ENERGY STORAGE SAFETY STRATEGIC PLAN

U.S. Department of Energy
Office of Electricity Delivery and Energy Reliability

December, 2014

Energy Storage Safety Strategic Plan

U.S. Department of Energy

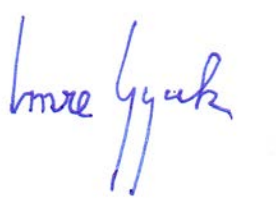
Office of Electricity Delivery and Energy Reliability

December, 2014

Acknowledgements

The Department of Energy Office of Electricity Delivery and Energy Reliability would like to acknowledge those who participated in the 2014 DOE OE Workshop for Grid Energy Storage Safety (Appendix A), as well as the core team dedicated to developing this report to address the safety of grid energy storage systems: Sean J. Hearne, Summer Ferreira, Mark Smith, Abbas Akhil & Amanda Spinney (Sandia National Laboratories); Landis Kannberg, Vincent Sprenkle, & David Conover (Pacific Northwest National Laboratory); Matthew Paiss (International Association of Fire Fighters); Michael A. Stosser (Sutherland Asbill & Brennan LLP); Robert S. Fleishman (Morrison & Foerster LLP).

Additionally, the Department of Energy Office of Electricity Delivery and Energy Reliability would like to acknowledge the generous efforts made to review the document from all the members of the 2014 DOE OE Workshop for Grid Energy Storage Safety (Appendix A), the members of the EPRI ESIC Working Group 3, and specifically Ken Willette (National Fire Protection Agency), Ryan Franks (National Electrical Manufacturers Association), Dean E. Philips & Conrad Eustis (Electric Power Research Institute), Jim Arseneaux (Beacon Power, LLC), Davion Hill (DNV-GL), Hiroyuki Kubo (Incorporated Administrative Agency, National Institute of Technology and Evaluation of Japan), and Nanamori Yasuyuki (Mitsubishi Research Institute, Inc.).



Dr. Imre Gyuk
Program Manager
Energy Storage Research
Office of Electricity Delivery and Energy Reliability
U.S. Dept. of Energy

Contents

Table of Figures

Tables

Executive Summary

Energy storage is emerging as an integral component to a resilient and efficient grid through a diverse array of potential application. The evolution of the grid that is currently underway will result in a greater need for services best provided by energy storage, including energy management, backup power, load leveling, frequency regulation, voltage support, and grid stabilization.[1] The increase in demand for specialized services will further drive energy storage research to produce systems with greater efficiency at a lower cost, which will lead to an influx of energy storage deployment across the country. To enable the success of these increased deployments of a wide variety of storage technologies, safety must be instilled within the energy storage community at every level and in a way that meets the need of every stakeholder.

In 2013, the U.S. Department of Energy released the Grid Energy Storage Strategy[2], which identified four challenges related to the widespread deployment of energy storage. The second of these challenges, the validation of energy storage safety and reliability, has recently garnered significant attention from the energy storage community at large.[3] This focus on safety must be immediately ensured to enable the success of the burgeoning energy storage industry, whereby community confidence that human life and property not be adversely affected is instilled from the earliest stages.[4] The resultant increase in consumer confidence in energy storage will ease and facilitate the expansion of energy storage's deployment, allowing for the electric grid to meet the ever-expanding needs of the consumer.

The safe application and use of energy storage technology knows no bounds. An energy storage system (ESS) will react to an external event, such as a seismic occurrence, regardless of its location in relation to the meter or the grid. Similarly, an incident triggered by an ESS, such as a fire, is 'blind' as to the location of the ESS in relation to the meter. This document will address grid-side safety, while recognizing that the efforts undertaken will apply to other ESS applications, regardless of deployment location.

---

1 Grid Energy Storage Strategy. U.S. Department of Energy, Dec. 2013.

2 Grid Energy Storage Strategy. U.S. Department of Energy, Dec. 2013, p. 5.

3 DOE OE Energy Storage Safety Workshop, Albuquerque, NM. 2014.

4 Gyuk, Imre. "Energy Storage Safety: An Essential Concern." DOE OE Energy Storage Safety Workshop, Feb. 2014.

Each stakeholder group has a specific motivation for pursuing energy storage safety. Manufacturers are producing an increasing number of systems and system components to meet a growing demand for energy storage and must be confident in the safety of these products. Regulators are required to address the system installations in terms of application space, ownership, risk, and potential litigation. Insurers must develop applicable risk assessments and first responders must be able to safely and successfully respond to any incidents.

The actions, responsibilities, and concerns of each stakeholder group are all interconnected. The science-based techniques used to validate the safety of energy storage systems must be documented a relevant way, that includes every level of the system and every type of system. These science-based safety validation techniques will be used by each stakeholder group to ensure the safety of each new energy storage system deployed onto the grid. Once researchers establish science-based validation and mitigation techniques, manufacturers will have guidelines that support the construction of systems that can be validated as safe. With standardized guidelines for safe component and system construction, regulators and insurance companies will be able to fully assess the risk of owning and insuring each system. Additionally, first responders must be included in the discussion to ensure that all areas of potential failure are identified and the best mitigation strategies are developed, spanning the chemistries and materials choices through components, module layouts and deployment.

Safety of any new technology can be broadly viewed as having three intimately-linked components: 1) a system must be engineered and validated to the highest level of safety possible; 2) techniques and processes must be developed for responding to incidences if they do occur; and 3) the best practices and system requirements must then be reflected standardized safety determinations in the form of codes, standards and regulations (CSR) so that there is uniform, written guidance for the community to follow when designing, building, testing and deploying the system. When successful, CSRs apply the best-known practices for safety to a system. The predictability of real-time operation, and therefore safety, is improved when systems are designed with similar system requirements.

A thread of complexity running through all three of the components of safety (i.e. validation techniques, incident response and safety documentation) is an ever increasingly diverse portfolio of technologies and the wide array of potential deployment environments. To provide the greatest impact, the validation techniques discussion presented in this document focuses primarily on batteries, with some discussion of flywheels, as these two technologies are undergoing rapid evolution and growth in the deployment.

Safety documentation provides guidance to the energy storage community in the form of codes, standards, and regulations. Two crucial considerations must be taken into account surrounding the adoption and administration of standards. First, system owners must understand which codes and standards are necessary before and after the installation of energy storage systems. Second, the parties responsible for the oversight, regulation and response must be identified. This identification will ensure a clear path of communication between owners, regulators and responders to best prevent any potential incident. Both of these considerations will make the installation process efficient and cost effective for owners, ensure that all responsible parties are communicating to best avoid an incident, and ensure effective incident response. They will also clearly outline risk, which will enable the application of effective risk mitigation and risk management measures. These safety documents will be informed by the science-based validation techniques established through research and development. This work will provide the basis for the protocols and design in the codes and standards and will meet the needs to minimize loss and protect the first responders.

The goal of this DOE Office of Electricity Delivery and Energy Reliability (OE) Strategic Plan for Energy Storage Safety is to develop a high-level roadmap to enable the safe deployment energy storage by identifying the current state and desired future state of energy storage safety. To that end, three interconnected areas are discussed within this document:

Science-based Safety Validation Techniques:

- Most of the current validation techniques that have been developed to address energy storage safety concerns have been motivated by the electric vehicle community, and are primarily focused on Li-ion chemistry and derived via empirical testing of systems. Additionally, techniques for Pb-acid batteries have been established, but must be revised to incorporate chemistry changes within the new technologies. Moving forward, all validation techniques must be expanded to encompass grid-scale energy storage systems, be relevant to the internal chemistries of each new storage system and have technical bases rooted in a fundamental-scientific understanding of the mechanistic responses of the materials. Experimental research and development efforts to inform models from cell to system scale must be the basis of the next generation of validation techniques needed for the new grid-scale storage systems, as empirically derived tests are not sufficient to ensure safety.

Incident Preparedness:

- First responders will be called upon to respond to an incident should it occur to protect the lives of anyone involved and minimize the damage to assists. Therefore, there must be a deliberate and concerted effort to engage the first responder community early in the design and siting of energy storage systems so that proper mitigation techniques can be developed and systems designed to improve the overall safety and ability to quickly and safety resolve the incident. This must include the development of techniques to extinguish any fires if they were to occur and respond to the variety of non-fire incidents that may require fire department response, developing site specific training for first responders, improved systems design, and the development of incident response plans. All of these must be based on the scientific understanding of the systems, materials and processes and embodied in the criteria in codes, standards and regulations.

Safety Documentation:

- Currently, safety-related criteria in the form of codes, standards and regulations that apply to system components and deployments need to be updated to reflect the growing verity of storage technologies. This documentation is not specific to the multitude of chemistries and assembled modules that compose the new storage systems being deployed. As a result, CSR are inefficient and ineffective and must be updated and standardized.

This document additionally highlights four key elements around which DOE efforts will revolve.

DOE programmatic efforts will focus on four elements:

- ESS safety technology
- Risk assessment and management
- Incident response

- Codes, standards and regulations

To ensure the thorough establishment of the scientific and technical basis for ESS safety in each technology, information concerning all safety hazards must be gathered and categorized. Testing and analysis procedures will then be defined in such a way that enables stakeholders to use them for each major class of ESS. Within risk assessment and management, the goal is that the framework and methodologies for assessing and managing deployment risk for ESS are accepted and adopted by industrial and regulatory stakeholders. Towards this end, current frameworks will be catalogued, and a model risk framework will be identified for specific ESS technologies. The ultimate goal for first and second responders is the complete awareness of hazards and the ability to address them in the field. Finally, it is the goal that codes, standards and regulations enable the deployment of safe ESS. Gaps in CSR that require additional technical research, development, and demonstration will be identified and addressed.

1.0 Introduction and Motivation

Grid energy storage systems are "enabling technologies"; they do not generate electricity, but they do enable critical advances to modernize the electric grid. For example, there have been numerous studies that have determined that the deployment of variable generation resources will impact the stability of grid unless storage is included.[5] Additionally, energy storage has been demonstrated to provide key grid support functions through frequency regulation.[6] The diversity in the performance needs and deployment environments drive the need of a wide array of storage technologies. Often, energy storage technologies are categorized as being high-power or high-energy. This division greatly benefits the end user of energy storage systems because it allows for the selection of a technology that fits an application's requirements, thus reducing cost and maximizing value. For example, frequency regulation requires very rapid response, i.e. high-power, but does not necessarily require high energy. By contrast, load-shifting requires very high-energy, but is more flexible in its power needs. Uninterruptible power and variable generation integration are applications where the needs for high-power versus high-energy fall

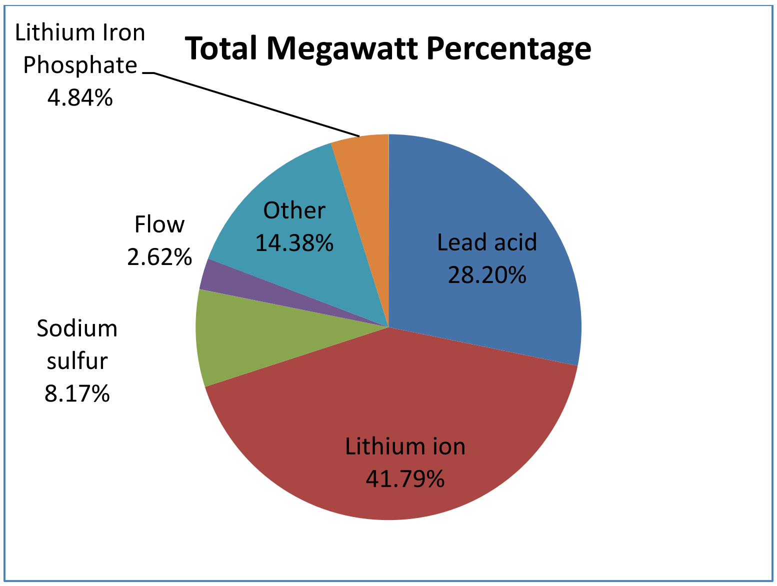
---

[5] Denholm, Paul; Ela, Erik; Kirby, Brendan; Milligan, Michael. "The Role of Energy Storage with Renewable Electricity Generation." National Renewable Energy Laboratory Technical Report: NREL/TP-6A2-47187. Jan 2010.

[6] Arseneaux, Jim. "20 MW Flywheel Frequency Regulation Plant (Hazle Spindle)." Beacon Power, LLC. EESAT Conference. Oct 2013.

somewhere in between the aforementioned extremes. Figure 1 shows the current energy storage techniques deployed onto the North American grid.[7] This variety in storage technologies increases the complexity in developing a single set of protocols for evaluating and improving the safety of grid storage technologies and drives the need for understanding across length scales, from fundamental materials processes through full scale system integration.

Figure 1. Percentage of Battery Energy Storage Systems Deployed[8]



The variety of deployment environments and application spaces compounds the complexity of the approaches needed to validate the safety of energy storage systems. The difference in deployment environment impacts the safety concerns, needs, risk, and challenges that affect stakeholders. For example, an energy storage system deployed in a remote location will have very different potential impacts on its environment and first responder needs than a system deployed in a room in an office suite, or on the top floor of a building in a city center. The closer the systems are to residences, schools, and hospitals, the higher the impact of any potential incident regardless of system size. Therefore, it is critical that the safety risk of each system be mitigated and the appropriate responder preparedness tailored to the specific risks, exposured

---

[7] DOE Global Energy Storage Database. July 2014.

[8] "Total Megawatt Percentage" includes contracted batteries as well as batteries with verification in progress. "Other" includes ultrabatteries, nickel ion, nickel cadmium, lithium polymer, lithium nickel cobalt aluminum, sodium nickel chloride, lithium ferrous phosphate, lead carbon, hybrid, and aqueous hybrid ion.

population and infrastructure, which reduces the potential losses and is key in determining the overall cost of ownership.

The discussion within this document explores the current landscape of energy storage deployments and technologies and identifies specific areas in validation techniques, incident response and safety codes, standards and regulations (CSR) where the community should focus its efforts. Ultimately, it is the goal of this strategic plan to lay the groundwork necessary to ensure the safety of energy storage deployments and instill confidence in the community of stakeholders who depend on an efficient, reliable and resilient electric grid.

2.0 Current State of Energy Storage Technologies

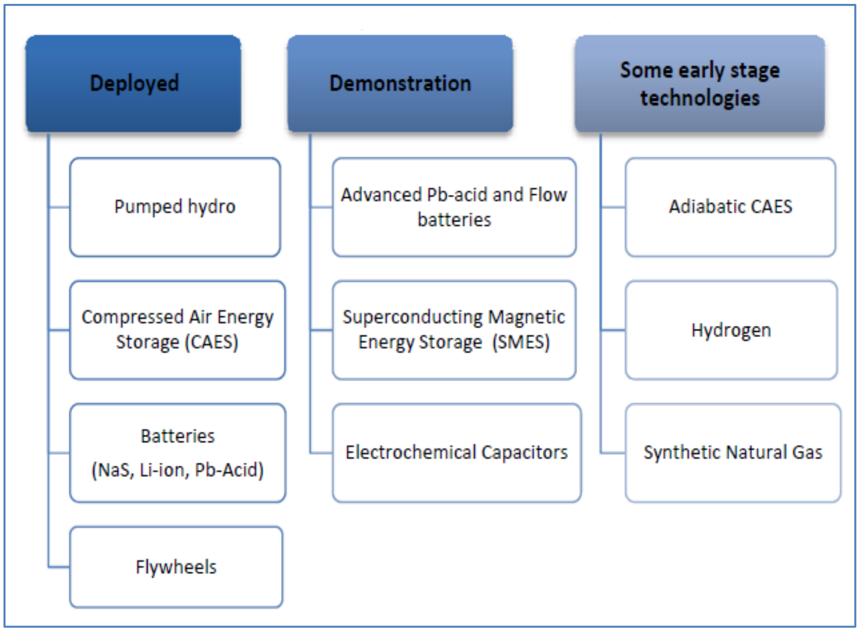
Each storage technology has unique performance characteristics that make it optimally suitable for certain grid services; however, the technologies are each at different maturity levels and are each deployed in varying amounts. These differences must be taken into consideration when addressing safety because the level of risk increases as the level of maturity decreases or the level of deployment increases. The different levels of maturity and deployment also illustrate which systems must immediately be validated as safe. As per the DOE Grid Strategy, "the categorization of 'deployed,' 'demonstrated,' and 'early stage,' is often blurred, and changes over time. Figure 2 lists technologies based on their present degree of adoption."[9]

Pumped hydro is one of the oldest and most mature energy storage technologies and represents 95% of the installed storage capacity. Other storage technologies, such as batteries, flywheels and others, make up the remaining 5% of the installed storage base, are much earlier in their deployment cycle and have likely not reached the full extent of their deployed capacity. Among these deployed storage technologies, this DOE OE Strategic Plan for Energy Storage Safety will focus primarily on batteries, with some attention to flywheels due to the rapid growth seen in these two relatively new grid-scale technologies.

---

[9] Grid Energy Storage Strategy. U.S. Department of Energy, Dec. 2013, p. 16.

Figure 2. Maturity of Electricity Storage Technologies



.

2.1 Pumped Hydro Storage

Pumped hydro is so established as a deployed storage technology that this is not a focus technology for addressing safety concerns. With over 100 GW of installed capacity in the world, and the first hydroelectric plants opening in the 1800s, the technology is well understood without large uncertainty remaining concerning its safety and reliability.

2.2 Compressed Air Energy Storage (CAES)

Although CAES is an earlier stage technology, the mechanics of conventional CAES have characteristics analogous to many commercial industrial processes, such as conventional piping and fittings. Established safety codes address the above-ground CAES pressure vessel concerns which are well mitigated with pressure relief valves implemented at pressures equal to 40% of the rupture pressure in steel vessels and 20% of the rupture pressure for fiber-wound vessels, as defined by code. Such established safety protocols in industry result in reduced concerns and uncertainly with respect to safety in CAES deployments.

2.3 Superconducting Magnetic Energy Storage (SMES)

SMES technology uses a superconducting coil to store DC current. As an early stage technology, it has not proven itself to be a viable piece of the bulk storage market for deployed technologies. As such, is not addressed in this strategy.

2.4 Flywheels

Though flywheels are relative newcomers to the grid energy storage arena, they have been used as energy storage devices for centuries with the earliest known flywheel being from 3100 BC Mesopotamia. Grid scale flywheels operate by spinning a rotor up to tens of thousands of RPM storing energy in a combination of rotational kinetic energy and elastic energy from deformation of the rotor. These systems typically have large rotational masses that in the case of a catastrophic radial failure need a robust enclosure to contain the debris. However, if the mass of the debris particles can be reduced through engineering design, the strength, size and cost of the containment system can be significantly reduced. For example, laminated flywheels where the bonding strength of the layers is lower that the tensile strength within a layer will "unwind" rather than throw off large arc sections of the rotor material. The engineering designs and safety factors in containing flywheels are not currently widely established by the CSRs and require further research. Current safety validation testing involves burst testing to probe containment integrity, loss-of-vacuum testing, overspeed testing of systems, as well as fatigue testing of sample materials. [10]

2.5 Capacitors

Electrochemical capacitors prompt similar concerns in terms of the safety of the stored energy within an electrochemical device and failures of devices. They are not therefore addressed independently here, but they do deserve attention in understanding and addressing safety for grid storage. Validation techniques can be considered in the context of approaches taken for battery safety.

---

[10] Flynn, M. M., Zierer J. J., Thompson, R. C. "Performance Testing of a Vehicle Flywheel Energy System" SAE Technical Paper Series. 2005. http://www.utexas.edu/research/cem/Energy_storage_photos/2005_Performance%20Testing%20of%20a%20Vehicular%20Flywheel%20Energy%20System%202005-01-0809.pdf

Electrostatic and electrolytic capacitors are used in board design and are a very common cause of faults that can lead to cascading failure resulting in voltage and or current surges and overcharge of storage devices or temperature rises that can lead to ignition of flammable materials either within the capacitor or adjacent components.

2.6 Batteries

As electrochemical technologies, battery systems used in grid storage can be further categorized as redox flow batteries, hybrid flow batteries, and secondary batteries without a flowing electrolyte. For the purposes of this document, vanadium redox flow batteries and zinc bromine flow batteries are considered for the first two categories, and lead-acid, lithium ion, sodium nickel chloride and sodium sulfur technologies in the latter category. As will be discussed in detail in this document, there are a number of safety concerns specific to batteries that should be addressed, e.g. release of the stored energy during an incident, cascading failure of battery cells, and fires.

3.0 State of Safety Validation in the U.S.

Several significant issues in the current state of safety validation that must be addressed, including: passive safety plans, reactionary safety approaches, and ineffective first response procedures. First, the typical safety plan is passive, i.e. addressing each deployed system on a case-by-case basis rather than having global standards and protocols for safety. Historically, technology has typically led regulations, i.e. each installation of megawatt-sized, battery-based energy storage systems since the 1980s has marked a technological milestone in the development and understanding of the operational characteristics of such large-scale battery systems. Because each installation was unique in size, functionality, and design, the unifying safety validation techniques and national CSR for the integrations and use of full systems was absent. While there are substantial CSR in existence for individual components within a storage system, current safety documents must now be updated to address the entire integrated system in order to fully validate its operational safety. Overall system safety is still determined on an installation-by-installation basis by the system vendor (either the system manufacturer or the system installer) who is charged with satisfying owner requests and meeting any applicable CSR on behalf of the owner. The CSR currently available and directives guide the approach to safety of systems on the grid side of the meter. However, fire marshals typically have little oversight of activities on the grid side of the meter, which is typically under the jurisdiction of the public utilities commission. On the customer side, a similar approach is found, but is based on enforcement of adopted CSR by state and local agencies. This individualized approach for evaluating safety is the current *modus operandi* and ultimately hinders the time and cost of deploying systems.

Second, safety approaches are reactionary instead of proactive and predictive, thus unnecessarily increasing costs with irrelevant and ineffective techniques. Energy storage systems manufacturers, owners, and installers will use validation techniques for new systems based on previous installation experience, disregarding differences in system type, battery chemistry, total capacity, or deployment environment. The result of this approach is that the validation techniques are not comprehensive, though substantial amounts of money and time are spent to initiate them. An example of ineffective safety validation can be found in method used by the Puerto Rico Electric Power Authority (PREPA) to install a 20 MW/17 MWh spinning reserve/frequency regulation battery system in 1994.[11] This installation was patterned after a similarly-sized, flooded-cell, lead-acid battery system installed at the West Berlin Electric Utility Company (BEWAG) in Berlin in 1986.[12] Even though the PREPA installation was fashioned after the BEWAG system, the local fire marshal in San Juan determined that the mandatory safety requirements at the PREPA installation were significantly different. Differences in the battery chemistry, the application space, and the deployment environment between the two systems were not accounted for before PREPA was installed. This initial oversight resulted in costly additional risk mitigation measures. PREPA was required to provide a structural design on the second floor, which housed the battery, as a virtual swimming pool to hold all the water required to extinguish a potential fire. In addition, PREPA was required to store on site a large quantity of water for firefighting, along with its necessary pumping infrastructure. The additional cost and space requirements, caused by the altered structural design of the building, dramatically increased the deployment cost.

System owners are often required to establish a safety margin based on their best engineering guess rather than on scientifically derived validation techniques developed from an

---

[11] Farber-DeAnda, Mindi. Boyes, John D. Wenceslao, Torres. "Lessons Learned from the Puerto Rico Battery Energy Storage System." Sandia National Laboratories, 1999.

[12] Wagner, Richard. "High-power lead-acid batteries for different applications." Journal of Power Sources, Nov. 2004. p 496.

understanding of the active processes and limitations of the system, as was the case with the PREPA system. As safety validation techniques are developed, validated, and documented for each type of storage technology in every potential deployment environment, system owners will be able to accurately estimate the full cost of each deployed system, including the risks associated with insuring the installation. Significant decreases in uncertainty and gains in process efficiencies will be the results of the development and documentation of these validation techniques. Additionally, standard validation and deployment techniques can be used to improve the safety and knowledge base of the first responders.

The third issue is that the historic and current first response procedures have also suffered as a result of reactive, ineffective safety validation techniques and lack of standardized documentation. Often, due to a lack of local experience in such events, response practices are based on events that occurred in different technologies, but were reported nationally. In the late 1980s, the question of fire safety arose concerning the lead-acid inside the containerized battery system PM250. The enclosed container design had to allow for the safe and fail-safe venting of hydrogen emitted during charging. Consideration was also given to how a first responder could look inside the container to observe the interior condition without opening the container's large doors.[13] However, neither design decision was addressed by the governing safety code, which lacked specifications about the design of hydrogen venting or the size and location of the glass portholes.

A reactive approach to energy storage safety is no longer viable. The number and types of energy storage deployments have reached a tipping point with dramatic growth anticipated in the next few years fueled in large part by major, new, policy-related storage initiatives in California[14], Hawaii[15], and New York.[16] The new storage technologies likely to be deployed in

---

[13] Corey, Garth; Nerburn, William; Porter, David. "Final Report on the Development of a 250-kW Modular, Factory-Assembled Battery Energy Storage System." Sandia National Laboratories, 1998.

[14] Program Opportunity Notice: "Developing Advanced Energy Storage Technology Solutions to Lower Costs and Achieve Policy Goals," PON-13-302. http://www.energy.ca.gov/contracts/PON-13-302/00_PON-13-302_Energy_Storage_2014-07-31.pdf

[15] Hawaiian Electric. O'ahu Energy Storage System, Request for Proposals No. 072114-01. http://www.hawaiianelectric.com/vcmcontent/StaticFiles/pdf/ESS_RFP_No_072114-01.pdf

[16] Reforming the Energy Vision: NYS Department of Public Service Staff Report and Proposal. Case 14-M-0101. 2014. http://www3.dps.ny.gov/W/PSCWeb.nsf/96f0fec0b45a3c6485257688006a701a/26be8a93967e604785257cc40066b91a/$FILE/ATTK0J3L.pdf/Reforming%20The%20Energy%20Vision%20%28REV%29%20REPORT%204.25.%2014.pdf

response to these and other initiatives are maturing too rapidly to justify moving ahead without a unified scientifically based set of safety validation techniques and protocols. A compounding challenge is that startup companies with limited resources and experience in deployment are developing many of these new storage technologies. Standardization of the safety processes will greatly enhance the cost and viability of new technologies, and of the startup companies themselves. The modular nature of ESS is such that there is just no single entity clearly responsible for ESS safety; instead, the each participant in the energy storage community has a role and a responsibility. The following sections outline the gaps in addressing the need for validated grid energy storage system safety.

4.0 Key Aspects for Addressing Energy Storage Safety

Safety of any new technology can be broadly viewed as having three intimately linked aspects, as follows: 1) the system must be engineered and validated to the highest level of safety; 2) techniques and processes must be developed to respond to incidents when they occur; and 3) best practices and system requirements must then be reflected in CSR so that there is uniform, consistent, understandable and enforceable criteria that must be satisfied when designing, building, testing, and deploying the system. It is clear within the grid energy storage community that specific efforts must be started or expanded to address each of these three areas.[17] Specifically, as the materials, technologies, and deployment applications for storing energy are created, new techniques and protocols must be developed to validate their safety and ensure the risk of failure and loss is minimized. These new techniques and protocols will allow manufacturers to design the systems to be as safe as possible, especially for the first and second responders. These techniques will additionally be used to educate first responders on the associated risk of responding to an incident involving the new technologies. Finally, codes, standards, and regulations will be developed to efficiently memorialize these design rules, response procedures and safety performance metrics to all stakeholders.

[17] DOE OE Energy Storage Safety Workshop, Albuquerque, NM. 2014.

5.0 Validation Techniques

To date, the most extensive energy storage safety and abuse R&D efforts have been done for Electric Vehicle (EV) battery technologies. These efforts have been limited to lithium ion, lead-acid and nickel metal hydride chemistries and, with the exception of grid-scale lead-acid systems, are restricted to smaller size battery packs applicable to vehicles.[18] Lessons learned from EV safety R&D can be useful in developing the grid storage energy storage safety area, and in fact, the use of EV batteries that are beyond their automotive service life in grid storage is emerging as a viable second life. However, the increased scale, complexity, and diversity in technologies being proposed for grid- scale storage necessitates a comprehensive strategy for adequately addressing safety in grid storage systems. The technologies deployed onto the grid fall into the categories of electro-chemical, electromechanical, and thermal, and are themselves within different categories of systems, including CAES, flywheels, pumped hydro and SMES. This presents a significant area of effort to be coordinated and tackled in the coming years, as a number of gap areas currently exist in codes and standards around safety in the field. R&D efforts must be coordinated to begin to address the challenges.

5.1 Current Validation Techniques

An energy storage system can be categorized primarily by its power, energy and technology platform. For grid-scale systems, the power/energy spectrum spans from smaller kW/kWh to large MW/MWh systems. Smaller kW/kWh systems can be deployed for residential and community storage applications, while larger MW/MWh systems are envisioned for electric utility transmission and distribution networks to provide grid level services. This is in contrast to electric vehicles, for which the U.S. Advanced Battery Consortium (USABC) goals are both clearly defined and narrow in scope with an energy goal of 40 kWh. While in practice some EV packs are as large as 90 kWh, the range of energy is still small compared with the grid storage applications. This research is critical to the ability of first responders to understand the risks posed by ESS technologies and allow for the development of safe stratagies to minimize risk and mitigate the event.

---

[18] Doughty, Daniel H.; Pesaran, Ahmad A. "Vehicle Battery Safety Roadmap Guidance." National Renewable Energy Laboratory. Oct. 2012. http://www.nrel.gov/docs/fy13osti/54404.pdf

Table 1. Range of Storage Technology and Size

Storage space	Technologies	Application	Storage Size (energy)	Storage Size (power)
Electric Vehicle Technology	Batteries (Li-ion, NiMH, Pb-acid)	City and highway driving	40 – 90 kWh	80 kW[19]
Stationary Storage	Batteries, CAES, flywheels, pumped hydro and SMES	Over 17 use cases identified[20]	5 kWh – 1 GWh[21]	10 kW – 1 GW

Furthermore, the diversity of battery technologies and stationary storage systems is not generally present in the EV community. Therefore, the testing protocols and procedures used historically and currently for storage systems for transportation are insufficient to adequately address this wide range of storage systems technologies for stationary applications. Table 1 summarizes the high level contrast between this range of technologies and sizes of storage in the more established area of EV. The magnitude of effort that must be taken on to encompass the needs of safety in stationary storage is considerable because most research and development to improve safety and efforts to develop safety validation techniques are in the EV space.

Notably, the size of EV batteries ranges by a factor of two; by contrast, stationary storage scales across many orders of magnitude. Likewise, the range of technologies and uses in stationary storage are much more varied than in EV. Therefore, while the EV safety efforts pave the way in developing R&D programs around safety and developing codes and standards, they are highly insufficient to address many of the significant challenges in approaching safe development, installation, commissioning, use and maintenance of stationary storage systems.

[19] Mackenzie, Angus. "2013 Motor Trend Car of the Year: Tesla Model S. Motor Trend. 2013.

[20] Akhil, Abbas; et al. "DOE/EPRI 2013 Electricity Storage Handbook in Collaboration with NRECA." Sandia National Laboratories. July 2013.

[21] The Tesla Motors Team. "A Supercharging Milestone." Tesla Motors. July 2014.

An additional complexity of grid storage systems is that the storage system can either be built on-site or pre-assembled, typically in shipping containers. These pre-assembled systems allow for factory testing of the fully integrated system, but are exposed to potential damage during shipping. For the systems built on site, the assembly is done in the field; much of the safety testing and qualification could potentially be done by local inspectors, who may or may not be as aware of the specifics of the storage system. Therefore, the safety validation of each type of system must be approached differently and each specific challenge must be addressed.

5.2 Areas of Interest in Safety Validation

Given the maturity and documented use of pumped hydro and CAES, batteries and flywheels are currently the primary focus for enhanced grid-scale safety. For these systems, the associated failure modes at grid-scale power and energy requirements have not been well characterized and there is much larger uncertainty around the risks and consequences of failures. This uncertainty around system safety can lead to barriers to adoption and market success, such as difficulty with assessing value and risk to these assets, and determining the possible consequences to health and the environment. To address these barriers, concerted efforts are needed in the following areas:

- Materials Science R&D – Research into all device components
- Engineering controls and system design
- Modeling
- System testing and analysis
- Commissioning and field system safety research

It is a notable challenge within the areas outlined above to develop understanding and confidence in relating results at one scale to expected outcomes at another scale, or predicting the interplay between components, as well as protecting against unexpected outcomes when one or more failure mode is present at the same time in a system. Extensive research, modeling and validation are required to address these challenges. Furthermore, it is necessary to pool the analysis approaches of failure mode and effects analysis (FMEA) and to use a safety basis in both research and commissioning to build a robust safety program. Furthermore, identifying, responding and mitigating to any observed safety events are critical in validating the safety of storage.

A holistic view with regard to setting standards to ensure thorough safety validation techniques is the desired end goal; the first step is to study on the R&D level failure from the cell to system level, and from the electrochemistry and kinetics of the materials to module scale behavior. Detailed hazards analysis must be conducted for entire systems in order to identify failure points caused by abuse conditions and the potential for cascading events, which may result in large scale damage and/or fire. While treating the storage system as a "black box" is helpful in setting practical standards for installation, understanding the system at the basic materials and chemistry levels and how issues can initiate failure at the cell and system level is critical to ensure overall system safety.

In batteries, understanding the fundamental electrochemistry and materials changes under selected operating conditions helps guide the cell level safety. Knowledge of cell-level failure modes and how they propagate to battery packs guides the cell chemistry, cell design and integration. Each system has different levels of risk associated with basic electrochemistry that must be understood; the tradeoff between electrochemical performance and safety must be managed. There are some commonalities of safety issues between storage technologies. For example, breeching of a Na/S (NAS) or $Na/NiCl_2$ (Zebra) battery could result in exposure of molten material and heat transfer to adjacent cells.[22,23,24] Evolution of H_2 from lead-acid cells or H_2 and solvent vapor from lithium-ion batteries during overcharge abuse could results in a flammable/combustible gas mixture.[25,26,27,28] Thermal runaway in lithium-ion (Li-ion) cells could transfer heat to adjacent cells and propagate the failure through a battery.[29] Moreover,

---

[22] "Cause of NAS Battery Fire Incident" NGK Insulators, LTD. June, 2012.

[23] A. V. Van Zyl; C.-H Dustmann (Nov. 1995). "Safety Aspects of Zebra High Energy Batteries," in Conference Proceedings, WEVA Conference for Electric Vehicle Research, Development and Operation, November 13, 14, 15, 1995; Paris. Bruxelles, Belgium. pp. 57–63.

[24] Current Status of Health and Safety Issues of Sodium/Metal Chloride (Zebra) Batteries" NREL/TP-460-25553. November, 1998.

[25] A. J. Salkind, A. G. Cannone, F. A. Trumbure in "The Handbook of Batteries" D. Linden and T. B. Reddy, 3rd Edition, 2002, pp. 23.77-23.78.

[26] A. W. Metwally "Generic environmental and safety assessment of five battery energy storage systems", Electr. Power Res. Inst. 1982

[27] D. P. Abraham, E. P. Roth, R. Kostecki, K. McCarthy, S. MacLaren, D. H. Doughty, "Diagnostic examination of thermally abused high-power lithium-ion cells" J. Power Sources, 161. 2006, pp. 648-657

[28] G. Nagasubramanian and C. J. Orendorff, "Hydrofluoroether electrotes for lithium-ion batteries: Reduces gas decomposition and nonflammable" J. Power Sources, 196. 2011, pp. 8604-8609.

[29] Mikolajczak, Celina; Kahn, Michael; White, Kevin; Long, Richard Thomas. "Lithium-Ion Batteries Hazard and Use Assessment." Exponent Failure Analysis Associates, Inc. July 2011.

while physical hazards are often considered, health and environmental safety issues also need to be evaluated to have a complete understanding of the potential hazards associated with a battery failure. These may include the toxicity of gas species evolved from a cell during abuse or when exposed to abnormal environments, [30,31] toxicity of electrolyte during a cell breech or spill in a Vanadium redox flow battery (VRB),[32] environmental impact of water runoff used to extinguish a battery fire containing heavy metals.[33] Flywheels provide an entirely different set of considerations, including mechanical containment testing and modeling, vacuum loss testing, and material fatigue testing under stress. A holistic approach needs to be taken to address all of the cell or component level through system-level safety issues with adequate mitigations, diagnostics, monitoring, and engineered controls.

Failure mode and effects analysis (FMEA) is conducted in installations. Research must consider current FMEA tactics specific to stationary storage, identify weaknesses in their execution with special attention to systems that have encountered field failure caused by abuse, and failures that were not well controlled, leading to cascading events resulting in large scale damage and/or fire. A comprehensive look at system level concerns with regard to failures and safety can be approached when R&D is incorporated into the standard basis for safety.

5.3 Materials Science R&D

The topic of Li-ion battery safety is rapidly gaining attention as the number of battery incidents increases. Recent incidents, such as a cell phone runaway during a regional flight in Australia and a United Parcel Service plane crash near Dubai, reinforce the potential consequence of Li-ion battery runaway events. The sheer size of grid storage needs and the operational demands make it increasingly difficult to find materials with the necessary properties, especially the required thermal behavior to ensure fail-proof operation. The main failure modes for these battery systems are either latent (manufacturing defects, operational heating, etc.) or abusive (mechanical, electrical, or thermal).

---

[30] A. J. Salkind, A. G. Cannone, F. A. Trumbure in "The Handbook of Batteries" D. Linden and T. B. Reddy, 3rd Edition, 2002, pp. 23.77-23.78.

[31] D. P. Abraham, E. P. Roth, R. Kostecki, K. McCarthy, S. MacLaren, D. H. Doughty, "Diagnostic examination of thermally abused high-power lithium-ion cells" J. Power Sources, 161. 2006, pp. 648-657.

[32] "Toxicology Profile for Vanadium" U.S. Department of Health and Human Services, Public Health Service, Agency for Toxic Substances and Disease Registry. September 2012.

[33] Wesoff, Eric. "Battery Room Fire at Kahuku Wind-Energy Storage Farm." Green Tech Grid. August 2012.

Any of these failures can increase the internal temperature of the cell, leading to electrolyte decomposition, venting, and possible ignition. While significant strides are being made, major challenges remain in combating solvent flammability still remain, which is the most significant area that needs improvement to address safety of Li-ion cells, and is therefore discussed here in greater detail. To mitigate thermal instability of the electrolyte, a number of different approaches have been developed with varied outcomes and moderate success. Conventional electrolytes typically vent flammable gas when overheated due to overcharging, internal shorting, manufacturing defects, physical damage, or other failure mechanisms. The prospects of employing Li-ion cells in applications depend on substantially reducing the flammability, which requires materials developments (including new lithium salts) to improve the thermal properties. One approach is to use fire retardants (FR) in the electrolyte as an additive to improve thermal stability. Most of these additives have a history of use as FR in the plastics industry. Broadly, these additives can be grouped into two categories—those containing phosphorous and that containing fluorine. A concerted effort to provide a hazard assessment and classification of the event and mitigation when an ESS fails, either through internal or external mechanical, thermal, or electrical stimulus is needed by the community.

Significant efforts have been made to develop tests to determine the safety margin in Li-ion batteries in both mobile devices and vehicles. For example, significant efforts have been made in the qualification of the response to battery cell thermal runaway, [34,35,36,37] safety response in packs to mechanically induced failure,[38] and model thermal abuse of cells.[39] A comprehensive report prepared by Exponent Failure Analysis Associate, Inc. for the Fire Protection Research Foundation provides a detailed review of validation techniques as part of the Lithium-Ion Batteries Hazard and Use Assessment.[40] This review and its references describe the state of

---

[34] J.R. Dahn, E.W. Fuller, M. Obrovac, U. Vonsacken. “Solid State Ionics.” 69. 1994, 265.
[35] D. Belov, M.H. Yang, “Solid State Ionics.” 179. 2008, 1816.
[36] D. Belov, M.H. Yang, J. “Solid State Electr.” 12, 2008, 885.
[37] S.J. Harris, A. Timmons, W.J. Pitz. “J Power Sources.” 193, 2009, 855.
[38] R.M. Spotnitz, J. Weaver, G. Yeduvaka, D.H. Doughty, E.P. Roth. “J Power Sources.” 163, 2007, 1080.
[39] G.H. Kim, A. Pesaran, R. Spotnitz. “J Power Sources” 170, 2007, 476.

understanding around battery failures and research into improved safety at that time, but are limited in the material systems and the size of the systems reviewed.

5.4 Electrolyte Safety R&D

The combustion process is a complex chemical reaction by which fuel and an oxidizer in the presence of heat react and burn. Convergence of heat (an oxidizer) and fuel (the substance that burns) must happen to have combustion. The oxidizer is the substance that produces the oxygen so that the fuel can be burned, and heat is the energy that drives the combustion process. In the combustion process a sequence of chemical reactions occur leading to fire.[41] In this situation a variety of oxidizing, hydrogen and fuel radicals are produced that keep the fire going until at least one of the three constituents is exhausted.

5.4.1 Electrolytes

Despite several studies on the issue of flammability, complete elimination of fire in Li-ion cells has yet to be achieved. One possible reason for the failure could be linked to lower flash point (F_P) (<38.7 °C) of the solvents.[42] Published data shows that polyphosphazene polymers and ionic liquids used as electrolytes are nonflammable.[43] However, the high F_P of these chemicals is generally accompanied by increased viscosity, thus limiting low temperature operation and degrading cell performance at sub-ambient temperatures. These materials may also have other problems such as poor wetting of the electrodes and separator materials, excluding them from use in cells despite being nonflammable.

Ideally, solvents would be used that have no F_P while simultaneously exhibiting ideal electrolyte behavior (see below for a number of critical properties that the electrolytes need to meet) and would remain liquid at low temperatures down to -50 ºC or below for use in Li-ion cells. A number of critical electrochemical and thermal properties are given below that FR have to meet simultaneously. The tradeoffs between properties are possible but when it comes to safety there cannot be tradeoffs.

---

[40] Mikolajczak, Celina; Kahn, Michael; White, Kevin; Long, Richard Thomas. “Lithium-Ion Batteries Hazard and Use Assessment.” Exponent Failure Analysis Associates, Inc. July 2011.

[41] S.M. Sarathy, C.K. Westbrook, M. Mehl, W.J. Pitz, C. Togbe, P. Dagaut, H. Wang, M.A. Oehlschlaeger, U. Niemann, K. Seshadri, P.S. Veloo, C. Ji, F.N. Egolfopoulos, T. Lu. “Combust Flame” 158, 2011, 2338.

[42] “CRC Handbook of Chemistry and Physics”, 79th ed., edited by D. R. Lide. CRC, Boca Raton. 1998–1999.

[43] S. Werner, M. Haumann, P. Wasserscheid, Annu Rev. “Chem Biomol Eng.” 1, 2010, 203

- High voltage stability
- Comparable conductivity to traditional electrolytes
- Lower flame propagation rate or no fire at all
- Lower self-heating rate
- Stable against both the electrodes
- Able to wet the electrodes and separator materials
- Higher onset temperature for exothermic peaks with reduced overall heat production
- No miscibility problems with co-solvents

Electrolyte non-flammability is essential for cell safety. Enhanced safety of electrolytes containing FR additives is mostly accompanied by performance degradation including low capacity utilization, high rate of capacity fade, or poor low temperature performance. Additionally, some are electrochemically unstable and are consumed during cycling, becoming unavailable for cell protection with time. Furthermore, limited information is available in the open literature on the performance of additives in large capacity cells under actual use conditions and subsequent abuse conditions. The higher energy density of Li-ion cells can only result in a more volatile device, and while significant efforts have been put forth to address safety, significant research is still needed. To improve safety of Li-ion batteries, the electrolyte flammability needs significant advances or further mitigation is needed in areas that will contain the effects of failures to provide graceful failures with safer outcomes in operation.

5.4.2 Additives

The most commonly accepted mechanism for fire propagation relies on a radical generation mechanism. Ground state oxygen absorbs heat and produces energetic and extremely reactive singlet oxygen. The identified mechanism clearly indicates that hydrogen radical and singlet oxygen play a key role in sustaining the flame.[44] This is the target for many of the materials proposed as FR additives. If a FR material is able to sufficiently bind to the free radicals during the reaction cascade, then propagation of the flame will be suppressed.

[44] J.L. Jurs. "Development and Testing of Flame Retardant Additives and Polymers." Rice University. 2007, 303.

Researchers have predominantly performed Differential Scanning Calorimetry (DSC) measurements on electrolytes to determine thermal stability with and without the FR. The ideal outcome is that the electrolyte with FR show very little peak in the DSC traces and even then only at higher temperatures compared to the electrolyte without the FR.[45] This observation seems to suggest that the FR additive improves the thermal stability of the electrolyte. Others have chosen to employ standard test procedures from the American Society for Testing and Materials (ASTM), Underwriters Laboratories (UL), and International Electrotechnical Commission (IEC) such as ASTM D-5306, ASTM D2863, UL-94VO, and IEC 62133 to compute both the self-extinguishing time (SET) and the limited oxygen index (LOI) to evaluate the flammability of the electrolytes. The shorter the SET and higher the LOI (this is the % of oxygen needed in the O_2/N_2 mixture to keep the electrolyte burning for at least 60s), the less flammable the electrolyte. In general, the electrolyte with the additives shows shorter SET and higher LOI than the electrolyte without FR. Descriptions of the thrust of the different ASTM and UL tests were discussed in depth by M. Otsuki, *et al.* [46] See Appendix A for a table of the variety of new and novel FR materials that have been synthesized and studied as well as low flash point electrolytes that have been developed to fight flame ignition.

In the vapor phase, the traditionally accepted mechanism is that FR decomposes, producing phosphorous or halogen radicals that act as scavengers and react with hydrogen radicals, thereby terminating the free radical reaction. Despite wide availability for FR materials, two primary classes of materials have been investigated extensively for use in Li-ion batteries, which are phosphorus-containing materials and fluorine containing materials. The phosphorous-containing materials primarily rely on the free radical scavenging mechanism, but on rare occasion inhibit reaction through char formation on the reactive surface. Alternately replacing hydrogen with fluorine, the compound should be more thermally stable due to the decrease in the available hydrogen for radical production. By eliminating the generation of hydrogen radicals, flammability could potentially be minimized or eliminated; however, advances to date are at the R&D scale.

---

[45] E-G Shim, T-H Nam, J-G Kim, H-S Kim, S-I Moon. "Electrochimica Acta." 53, 2007, 650.

[46] "Lithium-Ion Batteries: Science and Technology." Edited by M. Yoshio, R.J. Brodd, A. Kozawa. Springer-Verlag New York, LLC, 278, 2009.

5.4.3 Electrodes, separators, current collectors, casings, cell format headers and vent ports

While electrolytes are by far the most critical component in Li-ion battery safety, research has been pursued into safety considerations around the other components of the cell. These factors can become more critical as research continues in wider ranges of chemistries for stationary storage. Again, research to date has focused on Li-ion devices; however, insights in these components may be leveraged in designing safer technologies across electrochemical solutions. Within materials R&D, the exponent review describes efforts into improving safety in battery components including safer cathodes and separators in addition to electrolytes. It also details the state of other cell components in the context of hazards and safety; including anodes, charge collectors, casing, and safety devices including charge interrupt devices and positive temperature coefficient switches.[47]

5.4.4 Capacitors

Electrostatic capacitors are a major failure mechanism in power electronics. These predominately fail because of the strong focus on low cost devices, and low control over manufacturing. In response, they are used at a highly de-rated level, and often with redundant design. When they fail they often show slow degradation with decreasing resistivity leading eventually to shorting. Cascading failures can lead to higher consequence failures elsewhere in a system. Arcs or cascading failures can occur. The added complexity of redundant design is a safety risk. While there is a niche market for high reliability capacitors, they are not economically viable for most applications, including grid storage. These devices are made of precious metals and higher quality ceramic processing that leads to fewer oxygen vacancies in the device.

Polymer capacitors can have a safety advantage as they can be self-healing, and therefore graceful failure; however these are poor performers at elevated temperatures and are flammable. Testing of capacitors currently involves putting a DC bias or increasing the temperature to observe accelerated breakdown.

---

[47] Mikolajczak, Celina; Kahn, Michael; White, Kevin; Long, Richard Thomas. “Lithium-Ion Batteries Hazard and Use Assessment.” Exponent Failure Analysis Associates, Inc. July 2011.

Currently, the low cost and low reliability of capacitors make them a very common component that fails in devices, affecting the power electronics and providing a possible trigger for a cascading failure. While improved reliability has been achieved in capacitors such devices are cost prohibitive due to their manufacturing and testing. Development of improved capacitors at reasonable cost, or design to prevent cascading failures in the event of capacitor failure should be addressed.

5.4.5 Pumps tubing and tanks

Components specific to flow battery, and hybrid flow battery technologies have not been researched in the context of safety for battery technology. These include components such as pumps, tubing and storage tanks. Research from other areas that use similar components can be a starting point, but these demonstrate how the range of components is much broader than current R&D in battery safety.

5.4.6 Mechanical design and vacuum system

Similarly, components specific to flywheels have their own design considerations with respect to safety. The engineering design, and safety factors in containing flywheels is not currently widely established by CSR, and requires further research to be flushed out. Current safety validation testing involves burst testing to probe containment integrity, vacuum loss testing, overspeed testing of systems, as well as fatigue testing of sample materials.[48]

5.4.7 Manufacturing defects

The design of components and testing depends on understanding the range of purity in materials, and conformity in engineering. Defects are a large contributor to shorts in batteries for example. Understanding the reproducibility among parts, and the influence of defects on failure is critical to understanding and designing for safer storage systems.

---

[48] Sonnichsen, Eric. “Ensuring Spin Test Safety.” Test Devices Inc. December 1993.

5.5 Engineering controls and system design

5.5.1 Circuit design and safety mechanisms

Current safety mechanisms for Li-ion batteries are typically two-fold; cell based devices designed to prevent thermal runaway of single cells and devices integrated into the battery system intended to preserve the overall stability of the battery pack. The most well-recognized single cell protective systems are the Positive Temperature Coefficient (PTC) and Current Interrupt Devices (CID). [49,50] PTCs are typically used as protection against external short circuits. In case of elevated current, the PTC self-heats and become more resistive, blocking additional current flow and preventing a runaway condition. CID protection affixes a current break point to the safety vent, blocking current flow if internal pressure builds up. These prevent current flow during any condition that can cause gas generation, such as overcharge and voltage reversal. Other cell based safety devices include shutdown separators, electrolyte additives (such as redox shuttles for overcharge protection and flame retardant additives), electroactive separators and less energetic active materials (see Appendix A). One component to keep in mind when considering shutdown separators is that disconnecting the string or module may or may not arrest the exothermic processes already be underway.

Large Li-ion battery packs typically include safety features integrated into their circuit design as well. Commonly, each series string will be outfitted with a blocking diode which prevents parallel strings from discharging through a battery with an unforeseen short circuit.[51] Researchers such as Kim *et al.*[52] have also proposed more robust circuits capable of mitigating the electrical impacts of a single cell failure. Manufacturers of large battery systems typically integrate proprietary control system as well, to control issues such as cell balance, cell temperature and estimation of battery life.

---

[49] Balakrishnan, P.G., R. Ramesh, and T.P. Kumar. "Safety mechanisms in lithium-ion batteries." Journal of Power Sources, 2006. 155(2): p. 401-414.

[50] Friel, D.D. "*Battery Design*, in *Linden's Handbook of Batteries*." T.B. Reddy, Editor. 2011, McGraw Hill: New York. p. 5.1-5.23.

[51] Balakrishnan, P.G., R. Ramesh, and T.P. Kumar. "Safety mechanisms in lithium-ion batteries." Journal of Power Sources, 2006. **155**(2): p. 401-414.

[52] Kim, G.-H., et al. "Fail-safe design for large capacity lithium-ion battery systems." Journal of Power Sources. 2012, **210**(0): p. 243-253.

5.5.2 Fault detection

The science of fault detection within large battery systems is still within its infancy; most analysis and monitoring of large battery systems is focused on monitoring issues such as state of health and state of charge monitoring, however limited work has been performed. Offer *et al.*[53] first saw signs of a battery failure by monitoring the voltage of a battery system, then proceeded to diagnose the fault first using electrochemical impedance spectroscopy and a battery model constructed in Simulink. They found the fault related to faulty module construction rather than issues with the cell. Zheng *et al.*[54] proposed a fault detection method using Shannon entropy measurement to detect changes in internal or contact resistance within a battery. However, these works to not address detection of field failures (internal short circuits) or unstable batteries that may lead to a propagating failure. There are numerous sensors, including temperature, voltage, and off-gassing which have the potential to diagnose excursion. Additionally, software analytics can be critical tools in fault detection.

5.5.3 Software Analytics

In this day and age of information technology, any comprehensive research, development, and deployment strategy for energy storage should be rounded out with an appropriate complement of software analytics. Software is on a par with hardware in importance, not only for engineering controls, but for performance monitoring; anomaly detection, diagnosis, and tracking; degradation and failure prediction; maintenance; health management; and operations optimization. Ultimately, it will become an important factor in improving overall system and system-of-systems safety.

As with any new, potentially high consequence technology, improving safety will be an ongoing process. By analogy with airline safety, energy storage projects which use cutting-edge technologies would benefit from “black boxes” to record precursors to catastrophic failures. The black boxes would be located off-site and store minutes to months of data depending on the time scale of the phenomena being sensed. They would be required for large-scale installations,

[53] Offer, G.J., et al. “Module design and fault diagnosis in electric vehicle batteries.” Journal of Power Sources. 2012. **206**(0): p. 383-392.

[54] Zheng, Y., et al. “Lithium ion battery pack power fade fault identification based on Shannon entropy in electric vehicles.” Journal of Power Sources, 2013. **223**(0): p. 136-146.

recommended for medium-scale installations, and optional for small installations. Evolving standards for what and how much should be recorded will be based on the results from research as well as experience.

Since some energy storage technologies are still early in their development and deployment, there should be an emphasis on developing safety cases. Safety cases should cover the full range of safety events that could reasonably be anticipated, and would therefore highlight the areas in which software analytics are required to ensure the safety of each system. Each case would tell a story of an initiating event, an assessment of its probability over time, the likely subsequent events, and the likely final outcome or outcomes. The development of safety cases need not be onerous, but they should demonstrate to everyone involved that serious thought has been given to safety. Standard or example cases could be developed for each technology to facilitate the creation of site-specific documentation.

5.6 Testing and Analysis

Validation techniques are guided primarily by CSR. Standard validation techniques are most evolved in the areas of lead-acid and Lithium-ion battery technologies due to their use in vehicle technologies. The most common experimental tests to assess specific risk from electrical, mechanical and environmental conditions are identified in Table 2. Tests that have not been standardized, and are under current R&D efforts are listed in the final row of this table. To date this work has been confined to the vehicle battery space, and not evaluated for their applicability to grid storage areas.

Table 2. Common Tests to Assess Risk from Electrical, Mechanical, and Environmental Conditions[55]

Condition	Tests
Electrical	Test of current flow Abnormal charging test, overcharging and charging time Forced discharge test
Mechanical	Crush test Impact test Shock test Vibration test
Environmental	Heating test Temperature cycling test Low pressure altitude test
Tests under development	Failure propagation Internal short circuit (non-impact test) Ignition/flammability IR absorption diagnostics Separator testing

The established tests for electrical, mechanical and environmental conditions are therefore tailored to identifying and quantifying the consequence and likelihood of failure in lead-acid and lithium ion technologies with typical analyses that include burning characteristics, off-gassing, smoke particulates, and environmental run off from fire suppression efforts. Even for the most studied abuse case of lithium ion technologies, some tests have been identified as very crude or ineffective with limited technical merit. For example, the puncture test, used to replicate failure under an internal short, is widely believed to lack the ability to accurately to mimic this particular failure mode. These tests are less likely to reproduce potential field failures when

[55] Florence, Laurie B. "Safety Issues for Lithium-Ion Batteries." UL. 2014. http://newscience.ul.com/wp-content/uploads/sites/30/2014/04/Safety_Issues_for_Lithium_Ion_Batteries.pdf

applied to technologies for which they were not originally designed. The above testing relates exclusively to cell/pack/module level and does not take into consideration the balance of the storage system. Other tests on Li-ion system are targeted at invoking and quantifying specific events; for example, impact testing and overcharging tests probe the potential for thermal runaway which occurs during anode and cathode decomposition reactions. Other failure modes addressed by current validation techniques include electrolyte flammability, thermal stability of materials including the separators, electrolyte components and active materials, and cell-to-cell failure.[56]

5.7 Modeling

Current efforts in modeling failure in batteries are again confined to those of interest in EV technologies. These efforts have focused on lithium ion battery technologies. Thermal impacts on lithium ion batteries in terms of performance, life and safety have been carried out using multi-physics battery modeling with respect to temperature dependent concerns.[57]

5.7.1 Gap areas and opportunities

An energy storage system deployed on the grid, whether at the residential (<10kW) or bulk generation scale on the order of MW, is susceptible to similar failures as described above for Li-ion. However, given the multiple chemistries and application space, there is a significant gap in our ability to understand and quantify potential failures under real-world conditions; in order to ensure safety as grid storage systems are deployed, it is critical to understand their potential failure modes within each deployment environment. Furthermore, it must be considered that grid-scale systems include at the very least: power electronics, transformers, switchgear, heating and cooling systems and housing structures or enclosures. The size and the variety of technologies necessitate a rethinking of safety work as it is adopted from current validation techniques in the electrified vehicle space.

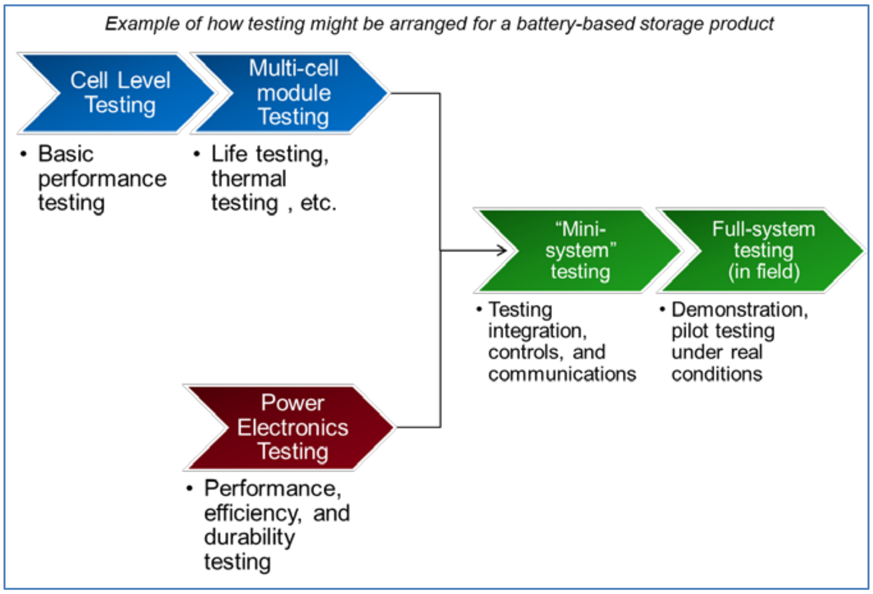
---

[56] Kim, Gi-Heon; Pesaran, Ahmad; Smith, Kandler. "Thermal Abuse Modeling of Li-Ion Cells and Propagation in Modules." 4th International Symposium on Large Lithium-Ion Battery Technology and Application. National Renewable Energy Laboratory. 2008. http://www.nrel.gov/vehiclesandfuels/energystorage/pdfs/43186.pdf

[57] Lin, Shaohua. "Multi-physics Modeling of Key Components in High Efficiency Vehicle Drive." University of Central Florida. Pg. iii. 2013. http://etd.fcla.edu/CF/CFE0005024/Shaohua_Lin_PHD_Dissertation_final.pdf

Safety work must encompass materials research and development, abuse testing to mimic potential threats within specific deployment environments, as well as simulations and modeling. This work cannot be limited solely to cell and module testing in order to achieve a holistic safety validation.

Figure 3. Example of Possible Testing Arrangement for a Battery-Based Storage Product



To address the component and system level safety concerns for all the technologies being developed for stationary energy storage, further efforts will be required to: understand these systems at the fundamental materials science, develop appropriate engineering controls, fire protection and suppression methods, system design, complete validation testing and analysis, and establish real world based models for operating. System level safety must also address several additional factors including the relevant codes, standards and regulations, the needs of first responders, and anticipate risks and consequences not covered by current CSR.

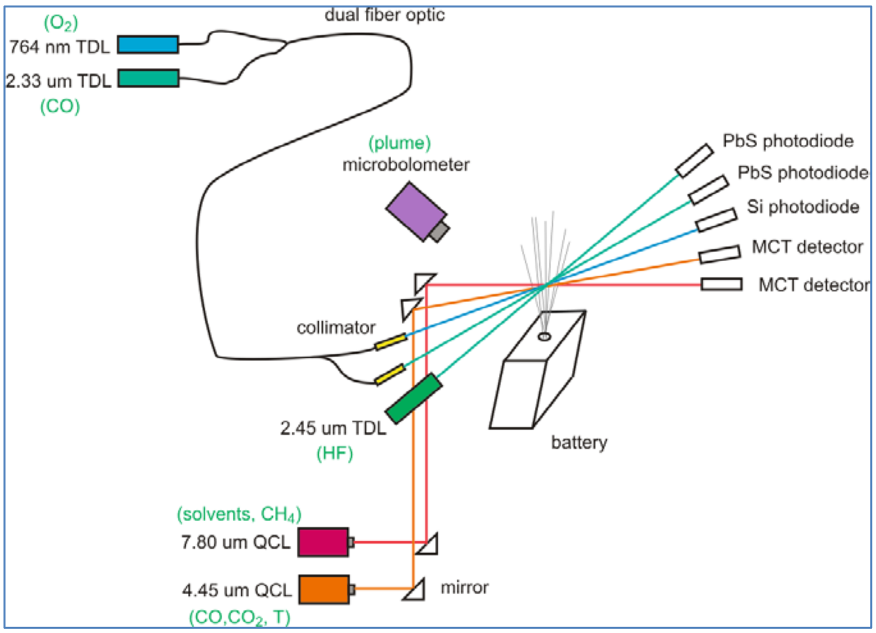
The wide range of chemistries and operating conditions required for grid-scale storage presents a significant challenge for safety R&D. The longer life requirements and wider range of uses for storage require a better understanding of degradation and end of life failures under normal operating and abuse conditions. The size of batteries also necessitates a stronger reliance on modeling. Multi-scale models for understanding thermal runaway, and fire propagation; whether originated in the chemistry, the electronics, or external to the system; have not been developed.

Currently gap areas for stationary energy storage exist from materials research and modeling through system life considerations such as operation and maintenance.

5.7.2 Materials science R&D

Materials safety can be validated through research. For example, in vehicle storage combustion research, facilities test with IR absorption the gas evolution and release in vented batteries as illustrated in Figure 4.

Figure 4. Experimental Setup of Gas Evolution and Release with Infrared Absorption



Opportunities are found in combining energy storage and power electronics safety and reliability testing from the cell to module levels. This could include projects to utilize on-line spread spectrum time domain reflectometry technique to determine the state of health of Wide Band Gap devices.[58] The amount of degradation depends on a number of factors including junction temperature, voltage and current stress, and duty cycle. Preliminary investigation will also be made for electrochemical systems to determine state of health. Furthermore, the thorough analysis and evaluation of abuse tolerance of energy storage systems including power electronics one may assess the tolerance of energy storage systems and engineering protections to short

[58] Ojeda, Juan. "Ultra-Wideband Technology and Test Solutions." Tektronix. 2007. http://www.afc-ingenieros.com/uploads/Afc/InfoTecn/RTSA/pdf/14%20Ultra-Wideband%20Technology%20and%20Test%20Solutions%20-%20AFC.pdf

circuit abuse, cell-to-cell failure propagation of the module and system level, and the severity of energy storage failure. Modeling the propagation of failed systems would be key to such work.

5.7.3. Engineering controls and system design

Currently the monitoring needs of batteries, as well as effectiveness of means to separate battery cells and modules, or various fire suppression systems and techniques in systems have not been studied extensively. Individual companies and installations have relied on past experience in designing these systems. For example: Na battery installations have focused on mitigating the potential impact of the high operating temperature, Pb-acid batteries has focused on controlling failures associated with hydrogen build up, while in technologies that don't use electrochemistry like flywheels, have focused on mechanical concerns such as run-out and high temperature, or change in chamber pressure. Detailed testing and modeling are required to fully understand the needs in system monitoring and containment of failure propagation. Rigorous design of safety features that adequately address potential failures are also still needed in most technology areas. Current efforts have widely focused on monitoring cell and module level voltages in addition to the thermal environment; however the tolerances for safe operation are not known for these systems. Further development efforts are needed to help manufacturers and installers understand the appropriate level of monitoring in order to safely operate a system and prevent failure resulting from internal short circuits, latent manufacturing defects or abused batteries from propagating to the full system.

5.7.4 Testing and analysis

Testing methodologies in the EV space are well established with respect to electrical, mechanical and environmental testing (Table 2). These efforts have focused on lithium ion technology and have not been established for most other electrochemical or mechanical storage technologies. New EV tests in failure propagation are of significant relevance to the grid storage space and must be applied to grid relevant technologies.

Table 3. Tests under Development for Specific Technologies

Technology	Tests under development
Batteries	Failure propagation Internal short circuit (non-impact test) Ignition/flammability IR absorption diagnostics Separator testing
Flywheel	Design margins in stress modulus Safety margins in containment Health monitoring and fault protection

5.7.5 Modeling

The size and cost of grid-scale storage system make it prohibitive to test full-scale systems, modeling can play a critical role in improved safety. System scale modeling efforts combined with experimental R&D cell/pack level validation can lead to improved designs for safe operation of larger systems. Cell level modeling can help gain a deeper understanding of batteries with respect to abuse tolerance and failure. These models must identify and account for: faster side reactions at increased temperature to prevent thermal runaway, increasing resistance at lower ambient temperature operation to capture the higher heat generation due to higher internal resistances. Temperature modeling can also account for the correlation between temperature and: dendrite growth, reaction rates, and cell degradation.

While EV safety research incorporating modeling has made some significant strides for the battery/pack level, system level installations may benefit mostly from the highly sophisticated modeling of fire containment within buildings developed for nuclear weapons. These models have over a decade of development into the detailed electrochemical, mechanical, and thermal properties and may be highly applicable to grid storage systems.

5.7.6 Fire suppression

Large-scale energy storage systems can mitigate risk of loss by isolating parts of a system in different transportation containers, or using materials or assemblies to section off batteries.

Most current systems have automated and manually triggered fire suppression systems within the enclosure but have limited knowledge if such suppression systems will be useful in the event of fire. Further work on fire dynamic simulations are needed to predict the size, scope and consequences of battery fires and the potential for propagation to the next enclosure. The information from kWh and MWh simulations can be used to design both the energy storage and the fire suppression systems. These efforts must be used to gain a better understanding of what containment measures are effective and economically viable.

The interactions between fire suppressants and system chemistries must be fully understood to determine the effectiveness of fire suppression. Key variables include the: volume of suppressant required, rate of suppressant release, and distribution of suppressants. Basic assumptions about electrochemical safety have not been elucidated, for example it is not even clear whether a battery fire is of higher consequence than other types of fires, and if so at what scale this is of concern. This is a very open area of research that needs quantitative findings in order to inform the industry.

The National Fire Protection Association (NFPA) has provided a questionnaire regarding suppressants for vehicle batteries.
Tactics for suppression of fires involving electric-drive vehicle (EDV) batteries:

a. How effective is water as a suppressant for large battery fires?
b. Are there projectile hazards?
c. How long must suppression efforts be conducted to place the fire under control and then fully extinguish it?
d. What level of resources will be needed to support these fire suppression efforts? 1
e. Is there a need for extended suppression efforts?
f. What are the indicators for instances where the fire service should allow a large battery pack to burn rather than attempt suppression?[59]

A suppression test was set up and fire, smoke and off-gassing were observed. Recommendations and future work identified included:

[59] "Best Practices for Emergency Response to Incidents Involving Electric Vehicles Battery Hazards." The Fire Protection Research Foundation. June 2013.

- Full-scale fire suppression testing of actual consumer EDVs to evaluate access issues in water application strategies in specific vehicle fire scenarios.
- Full-scale fire suppression testing of actual consumer EDVs to evaluate access issues in water application strategies in collision scenarios.
- Full-scale fire suppression testing of actual consumer EDVs to evaluate shock hazards when the entire vehicle electrical distribution system is present and possibly energized.
- Full-scale fire suppression testing of EDVs using cell formats different from those tested in this test series, such as 18650s.
- Free burn full-scale EDV fires to compare and contrast the advantages and disadvantages of letting EV fires burn out rather than suppressing.
- Evaluation of novel or alternate nozzle designs that may allow direct application of water to EDV batteries located below the vehicle underbody assembly.
- Determine the effectiveness of various water additives that may accelerate the cooling/extinguishment process.
- Conduct additional full-scale tests to evaluate the total water flow rates necessary to achieve extinguishment using new firefighter tactics, such as constant water application or a two hose line suppression team.

NFPA 13, *Standard for the Installation of Sprinkler Systems,*[60] does not contain specific sprinkler installation recommendations or protection requirements for Li-ion batteries. Reports and literature on suppressants universally recommended the use of water.[61] However, the quantity of water needed for a battery fire is large: 275-2639 gallons for a 40 kWh EV sized Li-ion battery pack. This is higher than recommended for internal combustion engine (ICE) vehicle fires. The NFPA report did not actually compare battery to a hydrocarbon fire in their experimental work on fire suppressants and was inconclusive as to the adequacy of a water sprinkler suppressant approach. To make use of previous studies of fire suppression, future R&D efforts should investigate identifying equivalencies of battery to fuel or other studied materials.

---

[60] "NFPA 13: Installation of Sprinkler Systems and Handbook Set" NFPA Catalog. 2013.

[61] "Best Practices for Emergency Response to Incidents Involving Electric Vehicles Battery Hazards." The Fire Protection Research Foundation. June 2013.

5.8 Summary

Science-based safety validation techniques for an entire energy storage system are critical as the deployments of energy storage systems expand. These techniques are currently based on previous industry knowledge and experience with energy storage for vehicles, as well as experience with grid-scale Pb-acid batteries. Now, they must be broadened to encompass grid-scale systems. The major hurtle to this expansion is encompassing both much broader range in scale stationary storage systems, as well as the much broader range of technologies. Furthermore, the larger scale of stationary storage over EV storage necessitates the consideration of a wider range of concerns, beyond the storage device. This includes areas such as power electronics and fire suppression. The required work to develop validation is significant. As progress is made in understanding validation through experiment and modeling, these evidence-based results can feed into codes, regulations and standards, and can inform manufacturers and customers of stationary storage solutions to improve the safety of deployed systems.

6.0 Incident Preparedness

As with any large-scale deployed technology, there are risks that unintended events could result in a safety incident, exposing life, the environment and critical infrastructure at risk. Therefore, it is critical to develop an understanding of the possible failure modes of the systems and create plans to mitigate the potential for and the risk of these events as much as possible. Additionally, the scope of the incident preparedness for these systems must extend past the immediate workers at the facility to include first and second responders, as well as those in the surrounding area.

6.1 Current Conditions

Today's Fire Service is frequently being considered "All Risk" in terms of their response service levels. This means that first responders must be equipped and ready to respond to a vast array of different types of events, with the majority of emergency responses divided into the following categories:

1. Medical emergencies
2. Hazardous material releases
3. Fires of various origins
4. Weather-related incidents

5. Industrial and manufacturing incidents
6. Utility (electrical & gas) incidents – ESS falls into this category, regardless of utility, commercial, or residential application.
7. Investigation of system troubles

Whenever possible, First Responders create Risk Profiles and Incident Action Plans to manage the risks associated with an incident at a facility or residence. These plans assist in real-time risk managing utilizing the following incident priorities: life, incident mitigation, and property and environmental protection, and commonly use the following guideline: "We will risk a life to save a life. We will risk very little, in a calculated manner, to save savable property. We will risk nothing for what is already lost." [62] These plans help the first responders identify and understand the unique challenges associated with responses to specific sites, and allow them to be equipped to efficiently structure a response. However, the education and training currently provided to first responders is limited. As a result, response teams must craft incident response plans with little to no background knowledge about the system.

Emergency responses to manufacturing, industrial or utility incidences are typically considered low-frequency, high-risk occurrences in most fire departments. Though these events rarely occur, they carry the potential of high loss to first responders and the facility. This risk profile typically results in a cautious approach with a commensurately increased property loss. If first responders are aware of all the factors that will impact the risk profile of the incident before the incident occurs, the response will be faster and more effective with a commensurate decrease in loss. By contrast, medical emergencies are considered high frequency, low risk to the responder. First responders are better equipped to respond to the high frequency, low risk emergencies as a result of a thorough understanding of the risk and extensive training for these events. An additional complication is that the risk profile during an incident can continually evolve and it is imperative to determine if mitigation actions are consistent with the changing risks and benefits. For example, an ESS technician suffering a medical emergency while performing work on an ESS requiring responders to enter the battery hazard area to access and treat the technician.

[62] "Rules of Engagement: Adopt the Rules as Standard Operating Procedures." International Association of Fire Chiefs. April 1, 2013. http://www.iafc.org/onScene/article.cfm?ItemNumber=6735

Currently, fire departments do not categorize ESS as stand-alone infrastructure capable of causing safety incidents independent of the systems that they support. Instead, fire departments categorize grid ESS as back-up power systems such as uninterruptible power supplies (UPS) for commercial, utility, communications and defense settings, or as PV battery-backed systems for on, or off-grid residential applications. This categorization results in limited awareness of ESS and their potential risks, and thus the optimal responses to incidents. This categorization of energy storage systems as merely back-up power systems also results in the treatment of ESS as peripheral to the risk management tools.

There is also a diverse array of stakeholders invested in each energy storage system installation, for which an incident represents a potential risk, be that financial or to their health. For residential or community based systems, these parties include the homeowner and occupants of the residence and surrounding residence, the utility, and the manufacturer of the photovoltaic system to which the energy storage system is often coupled. In these cases, the top concerns of the fire department are the occupants, limiting the spread of the incident to neighboring structures, and mitigating remaining safety hazards. In contrast, the fire department must account for a very different set of stakeholders when responding to an incident at an industrial location. In this case, the risk of loss of human life is typically limited to potential system operators and the incident response plans are centered on containing the incident for the least consequence possible to the facility and community. In these cases, the system operators are often better trained, the hazards are better marked and there is often fire suppression capability built into the facility. Facility operators must be able to operate under a unified incident management system to ensure responders are aware of these safety systems and utilize them appropriately. This enables the first responders to more effectively limit damage to these typically high-value facilities.

6.2 Incident Preparedness

Incident preparedness activities can be divided into two categories: engineered controls and administrative controls. Administrative controls include activities such as pre-planning for an incident, codes and standards, and risk management tools. Engineered controls include aspects of the system and its installation such as fire suppression, storage system design, and fail-safes.

6.2.1 Engineered controls

The first step in ensuring safety of any system is to ensure that the system is designed to the highest possible level of safety. As previously discussed, the engineering of safety into a system must start at the materials level and be designed all the way through to deployment. For mature technologies, the methods used to ensure safety of the materials used and systems design are written into the CSRs where they can guide the design, manufacture, and deployment of the storage system. However, for new technologies such as grid-scale energy storage, the CSRs are not fully codified.

Fixed facilities may have the added benefit of fire suppression systems, central station alarm monitoring, emergency power-off systems, site access control, ventilation systems, and on-site facilities or trained engineering staff. Challenges include the increased commodity storage, R&D complication issues due to experimental processes and/or procedures, and fire service access issues. The staffing model of the local fire department, available water supply, and level of ES awareness possessed by the responders can either positively or negatively impact any of the aforementioned challenges. Current fixed-facility suppression systems utilize extinguishing agents that typically include water mist, dry chemical, CO2, or other inert gas agents.

6.2.2 Administrative controls

Two main components of the administrative controls for energy storage system safety are the emergency preparedness plans and the CSR. The former guides first responders as to what actions to take in an emergency, and the latter dictates the facility signage, processes and procedures.

Because of the low frequency of energy storage incidents, the wide variety systems sizes and technologies, and deployment options there is a need to develop comprehensive emergency preparedness plans. These plans must begin with what is commonly referred to as a Community Risk Assessment (CRA) to identify potential emergency scenarios. The scenarios addressed in the CRA must be based on the energy storage system characteristics and application space, and must comply with OSHA requirements (Appendix A). The property owner/occupant develops several incident-specific response plans, based on the CRA. These plans identify performance objectives and action steps to support the local risks and incident scenarios and can include fire pre-incident plans created by first-response organizations. The pre-incident plans are typically based on several factors: fire department resources, unique or higher risk properties from an occupancy classification, life hazard, and special event. These pre-incident plans can include a casual building familiarization tour to a formal document complete with maps, fire control system locations, utility connections, high hazard contents, and building contact information. None of these elements by themselves should be considered adequate pre-incident planning, as all of them are fundamental requirements of pre-incident planning.

The CRA must take into account the diversity in deployment environments, applications, and interested parties surrounding the energy storage system (ESS). As previously discussed, an ESS used in conjunction with a residential PV installation has different risks than an energy storage system used at an industrial location. The risk management for the residential ESS application must be addressed with the occupancy load in mind; the risk of negative effects to human life is much higher. The physical location of a residential ESS must also be considered in order to best plan for strategies to extinguish a fire while also protecting human life. The risk management for the remote, industrial ESS installation must include the specific hazards and challenges of the physical location. For example, if the installation is on a hill with impassable roads, fire apparatus may not be able to reach the fire, thus increasing the risk of damage to surrounding property and/or land. OSHA requires an Incident Response Plan, or Emergency Action Plan (*29 CFR 1910.38*) when the following primary tasks are involved:

- Proper identification of specific hazard, i.e., fire, spill, emergency medical services (EMS) incident
- Proper identification of energized electrical equipment
- Rapid identification of available disconnects - requires clear, consistent marking with permanent labeling
- Liaison with responsible party, i.e., facility maintenance personnel with specific building systems knowledge
- Determination of resource requirements (an ongoing assessment based on scope and type of incident)

The energy storage industry is rapidly expanding due to market pressures. This expansion is surpassing both the updating of current CSR and development of new CSR needed for determining what is and is not safe and enabling first responders to craft pertinent pre-incident plans. Standards exist for mature ESS such as Lead-acid, NiCd, and NiMH, covering the technical features and testing of the system and its integration with other systems and buildings/facilities. For other storage technologies, however, less CSR guidance is provided. No general, technology-independent standard for ESS integration into a utility or a stand-alone grid has yet been developed. There is an International Electrotechnical Commission (IEC) standard planned for rechargeable batteries of any chemistry.[63] This IEC standard potentially could be used as a template for standards needed in North America, but currently is not significantly useful to American first responders.

6.3 Incident Response

Incident responses with standard equipment are tailored to the specific needs of the incident type and location, whether it's two "pumper" engines and a "ladder" truck with two to four personnel, plus a Battalion Chief to act as Incident Commander, for a total of nine to thirteen personnel responding to an injury/accident, or a structure fire that requires five engines, two trucks, and two Battalion Chiefs for a total of seventeen to thirty personnel. With each additional "alarm" struck will send another two to three "pumper" engines and a "ladder" truck. In all of these cases, the incident response personnel typically arrive on scene with only standard equipment. This equipment is guided by various NFPA standards for equipment on each apparatus, personal protective equipment (PPE), and other rescue tools. In responding to an ESS incident, the fire service seldom incorporates equipment specialized for electrical incidents. At best, many departments have a non-contact AC current detector that is used to detect AC current in structures, wires down-type incidents, or vehicles into energized equipment. Fire departments do not typically provide or maintain electrical PPE.

With this background in mind, a number of unique challenges must be considered in developing responses to any energy storage incident. In particular, difficulties securing energized electrical components can present significant safety challenges for fire service personnel. Typically, the primary tasks are to isolate power to the affected areas, contain spills, access and rescue possible victims, and limit access to the hazard area. The highest priority is given to actions that support

[63] http://www.iec.ch/whitepaper/pdf/iecWP-energystorage-LR-en.pdf

locating endangered persons and removing them to safety with the least possible risk to responders. Where the rescue of victims continues until it is either accomplished or determined that there are no survivors or the risk to responders is too great. Industrial fires can be quite dangerous depending on structure occupancy, i.e. the contents, process, and personnel inside. Water may be used from a safe distance on larger fires that have extended beyond the original equipment or area of origin, or which are threatening nearby exposures; however, determination of "safe" distance has been little researched by the fire service scientific community. In 2011, the safety testing and certification organization Underwriters Laboratories (UL), funded by the Federal Emergency Management Agency (FEMA), explored safe distances up to 1000Vdc for the purposes of water application on photovoltaic systems,[64] but there has been little education within the fire service on voltages above that level.

6.4 Gap Areas

The gaps in incident response pertaining to ESS are primarily a result of these systems being in early stages of deployment. As ESS begins to proliferate in residential, commercial and industrial settings, the probability of an incident increases and this knowledge gap must be addressed. Specifically, five areas have been identified as critical gaps:

1. Fire suppression and protection systems
2. Commodity classification
3. Verification and control of stored energy
4. Post-incident response and recovery
5. First responder awareness and response practices

6.4.1 Fire suppression and protection systems

Each ESS installation is guided by application of existing CSR that may not reflect the unique and varied chemistries in use. Fire-suppressant selection should be based on the efficacy of specific materials and needed quantities on site based on appropriate and representative testing, conducted in consultation with risk managers, fire protection engineers, and others, as well as alignment with existing codes and standards. For example, non-halogenated inert gas discharge systems may not be adequate for thermally unstable oxide chemistries, as they generate oxides in

[64] http://www.ul.com/global/documents/offerings/industries/buildingmaterials/fireservice/PV-FF_SafetyFinalReport.pdf

the process of heating, which may lead to combustion in oxygen deficient atmospheres. Ventilation requirements imposed by some Authorities Having Jurisdiction (AHJs) may work against the efficacy of these gaseous suppression agents. Similarly, water-based sprinkler systems may not prove effective for dissipating heat dissipation in large-scale commodity storage of similar chemistries. Therefore, additional research is needed to provide data on which to base proper agent selection for the occupancy and commodity, and to establish standards that reflect the variety of chemistries and their combustion profile.

6.4.2 Commodity classification

Current commodity classification systems used in fire sprinkler design (NFPA 13-Standard for Installation of Sprinkler Systems) do not have a classification for lithium or flow batteries. This is problematic, as the fire hazard may be significantly higher depending on the chemicals involved and will likely result in ineffective or inaccurate fire sprinkler coverage. Additionally, thermal decomposition of electrolytes may produce flammable gasses that present explosion risks. Better understanding of these gases and the combustion process of the overall battery chemistry is needed to identify adequate fire protection systems.

6.4.3 Verification and control of stored energy

Severe energy storage system damage resulting from fire, earthquake, or significant mechanical damage may require complete discharge, or neutralization of the chemistry, to facilitate safe handling of components. Though the deployment of PV currently exceeds that of ESS, there is still a lack of a clear response procedure to de-energize distributed PV generation in the field. Fire fighters typically rely on the local utility to secure supply-side power to facilities. In the case of small residential or commercial PV, the utility is not able to assist because the system is on the owner side of the meter, which presents a problem for securing a 600Vdc rooftop array. Identifying the PV integrators responsible for installation may not be possible, and other installers may be hesitant to assume any liability for a system they did not install. This leaves a vacuum for the safe, complete overhaul of a damaged structure with PV. Similarly, ESS faces the complication of unclear resources for assistance and the inabilities of many first responders to knowledgably verify that the ESS is discharged or de-energized. The need for response procedure for distributed PV may begin to be positively impacted by CSR, as there is proposed language for consideration by the NEC in January 2015 that addresses rapid shutdown of PV systems. However, this gap area must be more thoroughly addressed to ensure complete procedures that limit the risk to life and property.

6.4.4 Post-incident response and recovery

Thermal damage to ESS chemistries and components presents unique challenges to the fire service community, building owners, and insurers. As evidenced in full-scale testing of EV battery fires, fire suppression required more water than anticipated, and significantly more in some cases.[65] Additionally, confirming that the fire was completely extinguished was difficult due to the containment housings of EV batteries that can mask continued thermal reaction within undamaged cells. In one of the tests performed by Exponent, Inc., one battery reignited after being involved in a full-scale fire test some 22 hours post-extinguishment; in another case, an EV experienced a subsequent re-ignition 3 weeks post-crash testing.[66]

The results of the Fire Protection Research Foundation (FPRF) report on electric vehicle (EV) battery fires corroborate the additional need to educate "secondary responders" such a tow operators, repair facilities, and storage yards when damaged hybrid and EV batteries are on their properties. This need also exists in the grid energy storage context, where cleanup, salvage and recycling are all potentially components of a response to an incident.

6.4.5 First responder awareness and response practices

For the responder community, incident preparedness necessitates varying levels of education. The first responders in the U.S. fire service have divergent experience levels, career and volunteer staffing levels, and varying physical resources. Therefore, no singular training model can successfully engage the entire community. Fortunately, many models of fire service education, from instructor-led classes, to web based modules and webinars, print media, and conference presentations, have proven successful in reaching the fire-fighting community on issues such as incident response to electric vehicle accidents. Both UL and NFPA have received funding for research of responder tactics and hazards for emerging technologies and leveraged them into training curriculum. In the case of electric vehicle safety education, in 2009 NFPA

---

[65] http://www.nfpa.org/research/fire-protection-research-foundation/reports-and-proceedings/hazardous-materials/other-hazards/lithium-ion-batteries-hazard-and-use-assessment-ph-iib

[66] Long, Jr., R. Thomas; Blum, Andrew F.; Bress, Thomas J.; Cotts, Benjamin R.T. "Best Practices for Emergency Response to Incidents Involving Electric Vehicles Battery Hazards: A Report on Full-Scale Testing Results." Exponent, Inc. June 2013.

received a $4.4M grant through FEMA and DOE to support a nationwide education outreach program focused on first responders.[67] This program was delivered in all fifty states as a train-the-trainer program. It has since been developed as an online program managed by the NFPA, and has been viewed by tens of thousands of firefighters worldwide.

7.0 Safety Documentation

The research and development of innovative energy storage technologies is constantly advancing new technologies with a commensurate increase in the number and types of systems deployed. However, the safety documentation used to standardize the new technologies and serve as a basis for regulating the deployments of energy storage through CSR is lagging far behind this constant innovation and, as a result, is ineffective in validating the safety of each deployment and informing needed CSR criteria. To be effective, safety determination, documentation and verification must be standardized and specific to each chemistry, component, module, and deployment environment of each type of system. This standardization and relevance will ensure economically viable, validated safe deployments of increasingly innovative energy storage technologies. In order to ensure continued relevance, CSR must be actively updated according to innovations within the research and development of all systems. Ideally, determining what is and is not safe and the documentation associated with validating safety will enable the deployment of safe energy storage systems as the industry captures and communicates the best practices for engineered safety from components to full systems. The following discussion will explain the current risks in energy storage deployment that must be addressed through safety determination, documentation, and verification, and identify areas that need to be improved towards this end.

Crafting effective safety metrics and criteria requires recognition of two interconnected components, i.e., the myriad of stakeholders involved in the process and the complex and differing documentation required for each component, module, system, and deployment environment. A thorough safety determination involves standards that could apply to every step and stakeholder along the value chain, including first response. However, standards are merely a

[67] www.evsafetytraining.org

tool in the regulatory spectrum that may or may not be adopted, required, or used to establish acceptable practice. Each type of classification carries with it different legal implications for different stakeholder groups. Federal, state and local agencies, for instance, may be involved in the development, adoption and enforcement of building construction regulations, as well as safety, environmental, and occupational safety rules, all of which have legal implications. Some standards have been codified and are administered by regulators, whereas others, including protocols, guidelines and other documents, have not been codified and are merely guidelines for system manufacturers and owners. Standards that have not been adopted as mandatory, however, may have legal implications, as in cases of negligence when standards may be entered into evidence.

Standards complexity also arises from diverse regulatory requirements for every component of the ES system. Additionally, the components of a system may have individual standards to satisfy, but similar documentation may not exist for the systems as operational entities. Manufacturers of the individual components possess clear guidance, but system manufacturers and owners of an installed, operational system may lack such clarity. The safety regulations required may also differ between federal, state, and local agencies or utilities, thereby complicating the process needed for one manufacturer to sell its system in different states, to different buyers.

Federal, state, and local regulations, including those governing safety, affect every stakeholder, up and down the value chain. On the Federal level, the question with respect to regulation has to do with cost recovery for the utility, i.e., is energy storage generation or distribution? The Federal Energy Regulatory Commission (FERC) does not regulate power generation, but it does regulate the transmission, or distribution, of electricity in interstate commerce. To the extent that ES is considered generation, the utility cannot recover the associated costs through its rate base and be reimbursed for such costs by its customers. However, to the extent that ES is considered an ancillary service to transmission services provided by the utility, the utility can recover those costs through its rate base. In addition, ES is being evaluated and considered in the various Independent System Operators (ISOs) and Regional Transmission Organizations (RTOs).

On the state level, each state regulates ES differently. Several states have recognized the significance of ES and have addressed its role in power supplies, but most have not. For example, California has mandated that the three major investor-owned utilities in California (Pacific Gas & Electric, Southern California Edison, and San Diego Gas & Electric) incorporate energy storage into their state-mandated Renewable Portfolio Standards. Similar support for ESS also exists in Hawaii, Texas and New York. Other states are reviewing ES in the context of pilot or experimental programs. This regulatory gap between the states probably will narrow as the industry matures and market participants push the state to recognize the industry.

Ultimately, the goal is to standardize the safety documentation that will guide every step of the Energy Storage system process, from the manufacturing of components, to the structuring of entire systems, to system deployment and installation. This guidance is crucial to ensuring the validation of safe energy storage systems, and must be standardized and consistent on the federal, state, and municipal levels, and relevant to every battery chemistry and deployment environment. The following discussion gives an overview of codes, standards and regulations (CSR), and highlights the liability risks that are presented if CSR are disregarded or non-existent.

7.1 Overview of the CSR Deployment Process and Involved Stakeholders[68]

Deployment involves the processes associated with the adoption of model codes and standards as laws, rules, or regulations and the entities involved in that process. It also covers how compliance is documented and verified through processes associated with conformity assessment.

Any entity, whether a person, corporation, insurance carrier or utility, federal, state or local legislative body or governmental agency, can adopt model CSR. The act of adoption through a law, rule, regulation, statute, contract specification, tariff or any other vehicle is intended to ensure that the model codes and standards developed in the voluntary sector, or directly developed by the adopting entity, are required to be satisfied and that a basis for enforcement will ensure compliance. While federal, state, and local governments and other adopting entities have the authority to develop CSR, most adopt those developed in the voluntary sector at the national level with amendments, additions, and deletions to address any specific needs of theirs that are not addressed in those documents.

[68] Conover, David R. "Overview of Development and Deployment of Codes, Standards and Regulations Affecting Energy Storage System Safety in the U.S." Pacific Northwest National Laboratory. August 2014.

The federal government does not generally have the authority to mandate the adoption of CSR by state or local governments, although federal agencies can influence what is adopted through other means such as the availability of federal funding. Aside from buildings owned or leased by federal agencies and a few instances where the federal government has preemptive authority,[69] resulting in Congress or federal agencies adopting specific CSR, state and local regulations will apply to the built environment, including an ESS installation. For ESS on the grid side of the meter, equipment and buildings owned or operated by the utility are covered by what the utility adopts.

Once adopted, the model codes and standards are law; legal authority is granted by legislative bodies or regulatory agencies for their implementation and enforcement (e.g. conformity assessment). When adopted by utilities, insurance or corporate entities through tariffs, policies, specifications, contracts, or other legal documents, then what is adopted may apply over and above government adoptions, or will apply where no laws or regulations have been adopted or the government lacks the authority to adopt. The responsibility for documenting compliance with what is adopted rests with various private sector entities—manufacturers, builders, designers, product specifiers, contractors, building owners, utilities and others—involved in the design, construction, operation, use and demolition or decommissioning of what is regulated. The responsibility for determining and adjudging compliance rests with those representing the adopting authorities and is carried out based on an assessment of the documentation provided, including inspections, against what has been adopted. With respect to ESS, the manufacturer of the system components would be responsible for documenting component compliance; the system manufacturer for documenting system compliance and a builder, engineer or record or contractor responsible for documenting that the system installation is compliant. After an ESS installation is approved,[70] those engaged with its operation and maintenance would also be responsible for compliance with any applicable CSR, including those applicable to the repair, alteration, relocation or renovation of an existing ESS. Those verifying compliance (e.g. AHJs that enforce the adopted CSR) would include governmental agencies, utilities, insurance carriers

[69] Examples are product labeling (FTC), appliance efficiency (DOE) and manufactured housing construction (HUD).
[70] Approval is considered verification of compliance by the relevant Agencies Having Jurisdiction (AHJs) with what is adopted.

and others who adopted the CSR and made them applicable to the ESS components, system, system installation and operation and maintenance of the system.

7.1.1 Impacts of CSR on realizing ESS market opportunities[71]

The DOE/EPRI 2013 Electricity Storage Handbook indicates that the biggest challenges hindering adoption of energy storage technology are cost, the ability to deploy ESS, and lack of standards. [72] Standards and codes—or the lack thereof—have a direct impact on the cost of an ESS and its installation, in terms of material and manpower. Additionally, administrative burdens and time-to-approval issues affect technology deployment and increase costs. The absence of criteria upon which to evaluate technology performance, reliability and safety leaves those seeking to move ESS into the market and those responsible for public safety, with little on which to base a determination that the system and its installation are "safe." Until existing CSR are updated and/or new CSR are developed that specifically address the range of ESS technologies and installations and those CSR are adopted, it will be difficult to document what is safe and determine what can be approved in a uniform and timely manner. In some instances, the lack of specifics limits progress until appropriate CSR are available; in others, "outdated" CSR can be applied conservatively to the technology could affect the cost of the installation or limit its application.

Though CSR must be updated specifically to address new ESS technology and ESS applications, CSR still currently provide a path to documenting and validating compliance, assuming that what is proposed is no more hazardous nor less safe and performs at least as well as other technologies that are specifically covered by existing CSR. While affording approval, this path requires criteria for determining and documenting and "equivalent safety" by each entity that enforces the adopted CSR. This type of approval process can result in a "custom" documentation package for each jurisdiction (approval authority) where an ESS is desired on the customer side of the meter or each utility when the ESS is on the grid side.[73] In addition, those AHJs may not be

---

[71] Conover, David R. "Overview of Development and Deployment of Codes, Standards and Regulations Affecting Energy Storage System Safety in the U.S." Pacific Northwest National Laboratory. August 2014.

[72] Akhil, Abbas; et al. "DOE/EPRI 2013 Electricity Storage Handbook in Collaboration with NRECA." Sandia National Laboratories. July 2013.

[73] Those responsible for ESS approval (whether federal, state or local government, utilities, insurance carriers or others) can be classified as AHJs.

inclined to allow this path to compliance because they would have to develop those criteria, spend time assessing the evidence that documents equivalent performance, and then actually sign off that the installation is safe on that basis. Clearly, having updated and specific CSR to document and validate ESS safety is preferable and should be instituted soon.

In the immediate absence of updated CSR, a performance path to document and validate compliance, which can be facilitated at the national level through the development of formal acceptance criteria (pre-standards, protocols, or bench standards). An accredited third-party agency or entity could validate the safety of an ESS based on documented performance equivalent to that required by current CSR. In that case, AHJs could rely on those acceptance criteria and the assessment by an accredited third party in considering whether to approve an ESS installation, instead of making individual determinations. While a good short-term solution, even if facilitated through a nationally recognized AHJ process as an indication of CSR compliance, this scenario would require additional time and resources compared with securing approval based on compliance with ESS-specific CSR that specifically address the range of ESS available now and through continued updating of CSR those that will be developed in the future.

7.1.2 The role of research, analysis and documentation in the development and deployment of CSR[74]

To be relevant and useful to the safe deployment of grid-scale energy storage systems, CSR must incorporate best practices and lessons learned from innovation validation techniques for each system. However, a standards development organization (SDO) will find it difficult to approve the development of or reference to requirements or test methods unless some basis for their validity exists. Without documentation, it is difficult to secure approval to circulate for public review and comment on proposed criteria for CSR or to move through the remaining steps in standards and model code development. In most cases, the need for basis and documentation for the criteria will guide the development of the CSR language to be considered by an SDO, although it is not unusual to find these proposals with "soft" technical justification. Beyond development, if criteria appear controversial or marginally supported they are likely to be deleted or significantly revised when the CSR is considered for adoption.

[74] Conover, David R. "Overview of Development and Deployment of Codes, Standards and Regulations Affecting Energy Storage System Safety in the U.S." Pacific Northwest National Laboratory. August 2014.

Consider an ESS that is proposed for internal building use. The impact of any chemicals that comprise the system must be considered because building and fire codes limit the amount of chemical storage within buildings. Such limits could prohibit or significantly alter the intended installation as to building location, separate the system into smaller modules, or change the use group of the associated spaces in the building thereby imposing additional new requirements. In the short term, if existing CSR criteria are applied to an ESS installation inside a building, research, analysis and documentation may be required to address their inappropriate application to the system. In the long term, if changes to the CSR are to be proposed, it will be necessary to document all aspects of installation safety based on research and experience with existing ESS installations. The resulting body of knowledge would facilitate more appropriate treatment of ESS by updating CSR based on substantiated information. A prepared ESS industry is better able to advocate for designation of its technology as safe and achieve the successful updating of CSR and deployment of ESS with a robust and solid body of research and safety-related documentation. Without that assurance, AHJs, who are integrally involved in development and deployment of CSR and whose sole mission is protecting public health and life safety, will be less likely to approve ESS installations because they will lack the needed guidance in the previously adopted CSR.

Of particular relevance is the entity (and whom that entity represents) that does the research, analysis and documentation. While an ESS manufacturer may conduct its own testing, analysis and other work to evaluate and document system safety for internal purposes, an accredited third party should conduct testing, analysis and other work intended for use in documenting the safety of and securing approval for the ESS. Ideally, the development of the documentation and supporting materials needed to update CSR will be conducted on behalf of the ESS industry by recognized third parties that focus on common goals, objectives, and issues. In turn, third-party study yields a robust, defensible, uniform and reasonable set of CSR for the industry to use in documenting and verifying ESS safety. In short, a team approach founded on a common and collective body of research and analysis is generally preferable to separate initiatives that propose single technology or manufacturer solutions to addressing ESS safety. Without a community-wide approach to updating CSR based on scientific validation techniques, every stakeholder is open to risk, as will be discussed, below.

7.2 Compliance with Land Use Permitting and Environmental Requirements

Governmental approvals and permits related to the siting, construction, development, operation, and grid integration of energy storage facilities can pose significant hurdles to the timely and cost effective implementation of any energy storage technology. The process for obtaining those approvals and permits can be difficult to navigate, particularly for newer technologies for which the environmental, health, and safety impacts may not be well documented or understood either by the agencies or the public. This section provides a brief introductory overview of key issues and risks that energy storage developers, investors, utilities, and others should understand. The discussion is not exhaustive, as risks vary in scope and significance from project to project and permitting requirements vary significantly between jurisdictions.

7.2.1 Overview of regulatory and litigation risks

Regulatory and litigation risks generally fall into two categories, which are often interrelated: delay and cost. At the far end of the spectrum, there is a risk that a permit or approval will be denied entirely, or revoked (temporarily or permanently) due to a violation or other unforeseen circumstances. While this worst-case scenario should be considered, it is more likely that the key risks will consist of significant delays and the imposition of unforeseen permitting conditions. The pace at which an application for a permit or approval moves through the regulatory process depends largely on a jurisdiction's land use regulations and environmental review process. The federal, state or local building regulatory process also affects customer-side installations. Significant delays can arise if an agency requests voluminous information and studies about the project, or if there are extended negotiations with staff over permit terms and conditions. Gaps in interagency coordination and the intervention or participation of third parties can also lead to delays. Finally, even if all required permits and approvals are secured, an opponent can file a lawsuit which could lead to an injunction that halts construction, inhibits financing, or otherwise imposes additional delay and cost.

The potential risks depend on a number of factors that will vary widely from project to project. Key factors to consider when assessing such permitting and litigation risks include the following: jurisdictions involved, the siting of the project on private or government-owned land, the physical size and footprint of the project, the presence of sensitive natural resources (such as wildlife, scenic views, watersheds, or prime agricultural land) or cultural resources on the site or within the vicinity, the type of technology and intensity of operations, opposition from neighboring land owners and public interest groups or other third parties, and pending or anticipated legislative and regulatory changes.

While it is not possible to eliminate risks entirely, strategies to reduce or mitigate risks can be developed for a particular project based on its unique circumstances. These may include early engagement with agencies and their staff, outreach to third parties that may be affected, siting the project away from sensitive resource areas, designing the project to limit its footprint, and mitigating environmental impacts. Energy storage systems that are co-located, or concurrently permitted, with generation facilities may be able to use or otherwise benefit from the permitting and environmental review that had been conducted for the generation facility, significantly streamlining the process. In addition, a proponent may be able to leverage federal, state, and local policies to promote energy storage that could help clear any potential roadblocks.

7.2.2 Time Considerations

Proponents of energy storage systems should allow sufficient time in the project schedule for the permitting and government approvals process, with appropriate contingencies for appeals and litigation. The time needed to obtain all required approvals ranges from several months to several years, depending on the layers of regulatory review involved and the balance of risk factors outlined above. Consideration should also be given to contractual deadlines for commencement of initial operations and service delivery.

7.2.3 Potential Permits and Approvals Required

Siting

As a threshold matter, the agencies involved and the approvals and consents required will be determined by the geographic location of the energy storage system. For example, facilities sited on federal land require federal approval (*e.g.*, a right-of-way authorization) that is subject to review under the National Environmental Policy Act (NEPA). If federal agency approval or funding is not required, an energy storage facility likely will be subject only to state or local environmental review, the scope and burden of which varies considerably between jurisdictions. Permitting risk may be reduced for energy storage systems that are co-located and/or concurrently permitted with generation facilities or that are sited in previously disturbed areas.

Construction/Development

In addition to siting factors, the type of ESS technology will also determine the agencies involved and the permits and approvals required. For example, some battery installations may have a minimal footprint that reduces or avoids impacts triggered by land disturbance, compared with pumped hydroelectric storage projects with large footprints.

Most permits and approvals required for the development of an energy storage system must be obtained prior to commencement of construction. Permits and approvals required for construction (including any conditions that must be satisfied) should be prioritized over other approvals that are not required until commencement of operations.

Depending on the jurisdiction, environmental impacts from the development of an energy storage system, including the construction process itself, generally need to be analyzed and, in many jurisdictions, mitigated. The impacts from energy storage systems vary by technology, but common impacts to consider include aesthetics, air quality, biological resources, cultural resources, hazards and hazardous materials, and water quality impacts. Agencies may impose conditions and mitigation measures that the project proponent must satisfy, or they may approve an alternative project location or design that has less environmental impacts.

Operation

Once construction is complete, the permits and approvals required for the operations phase are tailored to the type of technology and the inputs and outputs involved. For example, there are a host of rules and regulations at the federal, state, and local levels applicable to the generation, handling, and disposal of hazardous materials and waste. Air emissions, including greenhouse gases and criteria air pollutants, and water and wastewater discharges are also regulated at multiple levels of government. Permits and other rights may be required to procure resources and inputs necessary for operations, such as water rights. Depending on the type of technology and life expectancy of the facility, a decommissioning and site restoration plan may also be required, with accompanying financial assurances.

Grid Integration

In addition to the permits and approvals required for the energy storage system itself, other approvals likely will be required for the interconnection infrastructure that will integrate the storage system with the grid. Transmission, distribution, and interconnection facilities may be permitted as components of the energy storage system, as components of the energy generation facility, or separately as independent projects. Permits and environmental review for interconnection infrastructure may follow a separate regulatory track and timeline, particularly if the infrastructure will serve multiple facilities. Thus, regulatory and litigation risks for interconnection infrastructure should be evaluated independent of the energy storage system itself.

7.3 Legal Framework for Energy Storage System Safety

Energy storage technologies are subject to various federal, state, and local legal and regulatory requirements that are designed to protect workers, the public, and the environment from unreasonable risks. Because energy storage systems may reflect advancement in existing technology—such as solid state and flow batteries—or entirely new technologies, fitting these systems into the existing regulatory framework often poses a challenge to the energy storage industry. The following discussion introduces the main regulatory structures that are in place beyond CSR discussed above to address potential health and safety risks. Of course, this discussion provides only an overview, as risks will vary in scope and significance depending on the type of technology and scale of the system.

7.3.1 Workplace Safety and Training

The U.S. Occupational Health and Safety Administration (OSHA) and its state agency counterparts are the lead agencies that regulate workplace safety, including any workplace that produces or relies on energy storage technologies. The federal Occupational Health and Safety Act outline the regulatory framework applicable to all employers. In almost every state, the requirements of the Occupational Safety and Health Act are administered and enforced by the States pursuant to approved plans. The OSH Act requires almost all employers to develop an Illness and Injury Prevention Plan, or IIPP, which sets forth potential safety risks and develops standards for worker protections in order to prevent any “unreasonable risk of injury.” To develop an IIPP, employers are required to analyze workplace hazards and develop effective protocols to prevent them, which may include personal protective equipment, pre-employment training or certification, accident investigation, and emergency response procedures.

OSHA also develops specific worker safety standards for certain equipment and industries that are known to be particularly hazardous. For example, OSHA recently updated its 1972 standard that prescribes safety protocols for workers in the electric power, generation, and transmission and distribution industry. OSHA has also regulated potentially hazardous energy sources for many years through its “lockout-tagout” protocols that protect service workers who work with electrical equipment. Certain OSHA regulations may be applicable to “new” energy storage technologies, such as the OSHA standards for compressed gas and equipment.

For workplaces that contain highly technical systems, OSHA works with experts in national standard-setting organizations to develop appropriate standards for worker safety. For example, OSHA has worked with various organizations discussed in other parts of this paper. The National Fire Protection Association (NFPA), for example, has developed the National Electrical Code, an ANSI-approved United States standard for the safe installation of electrical wiring and equipment. The NFPA has also developed the Uniform Fire Code, which is an internationally accepted guidance for fire suppression technology that is incorporated into every state’s law. The Uniform Fire Code (UFC) has specific standards for stationary lead-acid battery systems, and NFPA is carefully studying lithium ion and more advanced batteries. Even without guidance for a particular technology, the UFC sets forth key principles to guide fire suppression practices.

Similarly, OSHA has worked with the Institute of Electrical and Electronics Engineers, which has developed operating and safety standards for the installation and maintenance of lead battery storage systems. Finally, OSHA refers to the standards used by Underwriters Labs, which provides internationally accepted life safety and performance certification for electrical components.

Even with ample regulatory guidance, the energy storage s sector should be aware of the processes that can identify potential safety hazards for a specific technology. OSHA provides guidance to industry on the recognized hazard analysis methodologies, including the basic Job Hazard Analysis, Failure Mode and Effect Analysis, and Hazard and Operability Study. However, one of the challenges facing the industry is how to analyze not only the failure of the individual component in a lab setting, but also the potential hazards presented by that failure in the specific use environment. Mitigation of the hazards associated with a single component may require facility redesign.

As with many high-technology employers, energy storage industry participants must be aware of the multiple sets of regulatory requirements as they relate to the various U.S. and international standards discussed herein, to ensure that their workplace environment reflects the most relevant applicable standards, and that employees are trained to work safely with energy storage technology.

7.3.2 Hazardous Materials Management

Both traditional and flow battery systems rely on electrode and electrolyte compounds that are composed of potentially hazardous chemicals. Employers who handle certain threshold quantities of hazardous materials are required to prepare and have available Safety Data Sheets (SDS) under the OSHA Hazard Communication Standard, to ensure employees understand the health and safety risks posed by workplace materials. Pursuant to the federal Emergency Response and Community Right to Know Act (EPCRA), employers must also submit an inventory of their hazardous chemicals to the State Emergency Response Commission, Local Emergency Preparedness Committee, and the local fire department annually.

While OSHA is the lead agency for workplace safety, the Environmental Protection Agency and federal environmental laws govern many aspects of hazardous material handling. In addition to EPCRA, the Resource Conservation and Recovery Act and its implementing regulations (as well as parallel state laws) have detailed regulations for the precautions necessary to prevent hazardous materials releases. Certain unanticipated releases of hazardous materials must be reported to the appropriate emergency response agencies—whether a release requires local, state, and/or federal reporting depends on the nature and quantity of the released material.

7.3.3 Catastrophic Accidents and Liability Risks

Market participants in the energy storage sector, and especially producers and marketers of energy storage technologies, should be prepared to address potential legal liabilities in the event of a catastrophic accident. An industrial accident that injures persons or property will be subject to the basic principles of tort liability, which varies by state. For example, if an explosion or fire causes personal injury or property damage, like any business, an energy storage company may be subject to liability to the extent that an injured party can establish the company's negligence in how it managed the process that led to the accident. In some jurisdictions, a company can be subject to strict (no-fault) liability, if the harmed party can establish that the company was engaged in an "ultrahazardous activity" (*i.e.*, an action or process so inherently dangerous that it cannot be made safe). Whether an activity is ultrahazardous is determined by case-specific analysis. If an injured party establishes that a company's conduct was "malicious, oppressive or in reckless disregard of a plaintiff's rights"—the precise language varies from state to state—he or she may be able to seek an award of punitive damages.

Injuries to workers caused by industrial accidents are covered by a state's workers compensation program, which is administered exclusively by that state. Employers are required by law to purchase workers' compensation benefits for employees or to self-insure for such benefits.

OSHA requires each employer's Illness and Injury Prevention Plan to include a procedure for investigating accidents; an accident that involves employee injury must be recorded by the employer, and if sufficiently serious (i.e. requiring hospitalization), it must also be reported to OSHA or the designated State agency. If the accident results in a fatality, catastrophe (hospitalization of three or more workers), or "incident of national significance" (a mass exposure/injury event), OSHA will conduct a mandatory investigation into the cause of the accident to determine whether a violation of OSHA safety and health standards occurred, and any effect the violation had on the accident. Following that investigation, OSHA may issue a finding of a violation, including proposed civil penalties. In rare instances where there is a "willful violation" of the OSHA standards, the matter may be referred to a federal prosecutor for criminal prosecution.

8.0 Implementation of Goals to Reach Desired End States

For any ESS, the achievement of the desired end-state will require a comprehensive technical and institutional initiative by a large and diverse group of stakeholders. Specifically, it will require the following activities:

- Establishment of a framework for risk assessment and management and the associated processes to evaluate and manage ESS technology risk at all stages of its life
- Technical research to a) characterize fundamental safety-related attributes of ESS technologies and b) address risk reduction ranging from alternative material sets for various technologies to engineered safety methods including hazard suppression
- Development of prudent life-cycle safety testing and evaluation methodologies

- Development of new or enhancement of existing codes, standards and regulations (CSR), including the necessary safety documenting to accommodate existing knowledge, and translation of the growing body of experience and results of other ESS Safety initiative activities into future CSR
- Establishment of ESS requirements for ensuring safety of first and second responders (including post event re-commissioning or decommissioning), ranging from ESS design parameters (consistent with prudent risk management) to on-site signage, training, and information sharing
- Creation of a comprehensive information resource to serve as a clearinghouse of related reports and information, share progress in activities listed above, and document relevant safety incidences and off-normal events that are reported for deployed systems

Reaching the desired end state will require collaboration and contribution from many stakeholders. DOE will serve as a facilitator and convener of stakeholders to coordinate and support advancement of energy storage safety for grid applications. DOE will broadly engage stakeholders and support enhanced leadership by industry or stakeholder associations, as appropriate. DOE will organize an external stakeholder group whose mission will be to advise DOE on efforts to ensure ESS are developed, used, and decommissioned in a safe manner and that communities embrace ESS as safe technologies.

DOE programmatic efforts will focus on four elements:

- ESS safety technology
- Risk assessment and management
- Incident response
- Codes, standards and regulations

The goals, scope, near-term actions, and long-term agenda are described for each of these elements below. Near-term activities that will receive *high priority* are identified with bold italic text. While DOE may serve as a convener and principal performer for some activities that are beyond the current reach of industry and regulators, it is anticipated that many organizations, not mentioned here, will serve in critical roles, provide thought leadership and have extensive involvement.

8.1 ESS Safety Technology

Goal: The scientific and technical basis for ensuring ESS safety is well established and ESS stakeholders are incorporating new technologies that further enhance ESS safety or enable achievement of safe ESS at lower cost.

Scope: Ensuring, enhancing and validating ESS safety is underpinned by scientific and technical understanding of physical and chemical behavior of energy storage systems and associated life-cycle factors affecting their behavior (such as construction, transportation, installation, operation, decommissioning and disposal). This understanding requires both effective testing methods and methodologies (and their implementation), as well as validated models of ESS capable of assessing hazards under both normal and abnormal circumstances. Safety testing methods, informed by both experience and models, will be assembled to address inherent hazards as well as engineered safety systems through all system life stages. Models will be developed to characterize both inherent hazard attributes of materials and designs, as well as evaluate various engineered safety measures. Efforts will also be undertaken to identify and assess the relevant hazard attributes of alternative materials and designs that have the potential to reduce risks or achieve equally satisfactory risk levels at reduced cost.

Near-term Actions: ***Stakeholders will be surveyed to identify the ESS hazards most in need of attention based on the perceived risk levels, deployment activity, CSR status, and incident experience, for major classes of ESS.*** Plans for hazard characterization and mitigation testing and evaluation will be assembled for each major class of ESS. Preliminary models, suitable for hazard analysis for these ESS classes, will be assembled in conjunction with key stakeholders. Preliminary safety testing methodologies for ESS (and components thereof, as appropriate) will be assembled with key stakeholders. Of particular near-term interest is addressing scientific and technological gaps in existing CSR that impede ESS deployment.

Long-term Agenda: Consistent with the risk assessment and management framework, stakeholders will periodically reevaluate the hazards to ensure that safety information is consistent with evolving technologies, at both the component and system level, and the ever-expanding application spaces. Models and testing protocols for characterization and evaluation of ESS hazards will be refined and validated. Efforts will progressively shift from characterization of potential hazards to the development of alternative materials, designs and engineered safety systems that enable thorough safety validation that is economically viable.

8.2 Risk Assessment and Management

Goal: The framework and methodologies for assessing and managing deployment risk for ESS are accepted and adopted by industrial and regulatory stakeholders.

Scope: A general framework for risk assessment will be developed based on existing approaches employed for other established or emerging power system technologies but adapted for ESS use. This risk assessment framework will enable differentiation of risks for specific ESS classes of technologies consistent with existing risk management approaches. The framework will provide a means to harmonize science-based hazard analyses, as well as codes and standards and incidence response considerations. The evolving framework will permit early consideration of the wide range of factors affecting life-cycle safety. Based on this framework, specific tools will be developed to trade off and manage risk elements during design, transport, life-cycle operation, off-normal events and incidents, and retirement.

Near-Term Actions: ***A survey of industry and the responder community will be conducted regarding existing risk management frameworks will be conducted to identify candidate model frameworks as well as elements that might prudently be incorporated from other technologies. A straw-man framework will be prepared and reviewed by industry and regulatory representatives.*** A straw example of an assessment for a specific ESS technology will be developed to help explore the translation of the framework to practice, and the interactions with various other safety related interests such as operations, CSR, permitting, insurance, incident response, etc. Again, this example will be used to revise the framework and address specific technologies.

Long-term Agenda: The risk framework will continue to be refined and the implementation methodology will be applied to specific ESS technologies. Greater effort will be undertaken to harmonize the risk framework across other program elements and to identify and more thoroughly characterize the ESS risk framework and assessment methodologies.

Tools to better characterize the risks and their evolution during specific periods of ESS deployment (e.g. manufacture, acceptance testing, inventory, transportation, commissioning, operation, off-normal events, incident response, decommissioning, recycle or disposal) will be developed and disseminated. These tools are intended to enable tradeoff analysis to ensure safe systems that accommodate other societal goals (e.g. economic, environmentally desirable, efficient, robust, reliable, etc.).

8.3 Incident Response

Goal: First and second responders (including on-site staff) are well informed and equipped to address hazardous incidents regarding ESS, at all life stages, with no health impacts and minimal property loss.

Scope: Incident response focuses on preparation and training for first and second responders who may be called upon to enter hazardous conditions to limit destructive consequences of an ESS incident. Approaches for managing incident progression and consequences for all ESS will be identified and disseminated, thereby minimizing potential safety consequences (during and after the incident), and limiting property loss. Model ESS hazard documentation, incident action plans and incident response guidelines will be prepared and disseminated. Recommended notification, postings, system design, hazard management, and incident response practices will be provided. CSR relevant to ESS safety and incident response will be updated to address ESS. Training programs will be developed and used to prepare incident responders to obtain an awareness level to best deal with potentially hazardous ESS events, for all types of ESS and for all ESS life stages. ESS incident response issues amenable for addressing by improved technology will be identified and communicated to those developing ESS safety technology. Furthermore, testing and evaluation of incident response technology will be conducted. ESS incidents involving potentially hazardous circumstances will be catalogued and used to improve incident response methods, equipment, CSR, and after-incident evaluation, re-commissioning or decommissioning.

Near-term Actions: ***Documentation of reported ESS hazardous incidents will be assembled for use by all stakeholders. Guidelines for ESS hazard identification and documentation, postings and signage, and incident response preparations will be established.*** General guidelines on system design and installation, including recommendations for site safety systems (e.g. fire suppression) will be developed. ***A review of ESS CSR relevant to incident response requirements will be undertaken.***

Long-term Agenda: An ESS education and training curriculum will be developed and used for educating incident responders. Testing and evaluation of incident response technologies for ESS will be undertaken consistent with priorities established with incident response stakeholders. CSR development will be monitored and updates will be identified to enable improved incident response. Guidelines for ESS design and installation will be updated as new technologies become available, additional information on ESS incidents is documented, and new engineered safety systems are implemented.

8.4 Codes, Standards and Regulations

Goal: Codes, standards and regulations enable the deployment of safe ESS in a comprehensive, non-discriminatory, and institutionally efficient manner.

Scope: The tapestry of codes, standards and regulations that are relevant to safe development, deployment, and disposal of ESS, combined with the array of ESS technologies, and suite or potential applications create a complex environment for assurance of ESS safety. Therefore, the following actions will be undertaken: characterizing this environment; identifying and addressing critical near-term issues affecting CSR treatment of storage; expanding the breadth and depth of CSR treatment of ESS; and incorporating advances born of ongoing research, development, demonstration, and deployment in ESS-relevant CSR. Coordinated engagement of ESS stakeholders to prepare and prosecute revision and update of CSR through official CSR organizations will be performed, initially to provide timely contributions to ongoing CSR revision processes. Comprehensive mapping and coordination of safety-related efforts undertaken by DOE-coordinated activities, as well as those of other stakeholders such as Electric Power Research Institute (EPRI), Energy Storage Association (ESA), National Alliance for Advanced Technology Batteries (NAATBatt), National Electrical Manufacturers Association (NEMA), National Fire Protection Association (NFPA), etc., to ensure timely, comprehensive, technology neutral support of standards and code-making bodies will be undertaken to accomplish the goal. Guidance will be provided to ESS suppliers, project developers, utilities, customers, regulators and the CSR community regarding ESS-relevant CSR, not only to minimize potential safety incidents but also to improve CSR implementation efficiency. ESS-relevant CSR will be catalogued and tracked to enable the ESS community to remain abreast of the status of CSR requirements.

Near-Term Actions: ***A description of how codes and standards relevant to ESS are structured and used will be prepared as a primer on ESS CSR. A catalogue of existing relevant CSR that are relevant to ESS will be assembled. Engagement of time-critical CSR revision processes that are important for ESS will be undertaken (e.g. the National Electrical Code) in collaboration with ESS industry stakeholders.*** A thorough review of existing CSR regarding gaps related to ESS will be conducted; the gaps will be prioritized and approaches for their resolution will be determined; efforts will be undertaken to resolve the gaps based on their priority, focusing on those that are potential "showstoppers." Authorities having jurisdiction (AHJ) will be engaged, in regions where ESS is being actively deployed, to provide information and assistance related to resolving CSR uncertainties, and to gain insights on CSR challenges for ESS.

Long-Term Agenda: Gaps in CSR that require additional technical research, development, and demonstration will be identified and specific technical RD&D will be defined. Organizations responsible for promulgation of CSR will be engaged in an on-going, active basis to facilitate the progress of CSR revisions that are necessary to enable or facilitate deployment of ESS. CSR-relevant information and experience will be assembled and disseminated in a manner that enables frequent update and feedback. Where possible, model-CSR will be assembled to guide organizations in developing, modifying, or applying ESS-relevant CSR. An initiative will be undertaken to provide up-to-date training and education on ESS-relevant CSR. Periodic review of existing and proposed CSR relevant to ESS will be performed. Periodic surveys of CSR experiences and "events" will be performed to enable tuning of CSR support activities, and ensure up-to-date information for AHJ officials.

Appendix

A. List of DOE OE Energy Storage Safety Workshop Participants and Affiliations

Last Name	First Name	Affiliation
Gyuk	Imre	DOE OE
Acker	William P.	New York Battery and Energy Storage Technology Consortium, Inc.
Agarwal	Arun	DNV GL
Aguirre	Victor	Tucson Electric Power
Akhil	Abbas	Sandia National Laboratories, NM
Allendorf	Sarah	Sandia National Laboratories, CA
Andrews	George	Oak Ridge National Laboratory
Atcitty	Stanley	Sandia National Laboratories, NM
Baumgart	Gary	Curtiss Wright
Bear	Neal	FM Global
Becker	Martin	Princeton Power
Bocra	Gina	NYC Building Commission
Borneo	Dan	Sandia National Laboratories, NM
Bowles	Ryan	Duke Energy
Chalamala	Babu	SunEdison
Chaos	Marcos	FM Global
Chatwin	Troy	General Electric Company
Conover	Dave	Pacific Northwest National Laboratory
Cook	Kevin	McKean Defense
Danley	Doug	Contractor to NRECA Cooperative Research Network
Darrow	Chris	Imergy Power Systems
Dedrick	Daniel	Sandia National Laboratories, CA
Doughty	Daniel	Battery Safety Consulting, Inc.
Drew	Tim	California Public Utilities Commission
Duffy	Chad	National Fire Protection Association

Ferreira	Summer	Sandia National Laboratories, NM
Fioravanti	Richard	DNV GL
Florence	Laurie B.	UL
Franks	Ryan	National Electrical Manufacturers Association
Ganguli	Sham	FM Global
Hanley	Charles	Sandia National Laboratories, NM
Hearne	Sean	Sandia National Laboratories, NM
Hires	Jeff	GS Battery
Hockney	Richard	Beacon Power
Horne	Craig	EnerVault
Huque	Aminul	Electric Power Research Institute
Kamath	Haresh	Electric Power Research Institute
Kannberg	Landis	Pacific Northwest National Laboratory
Lazarewicz	Matt	Helix Power
Lee	Sang Bok	University of Maryland
Li	Liyu	UniEnergy Technologies
Lin	Roger	A123 Systems, LLC
Marshall	Andrew	Primus Power
McNutt	Ty	APEI
Meola	Carmine	ACI Technologies, Inc.
Noland	Jamie	Aquion Energy
Orendorff	Christopher	Sandia National Laboratories, NM
Orkney	Justin	Tucson Electric Power
Orrell	Andrew	Sandia National Laboratories, NM
Paiss	Matt	San Jose Fire Department
Pinksy	Naum	Southern California Edison
Porter	David	S&C Electric Company
Rima	Chris	Tucson Electric Power
Rinehart	Larry	Rinehart Motion
Rose	David	Sandia National Laboratories, NM

Scott	Paul	TransPower
Smith	Ryan	EPC Power
Smith	Matthew	NextEra Energy Resources
Sprenkle	Vince	Pacific Northwest National Laboratory
Stosser	Michael	Sutherland Asbill & Brennan LLP
Sullivan	John	Sandia National Laboratories, CA
Torre	William	University of California, San Diego
Weed	Russ	UniEnergy Technologies
Wessels	Colin	Alveo Energy
Wiles	John	New Mexico State University
Willard	Steve	PNM Resources
Willette	Kenneth	National Fire Protection Association
Wills	Robert	Intergrid, LLC/ Aquion Energy
Wunsch	Tom	Sandia National Laboratories, NM

B. Abridged List of Relevant Codes, Standards and Regulations

Several Occupational Safety and Health Administration (OSHA) standards explicitly require employers to have emergency action plans for their workplaces:

General Industry (29 CFR 1910) Requirements for Emergency Response and Preparedness[75]

General Requirements for Workplaces:

- 29 CFR 1910.36 Design and construction requirements for exit routes
- 29 CFR 1910.37 Maintenance, safeguards, and operational features for exit routes
- 29 CFR 1910.151 Medical services and first aid
- 29 CFR 1910.157 Portable fire extinguishers
- 29 CFR 1910.165 Employee alarm systems

Additional Requirements for Workplaces Referenced in Other Requirements:

- 29 CFR 1910.38 Emergency action plans
- 29 CFR 1910.39 Fire prevention plans
- 29 CFR 1910.269 Electric power generation, transmission and distribution
- UL 1642: Lithium Batteries
- UL 1973: (Proposed) Batteries for Use in Light Electric Rail (LER) Applications and Stationary Applications
- UL 2054: Household and Commercial Batteries
- UL Subject 2271: Batteries For Use in Light Electric Vehicle Applications
- UL 2575: Lithium-Ion Battery Systems for Use in Electric Power Tool and Motor Operated, Heating and Lighting Appliances
- UL Subject 2580: Batteries for Use in Electric Vehicles

The National Fire Protection Association has several standards on ESS and Fire Protection recommended practices for electrical generating plants:

- NFPA 110 – Standard for Emergency and Standby Power Systems

---

[75] https://www.osha.gov/Publications/osha3122.html

- NFPA 111 - Standard on Stored Electrical Energy Emergency and Standby Power Systems
- NFPA 850 - Recommended Practice for Fire Protection for Electric Generating Plants and High Voltage Direct Current Converter Stations
- NFPA 851 - Recommended Practice for Fire Protection for Hydroelectric Generating Plants
- NFPA 853 - Standard for the Installation of Stationary Fuel Cell Power Systems

C. References for Validation Techniques

1. Fire Retardants

Name of Fire Retardant	Reference
Phosphate/Phosphonate	
Triphenylphosphate (TPP)	[a15]
Vinyl ethylene carbonate (VEC) + biphenyl (BP) + TPP	[a16]
Dimethyl methylphosphonate (DMMP)	[a17] [a18]
Polyphosphonate	[a19]
Triphenyl phosphate (TPP), tris(trifluoroethyl)phosphate (TFP)	[a20]
Phosphorus-containing esters	[a21]
Methoxyethoxyethoxyphosphazenes	[a22]
Bis(N,N-diethyl)methoxyethoxymethylphosphonamidate	[a23]
Triphenyl Phosphate (TPP) and Trinutyl Phosphate (TBP)	[a24]
Trimethyl Phosphate (TMP) and Triethyl Phosphate (TEP)	[a25]
Ethylene Ethyl Phosphate(EEP) + TMP	[a26]
Diphenyloctyl phosphate(DPLP)	[a27]
Cyclic phosphate	[a28]
Fluorinated Phosphate/Ethers	
Tris(Trifluoroethyl)Phosphate (TFP), Bis(trifluoroethyl)Methyl Phosphate (BMP) and Trifluoroethyl Phosphate (TDP)	[a29, 30]
Flame retardant additives	
Methyl Nonafluorobutyl Ether (EFE)	[a31, 32]
Perfluoro-Ether	[a33]
Hydrofluoro Ether (HFE)	[a34, 35]
Phosphites	
Tris(2,2,2-Trifluoroethyl) Phosphite (TTFP)	[a36, 37]

Triethyl and Tributyl Phosphite	[a38]
Trimethyl phosphite (TMP)	[a39]
Ionic Liquids	
N-butyl-N-methylpyrrolidinium bis(fluorosulfonyl)imide (PYR14FSI)	[a40, 41]
N-butyl-N-methylpyrrolidinium bis(trifluoromethansulfonyl)imide, PYR14TFSI	[a42]
1-ethyl-3- Methylimidazolium tetrafluoroborate (EMIBF4)	[a43]
Tri-(4-methoxythphenyl) phosphate (TMTP)	[a44]
Miscellaneous compounds	
Hexamethylphosphoramide (HMPA)	[a45]
Dimethyl Methylphosphonate (DMMP)	[a46]
Phosphazene	
Phoslyte	[a14]
Ethyleneoxy Phosphazenes	[a22, 47]
Phosphazene-based flame retardants	[a48]
Hexamethoxycyclotriphosphazene	[a49, 50]

[a15] E.G. Shim, T.H. Nam, J.G. Kim, H.S. Kim, S.I. Moon, J Power Sources, 172 (2007) 919.
[a16] T.H. Nam, E.G. Shim, J.G. Kim, H.S. Kim, S.I. Moon, J Electrochem Soc, 154 (2007) A957.
[a17] H.F. Xiang, H.Y. Xu, Z.Z. Wang, C.H. Chen, Journal of Power Sources, 173 (2007) 562.
[a18] J.K. Feng, X.P. Ai, Y.L. Cao, H.X. Yang, Journal of Power Sources, 177 (2008) 194.
[a19] B. Dixon, MRS Bulletin, 30 (2005) 161.
[a20] D.H. Doughty, E.P. Roth, C.C. Crafts, G. Nagasubramanian, G. Henriksen, K. Amine, J Power Sources, 146 (2005) 116.
[a21] B.K. Mandal, A.K. Padhi, Z. Shi, S. Chakraborty, R. Filler, J Power Sources, 161 (2006) 1341.
[a22] S.T. Fei, H.R. Allcock, J Power Sources, 195 (2010) 2082.
[a23] J.L. Hu, Z.X. Jin, H. Hong, H. Zhan, Y.H. Zhou, Z.Y. Li, J Power Sources, 197 (2012) 297.
[a24] Y.E. Hyung, D.R. Vissers, K. Amine, J Power Sources, 119 (2003) 383.
[a25] X.M. Wang, E. Yasukawa, S. Kasuya, J Electrochem Soc, 148 (2001) A1058.
[a26] H. Ota, A. Kominato, W.J. Chun, E. Yasukawa, S. Kasuya, J Power Sources, 119 (2003) 393.
[a27] E.G. Shim, T.H. Nam, J.G. Kim, H.S. Kim, S.I. Moon, Electrochim Acta, 54 (2009) 2276.
[a28] Y.J. Li, H. Zhan, L. Wu, Z.Y. Li, Y.H. Zhou, Solid State Ionics, 177 (2006) 1179.
[a29] K. Xu, S.S. Zhang, J.L. Allen, T.R. Jow, J Electrochem Soc, 149 (2002) A1079.

[a30] M. Smart, K.A. Smith, R.V. Bugga, F.C. Krause, U.S. Patent 2010/0047695 A1, 2010.
[a31] J. Arai, J Appl Electrochem, 32 (2002) 1071.
[a32] J. Arai, J Electrochem Soc, 150 (2003) A219.
[a33] M. Morita, T. Kawasaki, N. Yoshimoto, M. Ishikawa, Electrochemistry, 71 (2003) 1067.
[a34] K. Naoi, E. Iwama, Y. Honda, F. Shimodate, J Electrochem Soc, 157 (2010) A190.
[a35] G. Nagasubramanian, C. Orendorff, J Power Sources, 196 (2011) 8604.
[a36] S.S. Zhang, K. Xu, T.R. Jow, Electrochem Solid St, 5 (2002) A206.
[a37] S.S. Zhang, K. Xu, T.R. Jow, J Power Sources, 113 (2003) 166.
[a38] N.D. Nam, I.J. Park, J.G. Kim, Met Mater Int, 18 (2012) 189.
[a39] H.Y. Xu, S. Xie, Q.Y. Wang, X.L. Yao, Q.S. Wang, C.H. Chen, Electrochim Acta, 52 (2006) 636.
[a40] G.T. Kim, S.S. Jeong, M. Joost, E. Rocca, M. Winter, S. Passerini, A. Balducci, J Power Sources, 196 (2011) 2187.
[a41] A. Lewandowski, A. Swiderska-Mocek, J Power Sources, 194 (2009) 601.
[a42] S.F. Lux, M. Schmuck, S. Jeong, S. Passerini, M. Winter, A. Balducci, Int J Energ Res, 34 (2010) 97.
[a43] H. Nakagawa, S. Izuchi, K. Kuwana, T. Nukuda, Y. Aihara, J Electrochem Soc, 150 (2003) A695.
[a44] J.K. Feng, Y.L. Cao, X.P. Ai, H.X. Yang, Electrochim Acta, 53 (2008) 8265.
[a45] S. Izquierdo-Gonzales, W.T. Li, B.L. Lucht, J Power Sources, 135 (2004) 291.
[a46] S. Dalavi, M.Q. Xu, B. Ravdel, L. Zhou, B.L. Lucht, J Electrochem Soc, 157 (2010) A1113.
[a47] S.T. Fei, H.R. Allcock, Mater. Res. Soc. Symp. Proc., 1127 (2009) 1127-T01.
[a48] T. Tsujikawa, K. Yabuta, T. Matsushita, T. Matsushima, K. Hayashi, M. Arakawa, J Power Sources, 189 (2009) 429.
[a49] C.W. Lee, R. Venkatachalapathy, J. Prakash, Electrochem Solid St, 3 (2000) 63.
[a50] J. Prakash, C.W. Lee, K. Amine, U.S. Patent, No. 6,455,200 (2002).

2. *Flash Point for some Common Organic Materials*

Flash Point* for some of the common organic materials

Chemical	Flash Point (ºC)
Acetone	-17
Ethanol	17
Gasoline	-42
DEC	33
DMC	18
EMC	23
EC	145
PC	132
HFEs (TMMP, TPTP)	No flash point
IL (1-ethyl-3-metgyl imadazolium TFSI)	283
Canola oil	327

Acronym List

A

AHJ	Authorities Having Jurisdiction
ANSI	American National Standards Institute
ASTM	American Society for Testing and Materials

B

BEWAG	West Berlin Electric Utility Company
BMP	Bis(trifluoroethyl)Methyl Phosphate
BP	Biphenyl

C

C	Centigrade
CAES	Compressed Air Energy Storage
Cl	Chloride
CID	Current interrupt devices
CO_2	Carbon Dioxide
CRA	Community Risk Assessment
CSR	Codes, Standards, and Regulations

D

DC	Direct current
DEC	Diethyl carbonate
DMC	Dimethyl carbonate
DMMP	Dimethyl methylphosphonate
DOE	Department of Energy
DSC	Differential Scanning Calorimetry

E

EC	Nusan 30 E.C.
EDV	Electric-drive vehicle
EFE	Methyl Nonafluorobutyl Ether
EMC	Ethyl methyl carbonate
EMIBF4	Methylimidazolium tetrafluoroborate
EPCRA	Emergency Response and Community Right to Know Act
EPRI	Electric Power Research Institute
ESA	Energy Storage Association
ESS	Energy Storage System
EV	Electric Vehicle

F

FEMA	Federal Emergency Management Agency
FERC	Federal Energy Regulatory Commission
FMEA	Failure Mode and Effects Analysis
F_P	Flash Point
FPRF	Fire Protection Research Foundation
FR	Fire Retardants

G

GW	Gigawatt

H

HFE	Hydrofluoroethers
HMPA	Hexamethylphosphoramide

I

ICE	Internal combustion engine
IEC	International Electrotechnical Commission

IIPP	Illness and Injury Prevention Plan
IL	1-ethyl-3-metgyl imadazolium TFSI
IR	Infrared
ISO	Independent system operator

K

kW/kWh	Kilowatt/Kilowatt hour

L

LER	Light Electric Rail
Li	Lithium
LOI	Limited oxygen index

M

MW/MWh	Megawatt/megawatt hour

N

Na	Sodium
NAATBatt	National Alliance for Advanced Technology Batteries
NEMA	National Electrical Manufacturers Association
NEPA	National Environmental Policy Act
NFPA	National Fire Protection Association
Ni	Nickel

O

OE	Office of Electricity Delivery and Energy Reliability
OSHA	Occupational Safety and Health Administration

P

Pb	Lead

PC	Propylene carbonate
PPE	Personal protective equipment
PREPA	Puerto Rico Electric Power Authority
PTC	Positive temperature coefficient
PYR14FSI	N-butyl-N-methylpyrrolidinium bis(fluorosulfonyl)imide

R

R&D	Research and Development
RTO	Regional transmission organization

S

s	Seconds
SDO	Standards development organization
SDS	Safety data sheets
SET	Self-extinguishing time
Si	Silicon
SMES	Superconducting Magnetic Energy Storage

T

TDP	Trifluoroethyl phosphate
TFSI	Bis(trifluoromethanesulfonyl)imide, trifluoromethanesulfonimide
TMMP	2-trifluoromethyl-3methoxyperfluoropentane
TMTP	Tri-(4-methoxythphenyl) phosphate
TPTP	Trifluoropentane
TTFP	Tris(2,2,2-Trifluoroethyl) Phosphite

U

UFC	Uniform Fire Code
UL	Underwriters Laboratories
UPS	Uninterruptible power supplies
USABC	United States Advanced Battery Consortium

V

Vdc	Voltage direct current
VEC	Vinyl ethylene carbonate
VRB	Vanadium Redox Flow