 MW/4.9 GWh), including very large installations, such

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[6] https://www.powermag.com/zinc-batteries-power-stationary-energy-storage/, Accessed July 23, 2023.

as a 108 MW/648 MWh system in 2022. With 6 hours of storage at rated power, they are used to support microgrids, BTM locations, and ancillary grid services. Early use cases for liquid metal batteries include data center support and renewables integration (including a 300 MW/1.2 GWh system to be installed in 2024). Na-$NiCl_2$ batteries support utility grid services, telecom (backup, power stabilization), oil and gas (onshore/offshore power), BTM, and renewables integration.

Of the three battery chemistries, only NaS has an inherent chemical safety concern during operation, as molten sodium combined directly with molten sulfur can lead to a highly exothermic, toxic fire. Modern manufacturing of NaS, however, has developed solutions to this challenge, employing measures such as sand filling to extinguish fire and absorb leaked active materials, thermal fuses to prevent short-circuits, hermetical cell seals, and a mechanically isolating thermal enclosure to protect against external shock or internal leakage. With GWh' of deployments in over 200 locations globally, no accidents have been reported since 2011, when a 2MW system in Tsukuba, Japan started a fire leading to a redesign of the system.

2.6 Hybrid Systems

Utility grid services encompass diverse operations that have widely varying requirements for operating time, responsiveness, ramp rate, annual cycling, energy density, and power rating. For instance, congestion relief requires 1-4 hours of discharge with approximately 100 cycles/year, whereas voltage regulation requires up to half an hour of support resulting in shallow intermittent cycling of the battery. The operating time required for frequency recovery ranges from less than a second to an hour, whereas time-shift services can span from an hour to six hours. In addition, recent climatic incidents point to the need for longer duration electric supply. For example, wildfires, hurricanes, and flooding events can require up to 24 hours or more of backup energy storage. A single storage technology fails to perform optimally in all the different aspects of generation, transmission, and distribution. This has paved the way for hybrid energy storage, where technologies with disparate energy density and power ratings can be integrated.

Technologies that are complementary in terms of energy and power density are often combined to leverage the benefits of fast charging/discharging with long duration energy storage. Some relevant demonstration and deployment projects include integrating batteries with supercapacitors or flywheels. These find applications in ancillary services, frequency stabilization, voltage regulation, PV/Wind power plants, and microgrids.

Another method of developing hybrid storage systems is to combine batteries with different chemistries. Such hybrid systems are particularly promising for long duration energy storage in grid applications. Pb-acid batteries are extensively used for their low capital cost and wide availability. However, they are heavier, with lower energy density, and their cycle life ranges from 300-1500 cycles if allowed to reach an 80% DOD. Li-ion batteries have high efficiency, energy, and power densities. However, they are expensive, and can degrade quickly if utilized at a high depth of discharge or are improperly charged. NaS batteries have excellent pulse-power capability but are expensive and have high operating temperatures. Redox flow batteries can provide long-duration storage services but are slow to ramp up, or are inefficient under small loads due to the parasitic losses of the mechanical pumps in the system. Thus, the benefits of the various battery technologies can be leveraged by creating a hybrid storage system.

While the potential of hybrid storage systems in supporting the grid is widely acknowledged, deployment projects are still scarce. One of the primary reasons behind this is the lack of a standardized procedure in integrating and controlling the different entities. There are still open questions on how various BESS technologies will safely work together or in concert with other hybrid devices over a long-term installation.

3. Current State of Non-Electrochemical Grid-Scale Energy Storage

This section describes methods of mechanical (e.g., pumped hydro storage, flywheels, gravity, and compressed air), thermal, and chemical (hydrogen) energy storage. Pumped hydro storage is commercially mature, with decades of implementation, but the other methods are under development without significant commercial deployments. Table 2 summarizes the primary safety concerns and upcoming developments for each technology.

Table 2. Summary of non-electrochemical energy storage deployments.

TECHNOLOGY	MATURITY	PRIMARY SAFETY CONCERNS	FUTURE DEVELOPMENTS
Pumped hydro storage	Nearly a century of application, 1.6 TWh deployed	Isolated maintenance issues led to electrical fires and dam failures	- Closed loop systems that don't rely on specific geologic formations - Improved turbines and motors
Flywheels	Several deployments < 20 MW	- Rotor cracking and expulsion	- Identification of new applications (e.g., fast EV charging)
Gravity storage	Pilot demonstrations	- Large falling masses	- Many options being explored, currently no consensus
Thermal energy storage (sensible energy, latent energy, chemical reaction)	- Sensible energy approach used in commercial concentrating solar plants	- Burns and heat-related injuries - Toxic/corrosive molten salt materials	- Sensible energy storage at > 600C - Demonstration of latent energy and thermo-chemical energy storage approaches
CAES	Several MW-scale demonstrations	- Containment of high pressure, pressure vessel integrity - Capturing heat safely during compression	- Different vessels for storing the compressed air (e.g., water tanks and wells)
Hydrogen	No major deployments	- Flammability	- DOE awarded billions for development of "hydrogen hubs" across the US

3.1 Pumped Hydro Storage

Pumped hydro storage plants store and generate energy by moving water between two reservoirs at different elevations. Water is pumped into an upper reservoir for charging and then released through pipes into turbines for discharging. The first use of pumped storage was in the early 1900s and in 2020, it accounted for over 90% of active storage installations worldwide, with a capacity of 1.6 TWh. The main drawback is that the technology is geographically limited and involves more permitting requirements because of the large size. Given its long history, the reliability of this technology is well established.

3.2 Flywheels

Flywheels store kinetic energy in a spinning mass called a rotor. During charging, the electrical energy is converted into kinetic energy using a motor to accelerate the rotor. Kinetic energy is stored in the spinning mass of the rotor. During discharge, the motor operates as a generator that decelerates the rotor, returning electrical power to the application. The rotor spins at very high speeds (>100 m/s), and it is usually enclosed in a rigid container for safety and performance. The rotors operate in a vacuum or a low pressure He gas atmosphere to reduce friction and minimize energy losses.

Flywheels respond quickly to charge and discharge commands. Because of their quick response time, they are good for frequency regulation services, or in UPSs to span generator ramp-up lag times. Today's flywheel systems are shorter energy duration systems, typically less than 10 kWh. The energy storage system can be scaled up by adding more flywheels. Flywheels are not generally attractive for large-scale grid support services that require many kWh or MWh of energy storage because of the cost, safety, and space requirements.

The most prominent safety issue in flywheels is failure of the rotor while it is rotating. In large rotors, such as those made of steel, failure typically results from the propagation of cracks, causing large pieces of the flywheel to break off during rotation. Unless the wheel is properly contained, this type of failure can cause damage to surrounding equipment and injury to people in the vicinity. Containment systems should be designed to prevent high-speed fragments from causing damage in the event of failure. Because of the heavy mass and/or high speeds, practical containment of even a relatively small 5 kWh rotor failure is expensive, requiring a containment structure many times larger than the rotor itself.

Flywheel technology has been demonstrated in several small deployments, the largest of which was 20 MW. Due to a drop in revenue models, the market saw a decline in flywheel installations. However, recently a few startup companies have started looking at fast EV charging market applications.

3.3 Gravity Storage

Several types of gravity-based solutions are under development for long duration energy storage. One approach involves lifting large concrete (or polymer/low-cost earth material composite) blocks to different heights with cranes to store energy as potential energy. This potential energy is then converted into kinetic energy by dropping the blocks. Kinetic energy is converted into electrical energy through a spinning rotor. In another approach, railway cars filled with concrete blocks or similar heavy loads are moved up an incline during charging and released under gravity for discharge. Currently, only a few pilot demonstrations are in progress.

Any failures of these systems during uncontrolled descent can be significant due to the large mass falling under gravity. The area around the storage system needs to be secured and offer protection to the people and property outside the periphery.

3.4 Thermal Energy Storage

Thermal energy storage involves storing heat in a medium (e.g., liquid, solid) that can be used to power a heat engine (e.g., steam turbine) for electricity production, or to provide industrial process heat. Thermal energy can be stored in three forms—sensible energy, latent energy, and chemical reaction.

Sensible energy involves heating or cooling a liquid or storage medium (e.g., water, sand, molten salts, rocks) without any phase change. It is the dominant thermal storage method used for large grid-scale applications. For example, molten nitrate salt ($NaNO_3$-KNO_3) is used in commercial concentrating solar plants, operating in a temperature range of 300-600 °C. Higher temperature operation, in the range of 600-1000 °C, has also been proposed using porous rock, ceramic, or graphite blocks, however, there have been no major commercial deployments.

Latent heat involves a phase change process at a constant temperature and offers a slightly higher energy density. Phase change can be solid-gas, solid-liquid or liquid-gas, the most common being solid-liquid (using inorganic fluoride, nitrate, carbonate or chloride salt mixtures). The operating temperature range is 200-600 °C. These systems are also mostly in the demonstration stage with no major commercial deployments.

Thermo-chemical heat storage involves a reversible exothermic/endothermic chemical reaction with thermo-chemical materials. There are also no major commercial deployments with this technology.

The main safety concerns with thermal energy storage are all heat-related. Good thermal insulation is needed to reduce heat losses as well as to prevent burns and other heat-related injuries. Molten salt storage requires consideration of the toxicity of the materials and difficulty of handling corrosive fluids.

3.5 Compressed Air Energy Storage (CAES)

CAES systems use off-peak electricity to compress air and store it in a reservoir, either in an underground cavern or depleted oil wells, or aboveground in pipes or vessels. When electricity is needed, the compressed air is heated, expanded, and directed through an expander or conventional turbine-generator to produce electricity. CAES can store a large amount of energy, however, the energy and power density are low, so a larger storage volume is needed.

The main safety issues associated with CAES are: containment of high pressure, pressure vessel integrity, and capturing heat safely during compression. The heater and turbines used to generate electrical power are very similar to commercial gas turbine power plants.

Since it is a multistage process, CAES cannot respond quickly and is not suitable for power quality, voltage, and frequency regulation applications. A few companies are exploring newer designs of CAES, including storing compressed air in water tanks (the water head maintains the pressure to hold compressed air) and water wells. There have been a few small demonstrations of CAES concepts (several MW), but no major deployments completed yet.

3.6 Hydrogen Storage

Hydrogen storage is attractive for very long duration energy storage and for seasonal storage. Excess energy from renewables can be used to generate hydrogen by electrolysis and it can be stored for later use in fuel cells or combustion engines to generate electricity. Hydrogen can be compressed in underground salt caverns or stored in aboveground tanks in the gaseous or liquid form. Hydrogen storage in metal hydrides and metal organic frameworks is not yet attractive at large volumes due to the cost and low energy density. Hydrogen can also be used to make ammonia. Liquified ammonia is easier to transport than liquified hydrogen and the chemical can also be used as a fertilizer.

Because hydrogen is a very flammable gas there are several safety precautions that need to be taken during handling. Installations need to be leak-tight, which can be challenging. There has been discussion of transporting hydrogen using existing pipelines, but natural gas pipelines are known to leak methane.[7] Hydrogen disperses quickly in the open air, however, precautions must be taken to avoid accumulation in closed rooms. Even a very small spark can ignite hydrogen, so it is important to avoid ignition sources near hydrogen.

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[7] Weller et al., “A National Estimate of Methane Leakage from Pipeline Mains in Natural Gas Local Distribution Systems,” *Environ. Sci. Technol*. **2020**, *14*, 8958.

There is no major commercial hydrogen storage yet, however, it is likely to pick up given the new funding from the Department of Energy for so-called hydrogen hubs. One of the largest proposed hydrogen storage projects is in the Utah salt domes for 1000 MW (currently at the preliminary small-scale drilling phase).

4. Safety Considerations During Energy Storage Project Deployment in the US

This section describes general considerations for safely deploying energy storage in the US, including the development of safety codes and standards, the process for project execution, permitting and zoning requirements, and insurance. While there are a number of technologies and chemistries being deployed, the bulk of the content in this section describes practices that were developed for Li-ion batteries (the most broadly deployed technology). Guidance for emerging technologies is provided in Section 7.

4.1 Codes and Standards

A project should begin with consideration of the existing codes and standards (the minimum requirements) especially as applicable and adopted for the local area in which the project is intended. In areas where no local codes and standards apply, special efforts should be made to design and plan to the most current published codes and standards and work with local officials, as outlined further in Section 4.2.

For energy storage applications there are three categories of codes or standards that are of critical importance: (1) fire protection codes, (2) building codes, and (3) electrical codes. There is a technical difference between a safety code and a standard, even though the terms are often used synonymously:

- A code is a model, a set of rules that knowledgeable people recommend for others to follow. It is not a law although it can be adopted into law when adopted by an Authority Having Jurisdiction (AH. (i.e., the ‘what’ that needs to be followed)
- A standard tends to be a more detailed elaboration (i.e., the nuts and bolts of meeting a code; ‘how’ to accomplish it). A standard becomes a part of regulatory law when the code which references it is adopted into law, or in some cases if adopted directly by the regulatory authority.

There are two major fire codes accepted within the United States and some of its ‘territories.’ The International Fire Code (IFC) published by the International Code Council (ICC) is the model fire code in 42 states, the District of Columbia, Puerto Rico, and the US Virgin Islands. NFPA 1, published by the National Fire Protection Association (NFPA), is the model fire code in the remaining 8 states and certain federal government agencies. Those two codes reference many standards from various sources, but fundamental as a bellwether standard for ESS projects is NFPA 855, *Standard for the Installation of Stationary Energy Storage Systems.*

The major electrical code adopted in all 50 states within the USA is NFPA 70, more commonly known as the National Electrical Code (NEC). Two articles within it deal with energy storage, including stationary standby power applications. The NEC and its corollary standards (NFPA 70A, 70B, and 70E) detail regulatory requirements for electrical installation, maintenance of electrical components and systems, and electrical worker and workplace safety.

The key building codes are the International Building Code published by the ICC and NFPA 5000, published by NFPA. There are a number of other standards and reference documents published by reputable standards development organizations (SDOs), but they are often guidance documents as opposed to the mandatory requirements of the NFPA or ICC codes in North America.

A byproduct of the codes described above are the inspection, testing, and maintenance standards published by organizations such as UL Standards and Engagement (ULSE), the Canadian Standards Association (CSA), and the International Electrical and Electrotechnical Commission (IEC). The standard will outline the product testing and verifications the product must pass to be approved for installation. Nationally recognized testing laboratories (NRTLs) such as UL, TUV Rheinland, ETL, FM, and CSA can all test to that standard. For example, a standard published by ULSE, such as UL 9540 - *Standard for Stationary Energy Storage Systems and Equipment*, may be used by NRTLs for testing even though they did not publish the standard themselves.

Development of product safety and installation standards as well as fire codes is accomplished through a consensus-based collaborative process through organizations known as Standards Development Organizations (SDOs). Both codes and standards are developed by volunteer technical committees representing various stakeholder groups and updated on either regular cycles, or as needed. The two major fire codes in the US are part of a triennial revision process and are enforced via legal adoption of the code at either a state or local level. Public input and comments are part of the process to support a consensus process and to comply with ANSI requirements.

One of the most common issues facing safety codes is the time it takes for new codes to be adopted at the state or local level. As a result, the technology can quickly outpace the adopted standards. At any one time across the US, states can be on up to three different editions of the IFC. Additionally, the most current edition may not be adopted for another two to six years in most states.

A further challenge is the fact that reputable manufacturers design their products to comply with the codes and standards in effect at the time of their design. Since energy storage is in a fluid state of progress, changes in these codes and standards may require manufacturers to redesign their products and retest them to the new standard. This can involve significant financial investment and time resources, potentially forcing delays in bringing the new or enhanced product to market.

It is recommended that a manufacturer or design engineering firm stay aware of the major ESS safety codes and standards. Most of the major SDOs publish upcoming meetings on their websites, and the majority are open to guest participation although becoming an active member of a working codes/standards committee is not an easy process in most cases. An alternative is to assign an in-house regulatory specialist who stays abreast of developments as they occur within this space.

Table 3 summarizes the most relevant codes and standards for an energy storage system. A more detailed listing of the relevant codes and standards can be found in a recent report to Congress.[8] Figure 2 indicates the portions of an energy storage system to which each code or standard applies.

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[8] Paiss, M. D., Franks, R. J., Searles, C. G., Twitchell, J. B., Vartanian, C. K., Ropp, M., and Sprenkle, V. L. *Study of Codes & Standards for Energy Storage Systems: A Report to Congress*. United States: N. p., 2022. Web. doi:10.2172/1985701.

Table 3. Key standards for energy storage systems.

STANDARD	NAME	KEY DETAILS
IEEE 1547	Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces	Standard for interconnection of distributed energy resources (DER) with electric power systems. DER as defined in IEEE 1547 includes energy storage systems capable of exchanging real power (kW, MW) with the local distribution utility grid. IEEE 1547 also defines the performance requirements that are the basis for UL 1741 listing. IEEE 1547.9 provides guidance on the application of IEEE 1547 to energy storage distributed energy resources.
IEEE 2800	IEEE Standard for Interconnection and Interoperability of Inverter-Based Resources (IBRs) Interconnecting with Associated Transmission Electric Power Systems	Included in this standard are performance requirements for reliable integration of inverter-based resources into the bulk power system, including, but not limited to: voltage and frequency ride-through, active power control, reactive power control, dynamic active power support under abnormal frequency conditions, dynamic voltage support under abnormal voltage conditions, power quality, negative sequence current injection, and system protection.
NFPA 70	National Electric Code	Adopted in all 50 states, considered the benchmark for safe electrical design, installation and inspection to protect both people and property from electrical hazards. Article 706 applies to energy storage systems while Article 480 remains applicable to batteries as used in standard stationary backup power applications.
NFPA 855	Standard for the Installation of Stationary Energy Storage Systems	Key standard for the safe design, installation, operation, and emergency response for stationary ESS.
UL 9540	Safety Standard for Energy Storage Systems and Equipment	Key N. American product safety standard for factory certification of an energy storage system. Includes requirements for the battery, PCS, enclosure, thermal management, functional safety, and explosion control.
IFC	International Fire Code	Chapter 12 addresses ESS and harmonizes fairly closely with NPFA 855.

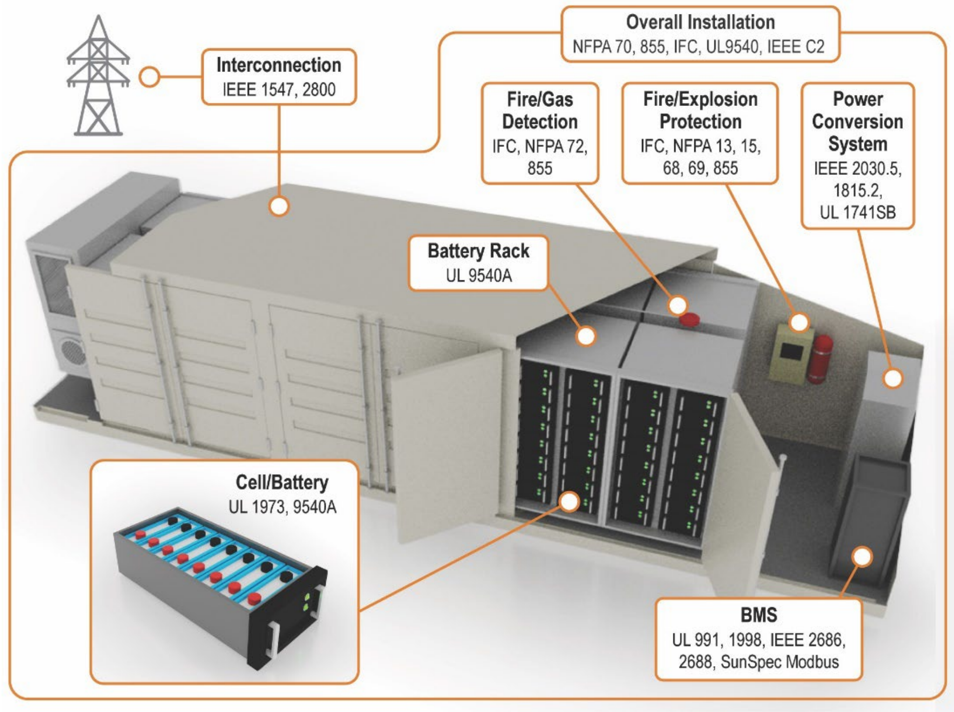


Figure 2. Applicability of codes and standards to different elements of an ESS

4.2 Project Execution

A typical energy storage deployment will consist of multiple project phases, including (1) planning (project initiation, development, and design activities), (2) procurement, (3) construction, (4) acceptance testing (i.e., commissioning), (5) operations and maintenance, and (6) decommissioning. Each of these activities involves decisions that will have an impact on safety during the installation of the system as well as during its operational lifetime. Figure 3 summarizes key safety considerations during each phase of energy storage project execution.

4.2.1 Planning

Development and design activities undertaken during this phase will result in preliminary specifications for the size (in power - kW and energy - kWh) of the system and the potential installation location. The size and where to physically locate the system have implications due to installation Codes/Standards requirements that must be considered. These considerations will drive the final engineering design and the acceptance testing schedule as the need for specialty contractors or equipment must be determined and planned for. Most importantly, it is in the planning phase that the local AHJ and first responders should be made aware, and their input actively sought on the project. These conversations will serve as the foundation for the final emergency response plan (ERP) for the system. Often, first responders are the last to know of the existence of an energy storage installation. This can lead to a lack of preparedness and potentially increased response times to a failure event. Overall safety and project support is compromised when AHJs and first responders are not part of the project process from the beginning.

4.2.2 Procurement

The predominant area of focus during the procurement phase should be the Request for Proposal (RFP) development. The RFP is the document that will determine what exactly the winning bid respondent (the ‘vendor’) will deliver to the system owner. This delivery involves not only the physical equipment that comprises a BESS but the plans, documentation, and installation practices that begin to lay the foundation of safety for the entire lifecycle of a BESS. There are typically several items that are often not specified in enough detail or even at all in the RFP that will impact subsequent project phases. The first gap is specifying the appropriate codes/standards to which the BESS should be designed, tested, and installed. Examples include requiring that the BESS be listed to UL9540 or its listed equivalent and be installed in accordance with the most recent version of either the IFC or NFPA 1 and NFPA 855. These standards are covered in more detail in section 4.1. Next, simply requiring these codes/standards without context can lead to unacceptably long delays in project delivery unless additional detail is provided in the RFP. Depending on the BESS chemistry there is a need to call out certain requirements within the installation codes/standards that are often misunderstood or not considered by the system vendor. Some examples of additional context include requirements for the system vendor to provide test data from large scale fire testing (see UL9540A), a Hazard Mitigation Analysis (HMA), potential design and installation of explosion mitigation methods (see NFPA 68 and NFPA 69), and a commissioning plan that clearly identifies roles and responsibilities (NFPA 855). Additional details of fire alarm design are also critical at the RFP stage to ensure proper communications are managed as expected by the AHJ.

4.2.3 Construction

The activities that take place during this phase will mostly fall under the category of monitoring. Monitoring refers to oversight of the construction and installation activities with respect to site safety and of project scope, schedule, and budget. Site safety during construction activities is critical as safety issues not only have the potential to result in worker injuries but also have the potential to shut down and cause serious delays to a project. Monitoring for project scope, schedule, and budget are all interrelated items that need oversight for changes that can impact construction activities or acceptance testing schedules. Another monitoring function is to track any design changes such as installation location, i.e., same general area but adjusted just enough to now be within a Code/Standard boundary that initiates additional installation requirements.

4.2.4 Acceptance Testing/Commissioning

Acceptance tests provide a baseline for how the BESS is expected to function when placed in operation. Acceptance testing can also identify malfunctioning components that could have created a safety issue if left unchecked. Although the primary vendor is responsible for providing the initial acceptance testing plan it is in the best interest of the commissioning process team to use BESS-specific commissioning guides to understand the tests being performed and expected results. It is essential to catalog and archive results from the BESS system components and sub-components acceptance tests.

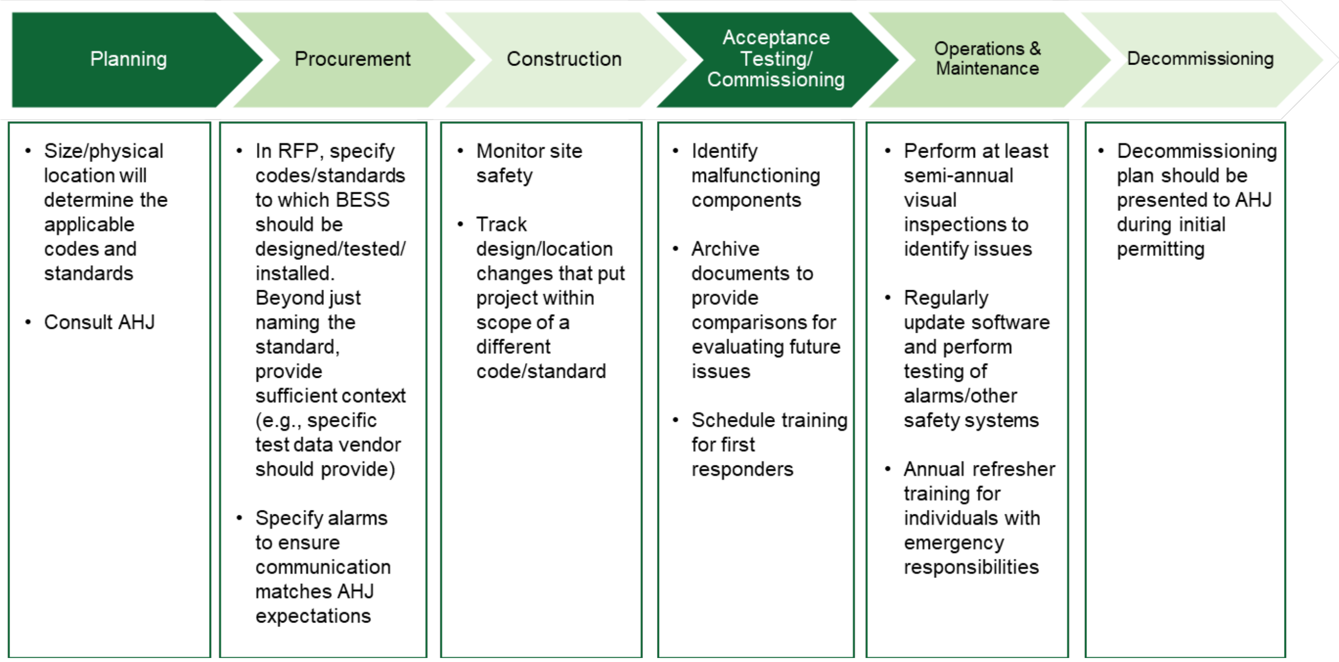
Unfortunately, commissioning tasks are often only partially performed or disregarded completely. Successful completion of this project phase provides the basis for a smooth handover of a project to the operations and maintenance (O&M) team, often a different set of personnel. Finally, and just prior to commencing full-scale operations, it is best practice to schedule training for local first responders. A classroom training session that includes battery safety awareness that is tailored to the specific BESS chemistry plus a site tour of the installation and location closes the loop on the project side with first responders. Including the O&M personnel in this training allows for introduction of those operating the BESS to those who would be responding to an upset condition at the BESS.

4.2.5 Operations and Maintenance

The O&M phase constitutes the majority of the BESS lifecycle and safe operations during this period are critically dependent on how well the entire project was executed. The energy storage asset owner may manage maintenance of a system themselves or they may outsource it to a third-party company (especially for geographically distributed sites). Recommended preventive maintenance actions include semi-annual visual inspections of the system and regular updates to the ESS software control and communications, as well as testing of the alarms and other safety systems. Additionally, there should be annual refresher training for individuals who have responsibilities under the emergency response plan, including first responders. In general, there is limited standard guidance on best practices for maintenance. Beyond preventive maintenance, there is a growing industry focused on BESS predictive maintenance – analyzing streaming data to identify early signs of malfunctioning components.

4.2.6 Decommissioning

A decommissioning plan will describe how: (1) a system will be shut down and removed from service; (2) components of the system will be disassembled, removed, and transported; (3) components of the system will be disposed, reused, or recycled; and (4) the site will be restored and remediated. Decommissioning can be a planned or unplanned event. A planned event is where the asset has met its expected life span based on normal degradation, while an unplanned event is due to a failure, and can involve a significant time delay depending on the failure event. There have been relatively few examples of energy storage decommissioning efforts due to the nascence of the industry. Key considerations for decommissioning include identifying under what circumstances the system will be decommissioned (e.g., component degradation, return on investment, etc.), who is responsible for system removal and costs, and how to ensure safety during decommissioning. Most jurisdictions are requiring decommissioning plans to be presented to the AHJ during the initial project permitting process, or prior to any decommissioning work beginning.



Planning	Procurement	Construction	Acceptance Testing/ Commissioning	Operations & Maintenance	Decommissioning
• Size/physical location will determine the applicable codes and standards • Consult AHJ	• In RFP, specify codes/standards to which BESS should be designed/tested/ installed. Beyond just naming the standard, provide sufficient context (e.g., specific test data vendor should provide) • Specify alarms to ensure communication matches AHJ expectations	• Monitor site safety • Track design/location changes that put project within scope of a different code/standard	• Identify malfunctioning components • Archive documents to provide comparisons for evaluating future issues • Schedule training for first responders	• Perform at least semi-annual visual inspections to identify issues • Regularly update software and perform testing of alarms/other safety systems • Annual refresher training for individuals with emergency responsibilities	• Decommissioning plan should be presented to AHJ during initial permitting

Figure 3. Key safety considerations throughout project execution.

4.3 Permitting and Zoning

Since 2015, the amount of utility-scale energy storage installed in the U.S. has grown at an average rate of 75 percent per year. Since 2020, the annual growth rate is 134 percent (including planned installations for 2023). As storage projects proliferate in the U.S., the potential for them to come into conflict with other land uses increases. Local zoning officials at the municipal and county levels are responsible for determining appropriate land uses and mitigating any impacts of a proposed project on nearby uses. Local planners, however, face two significant challenges in responding to proposed storage projects: 1) uncertain jurisdictional lines between state energy siting agencies and local planners; and 2) lack of familiarity with storage technologies and their potential impacts.

A large majority of municipalities and counties in the U.S. have not defined how storage fits into their zoning ordinances. Table 4 highlights the different ways that energy storage has appeared in local zoning ordinances. If a developer wants to install an energy storage project in a jurisdiction that has not defined where storage is allowed, the developer is responsible for identifying a potential site and petitioning the jurisdiction to issue a conditional use permit or rezone the site to enable the project. Such proceedings are subject to public hearing, which provides neighboring property owners an opportunity to express concerns. Communities are typically focused on understanding the physical impacts of energy storage: safety risks, environmental impacts, visual impacts, noise, odors, etc. Community opposition to storage projects is usually rooted in concern over safety and environmental risks, and public hearings tend to focus on the few, high-profile incidents of battery fires. These community impacts can be mitigated through local zoning requirements and conditional use permits, but doing so requires an awareness of energy storage characteristics that local planning officials and community members may not have.

Table 4. Energy storage in local zoning ordinances. Adapted from [9].

DESCRIPTION	NUMBER OF ORDINANCES FOUND	EXAMPLES
Ordinances written to regulate solar installations that also include storage. These ordinances generally only regulate storage systems when co-located with solar generation, and generally apply all solar PV regulations to storage components.	37	• *Plumsted, New Jersey* requires all equipment for a solar energy system, "including ... structures for batteries or storage cells" to "be completely enclosed by a minimum 12 foot high fence," and prohibits all systems from being located in a "front, side, or rear yard setback." *(Township of Plumsted, NJ Code § 15-5.21)* • *Boulder, Colorado*'s zoning ordinances define a "solar energy system" as "a system ... which may include an energy storage facility," and then defines permitting requirements and zoning districts eligible for installation of these systems. *(Boulder County Land Use Code Article 18, 18-199)*
Local adoption of fire or building codes that include standards for energy storage systems. County and municipalities have adopted fire and/or building codes that include explicit safety, labeling, and siting guidance for energy storage, such as the 2018 IFC, 2020 NEC, or NFPA 855.	12	• *Yarmouth, Maine* has locally adopted NFPA 855, "Standard for the Installation of Stationary Energy Storage," into its municipal fire and safety code. *(Town of Yarmouth, Maine Code Chapter 319: Fire Prevention and Life Safety Ordinance, 2021)* • *Several states have amended their Fire Codes (based on the IFC) to include language that allows the AHJ to enforce provisions in NFPA 855. (Michigan PUC Act No. 233, and WA State Building Code 2021 Edition §1201.1)*
Ordinances specifically targeted at energy storage technologies. These regulations include labeling standards, permitting requirements, setbacks, height standards, and visibility requirements. These ordinances may contain standards like those in standard fire or building codes and may be adopted in addition to these codes to add additional guidance. Alternatively, they may be adopted by local governments unable to exceed state code requirements.	12	• *King George County, Virginia* requires battery energy storage facilities to have access to water, provide access to the county fire department, have decommissioning plans, be labeled with NFPA 704 placards, and to not be visible from "any adjacent street, use or building." *(King George County, Virginia Code of Ordinances § 4.19)* • *Madison, Maine* requires battery storage systems to be enclosed by a minimum eight-foot fence with a locking gate and feature a visible sign to warn of potential voltage hazards. *(Town of Madison, Maine Code of Ordinances § 484-41)*
Ordinances that incent or encourage energy storage development. Some municipal ordinances protect the right to install energy storage systems or use local building codes to add incentives for storage.	5	• *Lancaster, California* ensures that all residents and businesses are "permitted to construct and operate stand-alone electric energy systems," including "fuel cell systems [and] battery systems." *(City of Lancaster, California, Ordinance No. 1067)* • *Wilton Manors, Florida*'s "Green Building Design Option" system, written into its code of ordinances, requires new buildings to earn a minimum number of green building "points," and allows on-site solar and storage systems to contribute to their total. *(Wilton Manors, Florida Code of Ordinances § 170-050).*

4.4 Insurance

Property insurance is fundamental to the long-term sustainability of industrial facilities. Any failure of an energy storage system poses the potential for significant financial loss. At the utility scale, ESSs are most often multi-megawatt-sized systems that consist of thousands or millions of individual Li-ion battery cells. Thermal runaway or, more importantly, the propagation of thermal runaway events, can result in damage that extends well beyond the initial failure point. Nearby supporting systems or critical infrastructure could also be damaged and lead to extended outages or reductions in power capacity.

Property insurance is about protecting the value associated with a facility. Ideally this is accomplished by preventing the loss from happening. However, when failures occur, it is important to mitigate the event to the least cost and disruption to the insured client. Insurance companies typically separate sources of

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[9] Twitchell, J.B., Powell D.W., and Paiss, M.D. 2023. **Energy Storage in Local Zoning Ordinances,** Richland, WA: Pacific Northwest National Laboratory.

financial losses into two categories, property damage and business interruption. Property damage relates to physical damage that requires repair or replacement. Business interruption addresses longer-term financial losses that occur while the property is unavailable, such as lost revenue or extra expenses incurred to maintain business operations. In some cases, the upfront property damage may be the leading loss cost; however, the accumulation of business interruption costs is often the dominant factor.

Loss prevention strategies focus on minimizing the two components of financial risk: frequency and severity. Current approaches to reduce loss frequency largely rely on manufacturers or integrators to implement good manufacturing practices and product design. A battery management system, for example, is an integral part of early abuse detection and intervention but can have limited impact once thermal runaway occurs. Thus, a layered protection strategy is recommended in guidance documents, such as FM Global Property Loss Prevention Data Sheet 5-33, *Electrical Energy Storage System*[10], to limit the severity of a loss. While not all protection options are available in every case, the general goals are to protect critical indoor equipment with automatic protection systems and to separate units from other ESS and buildings or other critical equipment to limit the damage area.

While there is beneficial alignment with installation standards, such as NFPA 855[11], achieving meaningful loss prevention often requires additional considerations. Regardless of the protection strategy, production of smoke, water runoff from fire protection efforts, and buildup of flammable gases can occur. Since fire generates smoke and sprinkler water damages electronics, any equipment near the origin of the fire would likely be lost in any case. This highlights the importance of continued development of high quality, robust and abuse tolerant battery systems and protection strategies to prevent an event from spreading beyond the initial point of failure.

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[10] FM Global Property Loss Prevention Data Sheet 5-33, Electrical Energy Storage Systems, Interim Revision, August 2023.

[11] NFPA 855, Standard for the Installation of Stationary Energy Storage Systems, 2023.

5. Developments in Validated ESS Safety for Li-ion Batteries

Li-ion batteries are currently the most common form of newly deployed energy storage due to their high production volumes, proven commercial performance, and desirable technical characteristics such as high energy density, high power, high efficiency, and low self-discharge. The key safety concern for Li-ion batteries is thermal runaway, which can be triggered by abuse or manufacturing defects. Propagation of thermal runaway can lead to major system fires or explosions. Thus, this section focuses on avoiding or mitigating the consequences of thermal runaway in Li-ion batteries, including current validation techniques, safety considerations for materials, engineering controls, and system design.

5.1 Current Validation Techniques

The rapid growth in energy storage deployments, along with a growing number of high-profile events involving fires and explosions, have resulted in ESS validation techniques diverging from those of the electric vehicle community. The accompanying evolution of ESS-specific codes and standards has given a clearer picture for battery manufacturers and integrators to validate their designs to meet the latest requirements.

However, codes and standards for ESS must be written to cover an extremely wide range of systems, from a few kilowatts and kilowatt-hours to hundreds of megawatts and more than a gigawatt-hour, and from 48-volt residential ESS to 1,500-volt grid-scale units. These diverse systems have widely varying validation needs. Residential systems represent the lowest level of absolute hazard but the highest risk for life safety, often consigning them to outdoor installations where they may be subject to widely varying ambient temperatures. Larger-scale ESS are normally temperature-controlled but are subject to other hazards; for example, a loss of isolation in a 1,500-volt battery can cause a multicell thermal runaway event with elevated risk of fire or explosion.

A major trend in the ESS industry is away from very large 40-foot and 53-foot ISO containers that must be assembled on-site, to smaller modular cabinets that can be shipped fully assembled. For optimum land utilization, these cabinets must be installed with minimal spacing, so avoiding propagation of thermal runaway becomes critical. Not only is it important to limit cell-to-cell propagation within modules, but the cabinet design must be validated to ensure that complete combustion of a single cabinet will not result in an explosion, or cause propagation to adjacent units.

At least some of the ESS incidents involving fire or explosion in recent years have occurred because integrators did not fully understand the failure modes and severity of hazards associated with Li-ion batteries. Lessons learned from these events have resulted in rapid evolution of codes and standards and improved understanding on the part of integrators. Large-scale fire and explosion testing has become a standard requirement for an increasing range of system sizes, and the significant cost of that testing may represent a barrier to some integrators entering the market.

Current validation techniques are generally adequate for today’s Li-ion chemistries, but there is ongoing work on emerging technologies, such as solid-state lithium and sodium-ion batteries. Both of these families of battery chemistries offer the hope of improved safety, but their failure modes and potential hazards must be more comprehensively understood. This understanding will inform the possible need for additional codes and standards and validation techniques.

5.2 Safety Considerations for Li-ion Battery Materials

Thermal runaway of Li-ion batteries, a process wherein the battery exhibits an accelerating heat release due to a series of uncontrollable exothermic reactions, is fueled by the interaction of component materials. Thus, there have been numerous efforts to develop ‘safe by design’ batteries by modifying the composition and architecture of the battery's anode, cathode, electrolyte, and their respective interfaces. However, it is important to note that safety is still typically evaluated at the whole-product (or cell) level after initial development of the battery to meet performance goals.

5.2.1 Anode (Negative Electrode)

Graphite is a well-established anode material in commercial Li-ion batteries. In Li-ion batteries with graphite electrodes, lithium ions react with the electrolyte during the initial cycles to form a passivation layer called the solid-electrolyte interphase (SEI). Further SEI growth is suppressed by the inability of electrolyte molecules to penetrate the established SEI layer, which in turn inhibits parasitic reactions at the anode.

The structure of the graphite creates limitations in charge rate, causing lithium plating on the outer surface of the negative electrode.[12] Li can plate in various morphologies, including tree-like crystals known as dendrites that can penetrate the separator and cause a short circuit. Attempts to modify graphite structures as 3D architectures have shown promise in increasing surface area and preventing lithium plating and dendrites during high charging rates. In addition, at a system level, to prevent lithium deposition, the battery management system (BMS) must limit charge currents to safe levels.

5.2.2 Cathode (Positive Electrode)

Many modern Li-ion batteries contain an NMC cathode with varying compositions of nickel, manganese, and cobalt. Recent research has focused on reducing the cost and ethical concerns of the NMC cathode by eliminating as much cobalt as possible. This has led to high nickel cathodes (e.g., NMC811). However, high nickel content can lead to challenges in fabrication and poor structural and thermal stability, which can affect safety. Many early grid-scale systems used an NMC cathode, and some BTM home storage systems continue to do so.

Recent grid-scale installations have used an LFP cathode due to its lower cost, better cycle life, and increased thermal stability (safety). Safety concerns are a significant driver due to BESS incidents that have harmed first responders and were widely covered in the media. However, it is important to note that LFP is not a silver bullet and incidents have occurred even in LFP-based systems (when LFP is experiencing thermal runaway, a greater volume of hydrogen gas is produced, leading to increased explosion risks). The drawback to LFP is its lower operating potential and hence, reduced energy density. A successor to the LFP chemistry may be $LiMn_xFe_{1-x}PO_4$ (LMFP). The inclusion of manganese in LFP can offer a >20% increase in energy density and high operating potential,[13] while maintaining the benefits of safety and cyclability. While some products could appear with pure LMFP as the cathode, it is likely that the trend toward blending cathodes will continue, with some manufacturers mixing LMFP and NMC.

5.2.3 Electrolytes

Commercial Li-ion batteries generally use an electrolyte solution composed of organic solvents, typically dimethyl carbonate (DMC) and diethyl carbonate (DEC), enhanced with lithium salts, such as $LiPF_6$, for ionic conductivity, and reinforced with ethylene carbonate (EC) to increase electrical resistivity. Organic electrolytes are more attractive for Li-ion batteries because of their wide electrochemical stability window

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[12] Janakiraman et al. "Review – Lithium Plating Detection Methods in Li-ion Batteries," *J. Electrochem. Soc.* **2020**, *167*, 160552.

[13] Yang et al. "Olivine $LiMn_xFe_{1-x}PO_4$ cathode materials for lithium ion batteries: restricted factors of rate perfromances," *J. Mater. Chem. A*, **2021**, *9*, 14214.

compared to aqueous electrolytes, which undergo water decomposition at relatively low potentials (1.23V vs. H/H^+). A major drawback of the commonly used organic electrolyte is its high volatility and flammability when operated outside of normal conditions. Operation at high voltage or high temperature can lead to the decomposition of the electrolyte constituents and further chemical reactions with the electrodes. Usually, these reactions are exothermic and self-sustaining, with aggressive gas release and flames. Flame retardant additives are under investigation to increase battery safety. Various additives based on phosphates and phosphazenes have been studied for this purpose, but their chemical stability, reactivity with other battery components, and the concentration required for them to be effective while still negligible to the overall weight of the cell is still under significant development.

5.2.4 Development of New Materials

The earlier sections described research on conventional, commercial Li-ion battery materials; this section describes the development of new materials.

Lithium metal anodes are theoretically capable of providing 10x higher gravimetric capacity than graphite. Electrolyte design improvements are constantly being made that may enable Li metal to replace conventional graphite electrodes. The development of electrolytes is focused on alternative salts, high salt concentrations, and/or alternative solvents that improve coulombic efficiency and morphological control. Because Li metal suffers from reactivity with liquid electrolytes and has traditionally exhibited poor morphological control, solid electrolytes are being developed and touted as the safer alternative to organic liquids.

Solid electrolytes are claimed to enable Li metal anodes and corresponding energy density gains by physically blocking dendrites and minimizing reactivity between the electrolyte and Li metal. Despite this common claim, the literature shows that Li dendrites readily form and grow through ceramic solid electrolytes.[14] Polymer electrolytes may more effectively block dendrites if they are engineered to exhibit sufficient shear modulus, but they are often still flammable like liquid electrolytes (with some exceptions). Recent research has indicated that solid-state batteries may be less safe than Li-ion batteries under short circuit failure because their higher energy density means that the same amount of heat is released in a smaller mass and volume, leading to higher temperatures. Solid-state batteries still need to undergo thorough modeling and experimental safety analysis prior to commercialization.

Another emerging technology is sodium-ion batteries, many of which use the same working principles and cell construction as Li-ion batteries. Sodium-ion batteries have received significant attention due to the natural abundance of sodium and the opportunity to avoid using metals such as cobalt, copper, and nickel. Limitations of sodium-ion batteries include lower energy density and cycling lifetime. Several companies have recently announced the production of sodium-ion battery packs for electric vehicles, however, there have not yet been major deployments. The safety of sodium-ion batteries has not yet been systematically studied, although this is changing as more commercial products are becoming available for testing. [15]

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[14] Barai et al. "Mechanical Stress Induced Current Focusing and Fracture in Grain Boundaries," *J. Electrochem. Soc.*, **2019**, *166*, A1752.

[15] https://www.phmsa.dot.gov/sites/phmsa.dot.gov/files/2023-04/DOT-SIB-Testing-Report-Web-Version.pdf, Accessed August 1, 2023.

5.3 Engineering Controls and System Design

The following section covers common practices and emerging guidance in the design of systems containing Li-ion cells. Table 5 summarizes engineering controls and system design approaches to enhance safety.

5.3.1 Module Design

The smallest replaceable unit in a Li-ion battery is typically the module, comprising multiple cells in series (and sometimes in parallel, depending on cell size) and BMS components for voltage sensing, temperature sensing, and cell balancing. The module design is integrated with the thermal management system, which may include air or liquid circulation. In air-cooled systems, the module may also include a BMS-controlled fan. While system cooling is important for maintaining the battery at a safe operating temperature, prevention of thermal runaway propagation should not normally be contingent on coolant circulation since this would require redundancy in the powering scheme and fans or pumps.

Module designs should include barriers between cells to provide passive protection against thermal runaway propagation. Examples of such barriers are air gaps, dielectric liquids, aerogels, and phase-change media. A typical arrangement has thermal barriers between cells and a cooling plate below them.

5.3.2 Enclosure Design

While some ESSs are still installed in buildings, codes and standards have evolved to the point where compliance is more onerous due to the proximity to people. Similarly, earlier containerized designs were mostly walk-in units, which are now treated like buildings from the perspective of fire codes. These issues have pushed designers towards cabinets that are serviced from the outside and only the technician’s arms cross the threshold of the enclosure. Such enclosures also allow for much higher energy density and reduced facility area.

In past years, many integrators standardized their designs on 40-foot and 53-foot ISO containers, and some still offer these units. The weight of these systems is such that they cannot be transported fully assembled, so it is necessary to install modules in the field. Furthermore, the requirements for product listing have led some integrators to adopt smaller cabinet-type units to modularize ESS project designs. These units, typically 10’-20’, can be shipped fully assembled, and, in the event of a fire, losses are reduced, and cabinets can be easily replaced. The cabinets are heavily insulated to allow them to be installed with very little spacing, while still preventing propagation of fire between units.

5.3.3 System Integration

Some earlier safety events resulted from poor integration of ESS components, particularly relating to electromagnetic compatibility and interoperability. The BMS should be resistant to any electromagnetic interference from the PCS (power conversion system) and must be able to cope with current ripple without nuisance warnings and alarms. Interoperability is achieved between the BMS, PCS controller, and energy storage management system with proper integration of communications. The *de facto* standard in this area is provided by the SunSpec Energy Storage Models. The SunSpec models are included in a draft IEEE recommended practice for BMSs, expected to be published in 2024. Another failure mode experienced in the field involves poor cell balancing across a string of cells as they degrade at different rates, which can lead to overcharging in higher SOC (state of charge) cells.

Table 5. Possible engineering controls and system design elements to enhance safety.

LEVEL	POSSIBLE FEATURES IN DEPLOYED SYSTEMS
Module	- Barriers between cells to minimize thermal runaway propagation - Integration of thermal management
System	- Cabinet/modular systems: 1) serviced from the outside to enhance technician safety; 2) reduced losses compared to larger container - BMS: 1) resistant to EM interference; 2) communications redundancy - Proper integration between BMS/PCS/EMS - Explosion control: deflagration panels, sparkers, etc.

5.3.4 Fire Versus Explosion Philosophy

When abused, Li-ion cells vent a flammable mixture of gases containing hydrogen, carbon monoxide, carbon dioxide, and organic compounds. If allowed to accumulate in the confines of an enclosure, this gas can quickly surpass the lower explosive limit and pose a risk of deflagration to first responders. Industry trends towards larger format cells and greatly reduced free air volume in enclosures can mean that a single cell venting could present an explosion risk.

In ESS designs where cell-to-cell thermal runaway propagation is possible, or in the event of a multi-cell arcing fault, suppressing a fire may knock down the visible flames but may not cool cells sufficiently to prevent propagation. In an enclosed space, continued cell venting can drive the gas concentration above the upper explosive limit, posing an extreme risk to first responders who may open the enclosure door, allow oxygen to enter, and then trigger an explosion. This is exactly what happened in McMicken, Arizona in April 2019, where four firefighters were injured.

Recognizing that explosion is a much greater hazard to personnel than fire, the codes require explosion control to mitigate the risk. Many integrators now employ venting strategies to flush flammable gases out of enclosures. Provisions for venting may be as simple as opening doors or roof vents, or may involve emergency fan operation. For the latter case, it is important to provide reliable power to the fans, possibly with an uninterruptible power system or generator, since the battery may have been tripped offline in response to the event.

Venting of flammable gases is likely to reduce the effectiveness of fire suppression, so some integrators have opted to eliminate fire suppression from their designs. This ‘let it burn’, or defensive, strategy has a benefit in that, if the enclosure is burning, flammable gases are consumed as they are generated, reducing the risk of explosion. For this reason, some integrators have extended the ‘let it burn’ concept to a ‘make it burn’ strategy, using sparkers to ignite vent gases. Allowing the fire to burn out also avoids problems with stranded energy and reignition.

Although it has been widely acknowledged that water is the most effective medium for cooling cells and arresting propagation, to be effective the water must be properly directed to contact all cells. Ceiling-mounted sprinklers and hose-directed water from firefighters are unlikely to achieve this close contact, potentially resulting in partial extinguishing while creating contaminated run-off, or requiring significant amounts of water. Additionally, water is conductive and large losses have occurred to previously unaffected battery racks. Where a defensive strategy is adopted, firefighters are trained to use water only to protect nearby exposures.

5.3.5 Event Detection

Detecting an ESS safety event and alerting the necessary personnel represents the first step in incident response. All ESS facilities are required to prepare an emergency response plan for submission to the AHJ, and this plan should be triggered by the initial detection.

The BMS may detect the early stages of an event through temperature measurements, evaluating temperature differences both between module sensors and between those sensors and the ambient. However, most BMS designs do not include temperature sensing for each individual cell, and a certain number of sensors per module are allowed to fail before string tripping, to maintain availability. Thus, the BMS capability to detect the beginnings of thermal runaway depends on the proximity of the faulty cell to the nearest sensor.

Another aspect of BMS design is communications redundancy. The internal BMS communications and communication to the system controller should be supplemented by a trip circuit activated by a dry contact. This circuit may be activated in a single string during normal operation as a result of a performance anomaly, or an external sensor or system may trip all strings in the enclosure when a safety event is detected. While BMSs are routinely used for isolating a battery from charging and discharging, they are not typically used for high-level emergency alert notifications, primarily due to the lack of a BMS standard addressing this use.

NFPA 855 (2023) requires the ESS area to have smoke detection or radiant heat sensors. Many designs go beyond this minimum requirement, installing both smoke and heat sensors and often additional detection. This additional detection typically senses one or more components of cell vent gas, such as volatile organic compounds, hydrogen, carbon monoxide, and carbon dioxide. Cell venting normally occurs some time before full-blown thermal runaway and may not be detected by smoke or heat sensors, so these vent-gas sensors can provide early warning of an event.

Communication to emergency responders typically occurs through the use of a FACP (Fire Alarm Control Panel) which receives alarm signals from any of the above sensors and transmits the alarm signal via central dispatch protocols.

6. Incident Response for Li-ion Batteries

This section covers lessons learned from recent incidents, translating knowledge and data gained from incidents to codes and standards, and how notable incidents have led to significant policy changes in the energy storage community.

6.1 Lessons Learned From Recent Events

Emergency services utilize a system to organize resources, assess risks, develop strategy, and implement the plan in the form of tactics. This may take the form of Standard Operating Procedures (SOPs) for well-defined incidents such as Hazardous Material Incidents (HAZMAT), structure fires, or vehicle rescues.

One of the best tools to utilize in planning any response is past experience from similar events. These are often formulated into what is commonly known as Best Practices. In the realm of ESS incidents, experience has shown that extinguishment of Li-ion BESSs is challenging, often ineffective, or even detrimental to saving property or protecting the environment. As a result, a best practice that is being validated on more and more events is the defensive (let it burn) strategy while protecting exposures. This is challenging for the fire service based on their deeply ingrained culture of taking personal risk to save lives and property and putting all fires out. However, as with wildland firefighting, where the fire is allowed to assist in the task of removing fuel and protecting high value exposures, a defensive strategy can actually be considered a part of the HMA. Allowing a BESS to burn, as long as no exposures are threatened, may actually result in an overall shorter incident duration, with less HAZMAT concerns with water run-off. Recent incidents with sprinkler system activations have actually led to significantly increased damage to previously unaffected modules and racks, not to mention millions of gallons of water use. The 'let it burn' approach has been challenged as more BESSs have been placed in populated areas (e.g., near homes, schools, or businesses). Clearly this defensive strategy is also not possible for indoor installations of BESS.

6.2 From Incidents to Codes and Standards

Codes and standards are often called "reactionary" but the reality is they should be based on data, and previous incidents provide valuable data to identify gaps or modifications to the codes. The best practices described above are only enforceable when they are codified. Additionally, with the model fire, electrical, and building codes being updated on a triennial cycle, it is critical to incorporate these lessons learned and resulting Best Practices into the code without delay to keep up with the fast pace of technological innovation. One example of code changes based on lessons learned is the requirement for explosion control in all enclosures. Another is allowing some exceptions for providing sprinkler suppression systems given the limited effectiveness from incidents. In fact, water has in some cases led to greater battery involvement and loss in several incidents.

6.3 Deflagration Prevention Challenges

Great care must be taken to prevent explosions, which have already led to several notable injuries and fatalities during BESS incident response. The highly unpredictable nature of thermal runaway with the potential for propagation into a large-scale ESS fire can make designing explosion control systems quite challenging. For example, while the characteristics of a single cell failure are predictable, failure does not always scale predictably at the system level. The rapid evolution of a mixture of flammable gases presents challenges for sensors and for designing systems with the level of reliability required to ensure an explosion does not occur.

While passive controls such as pressure relief vents are common in other industrial processes, the presence of passive-only devices on a BESS enclosure will not prevent the potential for an explosion, nor exhaust the gases. In fact, it can present great risk to anyone that will have to open a door at some point. It is critical to remove the flammable gases to avoid the potential for any explosion.

6.4 Suppression Options

There is a growing field of research focusing on identifying effective fire suppression for Li-ion fires, but the results have not yet pointed to a universally effective agent or method of application to suppress a thermal runaway fire in lithium-based incidents. Traditional fire suppression agents include water-based agents, gaseous clean agents, and aerosolized powders.

6.4.1 Water-based Agents

Water-based agents include foams which are typically used for fires in Class A (common combustibles) as well as Class B (hydrocarbon and alcohol-based liquid fuels) materials. Water is used in automatic sprinkler systems that can use temperature-fused heads, or in a system where all heads are open and the piping is dry (empty) until either an automatic valve delivers the water, or firefighters make an external connection on a standpipe.

One challenge with water application is getting the water directly to the source of the fire in a very dense rack of modules. Another challenge is the conductive quality of water creating short circuits and extending the damage. Some manufacturers have experimented with direct injection of water into each module. While this has shown effective results in UL9540A fire testing, it has also resulted in large scale damage to the ESS when inadvertently discharged, as well as challenges in preventing further equipment or environmental damage from the flowing water.

6.4.2 Gaseous Agents

In the gaseous-clean agent category, common systems include Novec 1230 and FM200. These agents are common in the protection of sensitive electronics and act by either cooling or displacing oxygen. Challenges in the suppression of ESS fires include limited effectiveness due to the extreme heat generated during the thermal runaway process, as well as the duration of the incident. Additional challenges are the need to have a sealed environment to achieve the designed concentration of the agent for long enough to extinguish flame. This is the key issue that actually creates an unintended risk. The elimination of visible flame does not stop the thermal runaway process and the continued production of flammable gas now creates an explosion risk as the gases are allowed to build in the sealed enclosure.

Some manufacturers are experimenting with direct injection of the liquid clean agent. One area of considerable interest is immersion cooling in a dielectric liquid (as opposed to submersion after an incident). Several manufacturers have presented early data on these designs but have limited field data to validate the concept.

6.4.3 Aerosol Agents

Aerosol agents are powders that are designed to be discharged into the enclosure or room to disrupt the chemical chain reaction and extinguish flames. These powders, like gaseous clean agents, are well established in other sensitive electronics protections, however, they are not effective for lithium battery fires due to their limitations in cooling as well as the need for a sealed environment to maintain agent concentration. This creates a similar conflict as gaseous agents with the need to prevent the build-up of flammable gases with rapid exhausting.

6.5 Firefighting Priorities

The tactics employed in responding to an ESS incident will take the same approach as described in the Lessons Learned section. With the priority of protecting exposures, any decision for a defensive versus offensive strategy is dependent on the incident and location. Considerations of smoke plume direction as well as runoff containment should be part of the incident management decisions. HAZMAT monitoring of runoff and airborne emissions may be required, so resources should be requested early in the incident to support these efforts.

The location of the battery will determine the exposures and direct the strategy for any incident. Water may only be used to protect nearby equipment or other structures. Indoor installations have more strict fire and life-safety code requirements, which will make the system more complex and costly. Luckily the number of incidents in this category remain very low, however, expectations are that as the cost of residential ESS is driven downward, quality and safety may suffer. ESS technologies that emit toxic or flammable gasses during failure should be placed outdoors or in garages.

6.6 Status of Training

Training for emergency responders is a code requirement for non-residential installations. This will typically include awareness of failure modes, hazards, system operation, and recommended response actions. As ESSs become more common, fire departments may require less training, but at this early stage in the electrification of our society more information is critical for successful adoption. When communities raise safety concerns about applications for ESS installations, planning commissions will reach out to local fire officials to obtain information on the safety topics. If the fire department has not received any training, very often these projects will experience delays up to and including moratoriums on development. Experience has shown that in communities where the local fire department has received training by independent experts, ESS projects encounter fewer concerns from the fire service in the community.

6.7 Resources

Training and education in emergency response for an ESS development should be driven by the developer or manufacturer as there may be site- or installation-specific concerns. However, a number of national organizations are also developing and delivering training for the fire service. For example, the NFPA as well as the International Association of Fire Chiefs (IAFC) have online training available.

An example incident response guidance document is given in Appendix B.

7. Evaluating Emerging Electrochemical Technologies

While ESS safety assessments tend to focus on Li-ion, the failure modes and risks of other chemistries still need to be considered during development. Not doing so can lead to significant delays in commercialization of new technologies and harm people and the environment.

One of the major challenges facing SDOs in developing meaningful safety codes or standards with a new technology is the lack of credible data to validate the safety and reliability of that new, emerging technology. In one respect, standards development organizations are like the railroad operator. Once a significant accident occurs at a railroad crossing, that operator puts up red lights and safety crossing gates. However, evaluation of the failure modes of a new technology needs to be done at all stages of development and deployment (Figure 4). This process begins during the development of small-scale systems in the lab. At this point, it is important to consider all potential hazards, regardless of how significant they may appear at the small scale. The data collected at the lab scale (e.g., gas generation) should be used to make rough projections of how the risk scales with system size. This allows for the development of mitigation strategies and identification of appropriate sensors for monitoring of expected failure modes in the commercial-scale product.

Lab-scale testing should simulate real-world operating conditions as much as possible to determine how factors such as temperature impact degradation and failure. Additionally, any safety assessments (i.e., response of the battery to thermal, electrical, or mechanical abuse) should be completed both on fresh and cycle/calendar-aged cells. One gap in current safety assessments is that validation tests are performed on new products under laboratory conditions, and do not reflect changes that can occur in service or as the product ages.

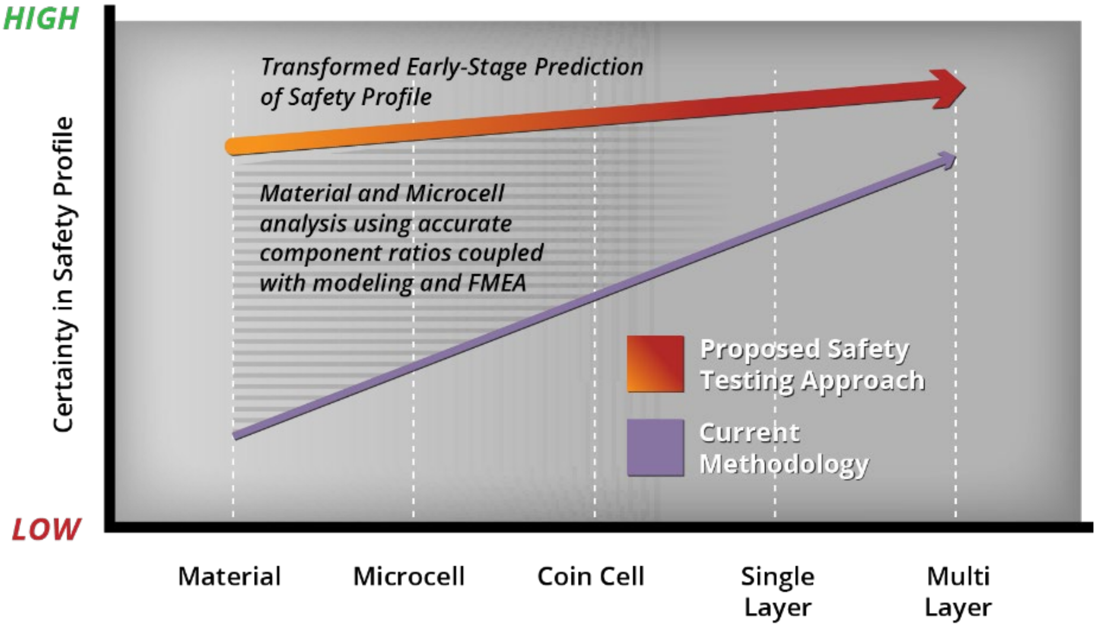

Figure 4. Increasing safety certainty earlier in the energy storage development cycle.

8. Summary of Gaps

Safety of any new technology can be broadly viewed as having three linked components: 1) a system must be engineered and validated to the highest safety level possible, 2) techniques and processes must be developed for responding to incidents if and when they do occur; 3) the best practices and system requirements must then be reflected in standardized safety determinations in the form of codes, standards, and regulations so there is uniform, written guidance for the community to follow when designing, building, testing, and deploying the system. The following section describes remaining gaps in each of these three areas based on the current state of ESS safety and reliability outlined earlier in this document and feedback solicited during the 2023 Energy Storage Systems Safety and Reliability Forum Breakout Sessions on these topics. Table 6 compares these gaps to those identified in the first version of the DOE Energy Storage Safety Strategic Plan published in 2014.

Table 6. Energy storage safety gaps identified in 2014 and 2023.

	2014	2023
Validated Safety and Reliability	• Materials science R&D – research into all device components • Engineering controls and system design • Modeling, cell to system • System testing and analysis • Commissioning and field system safety research	• Containment of Li-ion cell failure • O & M Guidance • End-of-life for Li-ion systems • System level fire modeling for Li-ion • Safety and degradation of beyond-Li-ion technology • Risks of energy storage in new applications • Standardized testing and reporting
Incident Response and Training	• First responder awareness and response practices • Fire suppression and protection system selection • Verification and control of stored energy • Post-incident response and recovery guidance • Battery-specific commodity classification for sprinklers	• Inclusion of energy storage data in guidebooks • Incident reporting • Decommissioning and stranded energy • Emergency response coordination • Physical status indicators • Impact of toxic emissions • Development of new tools for the fire service • Incident response during shipping and transportation

Codes, Standards, and Regulations	• Develop plan to assess existing CSR to identify gaps	• **Electrical**
		  • ESS-specific guidance for worker health & safety
		  • Grounding ESS
		  • Retesting a system over its lifetime
		• **Fire**
		  • Continue updating UL9540A (e.g., better module tests, impact of aged batteries, ignition of vent gases)
		  • ESS-specific guidance for minimizing explosions (NFPA69 generic)
		  • Acceptable emissions + spill containment
		• **Reliability**
		  • Data monitoring and reporting requirements
		• **Permitting**
		  • Uncertain jurisdictions of state agency vs. local planner
		  • Local planners lack of familiarity with storage

8.1 Validated Safety and Reliability

Several gap areas were identified for validated safety and reliability, with an emphasis on Li-ion system design and operation but a recognition that significant research is needed to identify the risks of emerging technologies.

1. **Containment of Li-ion cell failure**: Based on current Li-ion cell manufacturing processes, we expect the internal short-circuit failure of a certain number of fielded Li-ion cells. There have been no recent public examinations of these failure statistics, but studies in the 2010s of batteries in consumer electronics estimated the failure rate at less than one in one million.[16] This number may have decreased over time for established manufacturers, but the failure rate may be different for the many new battery cell manufacturers that are entering the industry due to growing demand for electric vehicles and energy storage. Energy storage developers must design systems that can contain these inevitable cell failures and prevent propagation to additional cells.

2. Operations and maintenance guidance: Currently, the certification process for BESS ensures that the overall system design is sound, the factory testing makes certain that the unit was constructed correctly, and the commissioning test confirms that there were no faults created or discovered immediately after the unit was installed at the site. However, there is limited public information on best practices for Day 2 operations and maintenance of Li-ion systems – what component failures should we be looking for (e.g., HVAC breakdown, rusting due to humidity, etc.), what are the most useful data points to track, and so on. One notable area of research is early detection of thermal runaway. Current devices and practices (e.g., gas sensors) aim to detect thermal runaway in a single cell before it occurs, leaving only enough time for a response that damages the system, such as a water deluge, or aerosol agent discharge. Identification of failure markers a week or at least a few days ahead of time would enable proactive maintenance of the affected area, such as replacing a faulty module. BMS analytics of battery degradation provide a possible avenue for failure detection.

3. End-of-life for Li-ion systems: There is currently limited guidance for end-of-life (EOL) management of Li-ion BESS because few systems have reached EOL, but this is a topic that merits research before more systems come offline in the next few years. There are currently detailed guides for BESS commissioning which may be used to inform the development of commissioning plans[17]; similarly detailed guidance is needed for system decommissioning. Current fire codes require a decommissioning plan, but there is currently limited documentation of best practices and advances in this area (including guidance for planned decommissioning based on system degradation and unplanned decommissioning due to a significant system failure). Tools to assess the health or stability of a battery for decommissioning or repurposing are critical. Additional questions include how to safely deenergize, disassemble, transport, and recycle batteries. Fires during transport and at recycling facilities have become a notable concern for consumer electronics and EV batteries.

4. System-level fire modeling for Li-ion: System-level experimental fire tests are an important tool for understanding the worst-case failure scenario for a BESS. However, they are expensive and may be difficult to support for emerging developers. Accurate system-level fire modeling including explosion control design would complement large-scale fire testing by evaluating many failure scenarios ahead of time and enabling the identification of issues and design of better systems prior to final testing. Additionally, this modeling would inform siting decisions, especially for large systems. There is a lack of

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[16] https://www.nrc.gov/docs/ML1719/ML17191A294.pdf, Accessed August 1, 2023.

[17] EPRI ESIC Energy Storage Commissioning Guide https://www.epri.com/research/products/000000003002013972, Accessed August 1, 2023.

guidance on clearances and setbacks required from critical grid infrastructure, such as substations or transmission lines. Current modeling tools primarily focus on cell-level failure and module-level propagation.

5. Safety and degradation of beyond-Li-ion technology: Many emerging energy storage technologies are presented as 'safer' alternatives to Li-ion systems. Full, rigorous FMEAs still need to be completed for these new technologies to understand their unique safety and degradation profiles. These FMEAs can then inform the development of new, technology-appropriate performance and safety testing protocols. Passing safety tests designed specifically for Li-ion batteries is not sufficient.

6. Risks of energy storage in new applications: Codes, standards, and testing protocols for energy storage systems tend to focus on grid-scale deployments. However, energy storage is increasingly being used in new applications such as support for EV charging stations and home back-up systems. Additionally, many jurisdictions are seeing increasing use of EVs and mobile energy storage systems which are moved around to be used as a temporary source of power. It would be beneficial to understand the performance and degradation of energy storage systems under these new duty profiles. These new applications also merit their own guidance for safe system design and emergency response protocols. A residential energy storage system will have different emergency response protocols from a utility-scale system.

7. Standardized testing and reporting: Many Li-ion battery safety and performance testing protocols are being developed, but tests are often executed in slightly different ways (e.g., different thermal runaway initiation methods) making it difficult to compare results across tests. Even when two labs try to strictly follow the same test procedure, the outcomes can still be slightly different. There should be an effort to make testing protocols descriptive enough to increase reproducibility. Standardized testing protocols should be complemented with standardized reporting protocols. Additionally, new safety tests can be informed by specific incidents in fielded systems (e.g., ARC flash between modules). Where possible, safety and performance tests should mimic conditions encountered in the field to yield the most accurate expectation of real outcomes; however, this can be challenging due to insufficient reporting of details and root causes in fielded system incidents.

8.2 Incident Response and Training

The gap areas identified for incident response generally fall into three categories: increasing knowledge about ESS safety prior to an incident, increasing situational awareness during an incident, and managing the aftermath of an incident.

1. Inclusion of energy storage data in guidebooks: Firefighters use the Department of Transportation Emergency Response Guidebook, or ERG, to find data on the properties of materials they might interact with during HAZMAT transportation accidents. Appropriate data on different battery chemistries should be incorporated into this manual and similar guides so that emergency responders have an easy, standard reference.

2. Emergency response coordination: Larger jurisdictions with significant experience with ESS have started coordinating emergency response plans. However, there is still no standard template to guide system owners through the development of a plan with all key elements (e.g., identifying all relevant stakeholders, all data to consider during an incident, etc.). Such a template would be especially useful in jurisdictions with volunteer fire departments.

3. Incident reporting: Incident reporting for emergency responders is commonly done via an electronic system called the National Fire Incident Reporting System (NFIRS) managed by FEMA. This is a system used by over 22,000 fire departments to log all emergency responses. One of the gaps in this system is the ability to track emerging risks such as newer technologies. More accurate incident reporting to capture these incidents is needed to understand the impact on fire departments, as well as incidents themselves. The US Fire Administration is launching a modernization effort to deploy a new reporting system called the National Emergency Response Information System (NERIS). NERIS will provide capabilities for documenting and introducing community risk reduction efforts, offering insight into vulnerability gaps where resources can be used to harden communities and minimize future emergency and disaster events.

Additionally, the nation would benefit from the public release of detailed reports on ESS incidents so that lessons learned can be shared and issues mitigated in other systems.

4. Physical status indicators: Emergency responders need stationary ESS to report out more data during incidents to support them in providing an appropriate response. Examples of physical status indicators include BMS data to help identify trending temperatures and gas-levels inside the enclosures. Gas levels are particularly important to understand the explosion risk and if gas sensors are utilized as part of the explosion control system, they should be able to report concentrations for the duration of an incident. Emergency responders should be able to access these physical status indicators outside of a suitable exclusion zone from the system. Outside of live data reporting, all BESS should have standardized hazard markings (e.g., “keep out” areas), signage, placards, and ground labeling so that emergency responders immediately know what they are approaching.

5. Impact of toxic emissions: The impact of toxic emissions from battery fires is critical to guide incident response strategies as well as to be able to provide better data-driven guidance for public safety protections. Early studies are considering the impact of heavy metals in both particulate emissions (air-borne), as well as those found in water run-off. Additional work is needed to identify toxicity impacts to firefighting PPE (personal protective equipment), as well as appropriate cleaning of the PPE. Some early studies are looking at SOC and chemistry impacts on emissions, as well as plume studies for airborne particulates. As current best practices are trending towards a defensive strategy on outdoor battery incidents, greater toxic emissions knowledge is needed to understand the long-term impacts of this approach.

6. Decommissioning and stranded energy: Stranded energy, the energy remaining in damaged batteries (if a fire does not burn everything), can pose a significant fire and shock hazard. Stranded energy impacts when and how batteries can be removed from their original installation, transported, and disposed of. Emergency responders need guidance on how to mitigate the hazards of stranded energy and tools for safely neutralizing batteries. Current areas of research include tools to short circuit batteries and the effectiveness of water submersion.

7. Development of new tools for the fire service: Development of new tools for the fire service to effectively respond to ESS incidents is also an emerging field. Fire suppression tools common in Europe are being evaluated for EV fires where extinguishment is challenging. Piercing nozzles and high-pressure cutting tools are common on fire apparatus in Europe and several studies have evaluated these tools in direct injection of water to damaged EV packs with successful results. Fire suppression tools may be seen as ‘counter’ to the defensive ‘let it burn’ philosophy, but the defensive approach has been challenged as more BESS have been placed in residential areas and near schools).

For stationary ESS, there has also been a call for more physical status indicators, as documented in (5). Outdoor ESSs with automatic door systems for deflagration prevention are increasingly being considered to provide direct visualization from a safe distance; automatic door opening also increases the situational awareness in a way that other data streams can't.

8. Incident response during shipping and transportation: Battery incidents may occur outside of an ESS installation, either during shipping or transport to a site or, more likely, after batteries are removed from a site. The maritime environment presents unique challenges and risks for the transportation of Li-ion batteries, particularly due to the potential for thermal runaway and fires, which can be difficult to manage at sea. To ensure the safe transportation and shipping of Li-ion batteries, several international codes and standards have been established. These include: the International Maritime Organization Dangerous Goods Code and Circulars, IEC 62619 and 62660, and United Nations Recommendations on the Transport of Dangerous Goods. To further enhance the safety of Li-ion battery transportation and shipping in the maritime environment, the following recommendations are proposed. Companies involved in the transportation and shipping of Li-ion batteries should provide regular training and education to their employees on the safe handling, storage, and shipping of these batteries. This includes updates on the latest regulations, guidelines, and best practices. The maritime industry should establish a centralized system for reporting and analyzing incidents related to the transportation and shipping of Li-ion batteries. This system would help to identify trends and patterns, allowing for targeted improvements in safety measures and best practices. Additionally, close collaboration between battery manufacturers and shipping companies can help to ensure that Li-ion batteries are designed and produced with transportation safety in mind.

8.3 Codes, Standards, and Regulations

While progress has been made in the three critical areas of CSR (fire and explosion safety, electrical safety, and worker/workplace safety), ESS applications are still relatively new and gaps still need to be addressed.

8.3.1 Electrical Safety

In the area of electrical codes and standards, the community would benefit from ESS-specific guidance for electrical worker health and safety, for example, on the topics of PPE and lockout tagout procedures. NFPA 70B and NFPA 70E are in the process of being updated to better reflect ESS-related concerns.

Development of an understanding of minimum requirements for grounding an ESS, both for the DC and AC components, would also be helpful. Recent incidents in ESS have involved arcing faults, some even triggered by the water released by emergency sprinkler systems. Understanding the principles of arc flash versus arc burns as they apply to both vdc and vac current flows would be very useful.

Lastly, full electrical testing of a system is normally completed only during factory development or commissioning. Standards for retesting a system over the course of its lifetime would lead to the identification of any changes that are caused by component aging and degradation. [18]

8.3.2 Fire Safety

UL9540A is currently the most common standard for large-scale fire testing of ESS. It should continue to evolve as more data is collected about incidents in fielded systems. Some areas worth addressing include better tests for module-level propagation (propagation is still occasionally observed in packs approved to the standard), the impact of aging on battery safety, and the ignition of vent gases to assess the fire resistance of the system.

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[18] IEEE has an active project (P2962) on Li-ion installation, maintenance, and testing. It will include a recommendation for annual testing of systems like ESS that are regularly cycled. Likely publication is in 2024.

Recent incidents in fielded systems have driven interest in the establishment of clear minimum requirements to mitigate the risk of explosions in Li-ion-based BESS (see also 5.3.4 Fire versus explosion philosophy). Currently, developers refer to NFPA 69, a general standard for installing systems for the prevention and control of explosions that contain flammable concentrations of flammable gases, vapors, mists, dusts, or hybrid mixtures. However, there is some concern that this standard does not provide sufficient ESS-specific design context and leaves too much room for interpretation.

Lastly, research on the impact of toxic emissions on beings and the environment, described in the incident response section, should lead to the development of new codes and standards for emergency response. These standards should address topics like exclusion zones, acceptable concentrations of pollutants in the air and water, and spill containment if the fire approach is to let the container burn.

8.3.3 Reliability

Most codes and standards for energy storage systems focus on safe system design and emergency response. There is relatively little guidance on reliability concerns, including what data points should be monitored during operation to enhance insight into the system. Performance reporting has traditionally been mandated by the North American Electric Reliability Corporation (NERC) for the Generator Availability Data System (GADS) for fossil-based, NERC-registered entities. Draft requirements for solar generation systems include energy storage reporting requirements for photovoltaic hybrid systems. Standalone ESS would also benefit from data monitoring and reporting requirements.

While reliability of interconnected power sources is part of the requirements found in the IEEE 1547 family of standards, the industry would also benefit from formal standards for ESS reliability and performance testing. This involves the development of reference performance tests and duty cycles for specific use cases. Information from these standards would enable an apples-to-apples comparison of ESS and make it clear whether an ESS can truly reach a desired metric. PNNL and SNL developed protocols for uniformly measuring and expressing the performance of energy storage systems in the mid-2010s. More recently, the scope of IEC TC 120 has included the “preparation of normative documents dealing with the system aspects of ESS” including “defining unit parameters and testing methods.”

8.3.4 Land Use Permitting

Land use permitting for energy storage faces two significant challenges: 1) Uncertain jurisdictional lines between state energy siting agencies and local planners; 2) Local planners’ lack of familiarity with storage technologies and their potential impacts. For the first challenge, state and local jurisdictions need to come to an agreement on their areas of authority. Actions to address the second challenge include the development of educational materials for local planners that define ESS impacts through a local zoning lens and a best-practices guide in local zoning for storage. A good starting point is a review of past community engagement models, i.e., how have successful projects engaged and won the support of their local community?

9. Conclusion

Since the publication of the first Energy Storage Safety Strategic Plan in 2014, the field has seen the emergence of new technologies, use cases, emergency response procedures, and regulations. This document reviewed the current state of energy storage safety according to three pillars: 1) science-based safety validation, 2) incident preparedness and response, and 3) codes and standards. A key outcome of this review was the identification of gap areas and future research priorities for each of these pillars. These recommendations are intended to ensure that safety concerns do not serve as a barrier to deployment of grid energy storage to support an efficient, reliable, and resilient electric grid.

Appendix A. Relevant Sections for Different Stakeholders

The overall document is intended to provide a broad survey of key issues in energy storage safety in the United States. This appendix is intended to support various stakeholder groups in parsing this document by identifying which sections contain information that is most relevant to them.

A.1 Energy Storage Project Developers

The following sections in the report are most relevant for energy storage developers who are seeking to advance new projects:

- Section 4 "Safety considerations during energy storage deployment" describes general considerations for safely deploying energy storage in the US, including the development of safety codes and standards, the process for project execution, permitting and zoning requirements, and insurance.
- Section 5.3 "Engineering controls and system design" covers common practices and emerging guidance in the design of systems containing Li-ion cells.
- Section 7 "Evaluating emerging electrochemical technologies" highlights the importance and general process for assessing the risks of beyond lithium-ion technologies.

A.2 Codes & Standards Contributors

The following sections in the report are most relevant for individuals who provide input to new codes and standards:

- Section 8.3 "Summary of gaps: codes, standards, and regulations" describes gaps in existing standards identified by a broad cross-section of stakeholders during the 2023 Energy Storage Systems Safety and Reliability Forum. This section touches on gaps in electrical safety, fire safety, system reliability, and land use permitting.

A.3 State and Local Regulatory and Policy Community

The following sections in the report are most relevant for individuals who contribute to the development of regulations and policies at the state and local level:

- Section 4 "Safety considerations during energy storage deployment" describes general considerations for safely deploying energy storage in the US, including the development of safety codes and standards, the process for project execution, permitting and zoning requirements, and insurance.
- Section 8.3.4 "Summary of gaps: land use permitting" describes gaps in existing approaches to land use permitting identified by a broad cross-section of stakeholders during the 2023 Energy Storage Systems Safety and Reliability Forum.

A.4 First Responders

The following sections in the report are most relevant for individuals who are the first line of response whenever there are incidents involving fielded energy storage systems:

- Section 6 “Incident response for Li-ion batteries” covers lessons learned from recent incidents and how notable incidents have led to significant policy changes in the energy storage community.
- Section 8.2 “Summary of gaps: incident response and training” describes gaps in incident response identified by a broad cross-section of stakeholders during the 2023 Energy Storage Systems Safety and Reliability Forum. The gap areas identified for incident response generally fall into three categories: increasing knowledge about ESS safety prior to an incident, increasing situational awareness during an incident, and managing the aftermath of an incident.

Appendix B. Sample Incident Response Guidance

This sample Standard Operating Procedure has been designed to provide an example for agencies to adopt and modify as necessary, as it pertains to responding to incidents involving batteries. The steps in this document represent best practices from field incidents as of the date of this publication.

This document had been developed with a risk-based approach in mind, considering indoor as the highest risk, and then outdoor incidents. Accordingly, separate response procedures are outlined for indoor and outdoor incidents. This approach is not based on type of battery/device (stationary ESS, electric vehicle, micromobility device, etc), rather the overall risk profile of the incident.

Purpose

To establish operational guidelines for effective response, mitigation, and safe operational procedures for battery failures in all formats; personal mobility, electric vehicles (EVs), and stationary storage systems.

Scope

This policy shall apply to all sworn XX Department personnel.

Authority

The fire chief authorizes the information within this policy.

Definitions

Battery Energy Storage System (BESS): Battery Energy Storage Systems, or BESS, are rechargeable batteries that can store energy from different sources and discharge it when needed. BESS consist of one or more batteries.

Personal Mobility Device: Potable electric mobility devices such as e-bikes, e-scooters, and e-unicycles.

Thermal Runaway: Lithium-ion (Li-ion) battery thermal runaway occurs when a cell, or area within the cell, achieves elevated temperatures due to thermal damage, mechanical damage, internal/external short circuiting, or electrochemical abuse. This elevated temperature releases energy which in turn further increases temperature. It is a phenomenon known as a positive feedback loop in which the lithium-ion cell enters an uncontrollable, self-heating state.

Propagation: The spreading of *fire* between *Lithium*-ion battery cells initiated by a thermal runaway.

Policy

A. PPE
    1. Wear self-contained breathing apparatus (SCBA).
    2. Wear structural firefighting gear.

B. Determine if device is located indoors or outdoors.
    1. Devices or systems located indoors may represent a life safety priority and do represent exposure risks to the structure.
    2. Outdoor installations may support a defensive operation where no life safety rescue exist.

C. Signs of possible Battery Failure

1. Visible gas, popping sounds, or suspicious odor emanating from an electrified device can be an indication of an abnormal and hazardous condition.
2. Battery thermal runaway fires are frequently preceded by visible gas vapors.
3. Do not rely on thermal imaging cameras as the sole source of identifying battery failure.
4. The absence of flaming or gases/smoke does not indicate there is no event. Flaming and off-gassing may be intermittent over minutes, hours, or days.

D. Outdoor Incidents.
1. Stage engines upwind of event.
2. Complete area size-up and establish hazmat exclusion zone and water supply.
3. Evacuate the area of all non-emergency personnel and consider evacuation/shelter-in-place for the public.
4. If fire, gas vapors, popping sounds, or suspicious odor is observed emanating from the product at any time, perform the following:
5. If possible, shut off the unit/system. Note: It is not possible to discharge all energy from battery cells. The goal is to isolate the battery from charging/discharging.
6. For stationary BESS incidents determine if any provided exhaust systems are operating.
7. Do not approach the unit and attempt to open any doors. BESS have a variety of safety mechanisms. Some are designed to maintain the doors shut, and some have automatic doors designed to aid in ventilation.
8. For stationary BESS incidents, if not already done, contact the site emergency contact and/or manufacturer.
9. For electric vehicles, identify make, model, and year, and locate Emergency Vehicle Field Guide.
10. There may be periods of during which the thermal runaway propagates from battery modules to battery modules. During such time, the battery may not generate visible signs of thermal event although the event can still be active, and the battery can flare up.
11. If a fire has not developed: be aware of explosion risks and remain up wind of gas cloud.
12. If a fire develops:
    i. Allow the affected unit to consume itself as it is designed to do. Applying water to the burning unit will only slow its eventual combustion.
    ii. If exposure protection is required, use wide-fog stream, at lowest volume possible, to achieve desired cooling of exposures including neighboring battery enclosures. Be cautious of potential for water ingress to result in additional battery damage.
13. Allow the battery pack to cool down (this process may take multiple days) prior to opening of any doors.

E. Indoor Incidents
1. Identify the presence of any visible gas cloud and recognize the potential for explosion risk. Ventilation is key.
2. Rescue if required.

3. Secure building utilities to isolate any connected and charging or discharging battery devices or ESS.
4. Fire suppression strategy & tactics as directed to protect exposures.

F. Overhaul
   1. Perform search for stray battery cells that could re-ignite during overhaul operations.
   2. When packing damaged batteries in noncombustible containers for hazardous material transport ensure damaged batteries are overpacked with an appropriate material.
   3. Implement solutions for storage of EVs and personal mobility devices that will allow the battery to be placed in a safe state prior to transport and disposal. Potential options include:
      i. Appropriately sized open top trailer/tank for submersion of EV or mobility device in water.
      ii. Appropriately sized open top trailer/tank for covering EV or mobility device in sand. Procure necessary equipment such as front-end loaders and fork lifts to move equipment and sand. Procure sand in advance or have a vendor ready.
   4. Pre-plan for transport of affected battery off-site for disposal. This could include coordinating with transportation vendors with requisite capabilities or procuring appropriate equipment for site use.