ATTACHMENT F: SAFETY BEST PRACTICES[1]

Due to the market readiness and scalability, installations of stationary lithium-ion battery energy storage systems are ramping up quickly to play a major role in California's clean energy portfolio. California's dependence on this technology is expected to grow from just over 2,500 MW at the end of 2021 to potentially tens of gigawatts by 2045. As installations accelerate, so does the urgency to address safety.

Over the course of one year, from September 2021 through September 2022, safety events occurred at each of the three separate (and distinct) grid-scale battery systems installed on California's Moss Landing site. These events, plus the industry's broader experience with safety events over the last decade, underscore the need to manage the risks stemming from hazardous materials in batteries and the unique properties of thermal runaway. For the safety and reliability of California's electricity system the CPUC and other stakeholders will need to continuously monitor and guide safe designs, development, maintenance, and operations of stationary batteries according to best practices.

Energy storage safety is a risk management issue—and a complex one. Large-scale battery systems in themselves are complex with many potential points of failure and potential situations that could lead to harm from fire, thermal runaway, or explosion. How these systems interface with the local environment is a challenge. Effective management and mitigation of these risks also require communication and coordination channels that are a challenge to develop given the number and scope of parties involved.

Historically, major safety-related events involved about 2% of large-scale battery storage installations in the U.S., occurred within 1–2 years of installation, and destroyed about 1–2% of its capacity. Based on this very limited information, for every 10 GW of new battery storage installed in California it would be reasonable to expect a handful of safety-related events at new sites, affecting operations of installations potentially several hundred MW in size. This outlook may change as we observe lithium-ion batteries age and as the industry evolves towards different technologies.

The observed range of outcomes of actual safety-related events provide opportunities to learn and improve battery technology. These events help us to better understand the risk profile of battery storage investments and the potential harm to people, communities, the environment, and electricity supply when risks are poorly understood, under-mitigated, or under-managed. Investigations and assessments of these events have driven and shaped the industry's efforts towards improving safety best practices.

This attachment aims to provide the most current understanding of safety best practices for stationary energy storage systems with a focus on lithium-ion batteries. We draw from industry studies, lessons learned from specific safety-related events, and expert opinion to summarize safety risks and remedies associated these installations. Although this attachment (and most of the industry's codes and standards we reference) focuses on lithium-ion batteries, many of the best practices we outline are translatable to other energy storage technologies as they reach commercial scalability.

We address three major questions:

- **What are the key safety issues**, considering actual events and types of safety impacts we observe?
- **What are current best practices**, including perspectives of regulators, utilities, technical experts, and energy storage developers?
- **What are the remaining concerns and next steps**?

[1] This is an attachment to the CPUC Energy Storage Procurement Study Access the main report and other attachments at www.lumenenergystrategy.com/energystorage.

CONTENTS

Definition of Safety

We define **safety risk** as the possibility of the following undesirable outcomes of energy storage installation and operations: harm to humans, harm to surrounding communities, and/or harm to the environment. These outcomes may have secondary negative impacts in the form of destruction of infrastructure and property, associated financial losses, and/or reduced reliability of electricity supply.

It follows that **safety** is our ability to mitigate and manage those defined risks of harm. For the purposes of this paper, energy storage equipment, hardware, and software safety reflect the ability of the installation, as it is designed and built, to mitigate and manage system failures that lead to undesirable outcomes. The effectiveness of safe operations, procedures, and processes depend upon the safety of a system's components and design. Safe operations, procedures, and processes also refer to additional actions involved parties take to further reduce risks over the life of an energy storage installation.

Specific safety thresholds, defining a "safe" versus "unsafe" installation, must be established by the regulatory authority as the acceptable amount of residual risk after mitigation and management efforts are in place. Generally, we find that public reactions and the evolution of safety codes and standards imply that any degree of direct harm to humans, the environment, or surrounding communities is unacceptable and should be avoided. A "safe" failure, for example, results in no harm to humans, communities, nor the environment—although it may result in complete destruction of the energy storage system. From a regulatory perspective, safety thresholds must also be in harmony with other regulatory objectives of reliable and resilient electricity supply, avoiding the harm of fossil fuel-based energy investments, and cost-effectiveness. So, even a "safe" failure, as defined by safety codes and standards, is undesirable from an electricity regulator's perspective unless damage to the storage system and other infrastructure is minimal and recovery is within an acceptable timeframe.

Best practices in safety are clearer and more effective if they are determined with these specific safety objectives and risk tolerances in mind. In this paper we do not speak for the CPUC on their safety objectives and risk tolerances. However, we do make the general assumption of an extremely low tolerance for any direct harm to humans, the environment, or surrounding communities. We also assume some desire to (a) synergize with efforts to support the reliability and resiliency of electricity supply, and (b) consider impacts on ratepayer cost-effectiveness.

Fire Versus Thermal Runaway

The main vehicles of harm from an energy storage system are uncontrolled fire and thermal runaway.

In our research and in various accounts of actual safety-related events we find a strong theme of confusion over the characteristics of thermal runaway versus fire. Specifically, we observe that insufficient knowledge transfer and coordination among the technical community, utilities, emergency responders, and regulators—on how thermal runaway is distinct as a chemical process, how to prevent it, and what to do if it starts—significantly contributes to undermanaged safety risk.

A few important characteristics of thermal runaway are as follows:

- Thermal runaway is a chemical reaction **distinct from fire** but with similar characteristics.
- Thermal runaway is similar to fire in that it is preceded by a temperature spike (which may or may not be due to a short circuit) and it releases significant heat and pressure once initiated.

- Lithium-ion battery cells in thermal runaway rupture and release large volumes of **toxic and flammable gases** including hydrogen fluoride. If the released gases come in contact with water they produce environmental contaminants including hydrofluoric acid (CDC n.d.).
- Thermal runaway is similar to fire in that it can lead to a catastrophic chain reaction, or **thermal runaway propagation**, if it is able to heat nearby battery cells beyond certain thresholds.
- If oxygen is present, **thermal runaway can also start a fire** as surrounding materials are overheated or damaged surrounding materials and with buildup of flammable gases.
- However, thermal runaway is distinct from fire in that it is an internal chemical reaction that **does not involve oxygen or flame**.
- Thus **thermal runaway cannot be stopped by firefighting techniques** to deprive fire of oxygen, nor can it be observed by presence of flame.

Propagation of thermal runaway through an energy storage system can be limited by two methods:

- The first method is to disperse its fuel—in this case, battery cells. As a practical matter fuel is best dispersed <u>prior to a thermal runaway event and as part of the design of the energy storage system</u>. This can be done by building a system with sufficient physical and/or thermal barriers between cells, modules, and racks.
- The second method is to cool thermal runaway enough to interrupt the chain reaction to surrounding cells. In practice, this has been most frequently attempted by application of large volumes of water spray, albeit with risk of worsening the situation depending on battery chemistry and packaging, arcing from energized equipment, chemical reaction and runoff (e.g., production of flammable gases, hydrofluoric acid), and/or steam-related damage to the system.

Water spray in controlled lab experiments has been shown to inhibit thermal runaway propagation temporarily and with extremely large volumes of water (Zhang et al. 2021; Long et al. 2013.). In practice, thermal runaway propagation in large stationary systems has not been successfully "extinguished" (a misleading fire-related term) by emergency responders once it starts. Limitations on exactly where water can be safely applied, coupled with the very large volumes of water needed, have made water spray as an emergency treatment of thermal runaway mostly ineffective with stationary energy systems in practice. Future system and site designs may improve the effectiveness of water applications. Overall, proactive and preventative measures to slow or limit thermal runaway through <u>energy storage system design</u> and to contain its impacts through <u>site configuration</u> are essential components of an effective risk management approach.

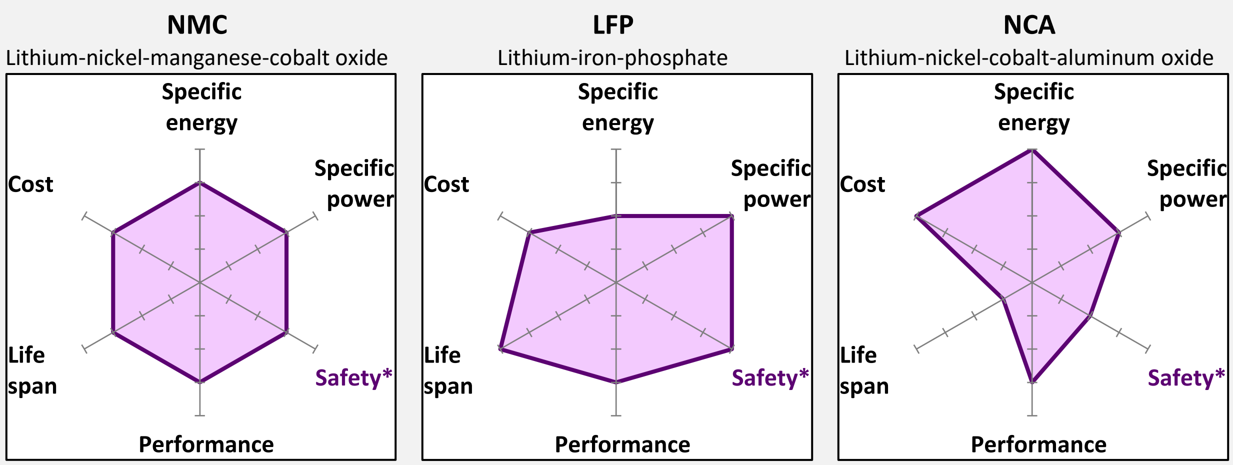
When faced with actual thermal runaway, industry literature and case studies indicate emergency responders' most effective response is to focus on site containment rather than on trying to "extinguish" thermal runaway—especially if responders do not have specific information about what it would take to stop or slow thermal runaway propagation at a particular site. This containment approach includes efforts to (a) prevent heat and flame from spreading to surrounding area and structures, (b) prevent toxic gas release from harming nearby people and communities, and (c) maintain a safe distance from the storage system and allow thermal runaway to self-extinguish. In the section below, "Case Studies of Safety-Related Events" we highlight some of the unmistakably brave but largely unsuccessful trial-and-error emergency responders have gone through when attempting to extinguish or slow thermal runaway propagation once it starts.

How Lithium-Ion Chemistries Compare

Underlying battery chemistries differ in how prone they are to thermal runaway and this is an important safety risk factor to consider. Battery chemistries have other tradeoffs that must also be considered in order to develop a market-ready and scalable technology (Figure 1).

In 2021 the dominant chemistry in global stationary battery energy storage markets—and in California's stationary battery energy storage fleet—is **lithium-nickel-manganese-cobalt oxide (NMC)**. NMC measures relatively well across many dimensions, including energy and power ratings, safety, performance under heat and cold, life span, and cost. Thermal runaway is typically triggered at 410°F (210°C) with additional risk at a high state of charge (Cadex 2019). In practice, however, cost and supply chain issues with cobalt, plus rare but dramatic safety failures and public scares, have driven developers and electricity system planners to consider alternative chemistries. Wood Mackenzie projects NMC market share in global stationary energy storage to drop from 60% in 2020 to 30% in 2030 (Wood Mackenzie 2020).

Lithium-iron-phosphate (LFP), by comparison, is projected to grow from 15% market share in global stationary battery energy storage in 2020 to 35% by 2030 (Wood Mackenzie 2020). LFP generally measures better in safety, power rating, and life span compared to NMC, with the tradeoff of a lower energy rating. Previously higher cost than NMC, LFP total installed costs dropped slightly below NMC by the end of 2021 (Viswanathan et al. 2022). LFP is more tolerant of full charge and high voltage, but it has higher stationary energy losses than NMC. Thermal runaway is typically triggered at a higher temperature of 518°F (270°C) regardless of state of charge (Cadex 2019). LFP is considered one of the safest lithium-ion chemistries.



*Thermal runaway triggered at **410°F** (210°C) with additional risk at a high state of charge

*Thermal runaway triggered at **518°F** (270°C)

*Thermal runaway triggered at **302°F** (150°C), with additional risk at a high state of charge

Note: Higher score reflects more desirable characteristics, e.g., higher cost score means lower cost.
Source: Modified from (Cadex 2019) and using updated cost data from (Viswanathan et al. 2022).

Figure 1: Key tradeoffs of lithium-ion battery chemistries.

Lithium-nickel-cobalt-aluminum oxide (NCA) also has a substantial global market share: about 15% in 2020. Wood Mackenzie projects NCA's market share to grow to about 20% by 2030 (Wood Mackenzie 2020). NCA is lower cost compared to NMC, but it measures worse in safety. Thermal runaway is triggered at a lower temperature of 302°F (150°C), with additional risk at a high state of charge as with NMC (Cadex 2019).

Risk Management of Complex Systems

Risk management of a complex system is a difficult process of addressing many layers of risks that are interrelated. Throughout this paper we refer to four layers of risk: points of failure, failure modes, system risks, and residual risk.

Points of failure. An energy storage system has many components especially considering the number of individual battery cells required for a lithium-ion battery system. Lithium-ion systems involve about 5,000 cells per MWh of capacity, which scales up to millions of cells making up the 300+ MWh systems being installed in the 2020s. Each cell and other component of the system is a potential **point of failure**—the risk of which can be minimized via quality control, testing, and ongoing monitoring and maintenance but cannot be entirely eliminated.

Failure modes. Failure of a single component (such as one cell) has the potential to trigger thermal runaway and instigate a cascading catastrophic event. Ex post investigations into actual events have yielded valuable information about how potential points of failure translate into **failure modes**. Failure modes are essentially points of failure expressed in the context of a broader situation, like overheating due to a short circuit or flaws in hardware design.[2] Development and refinements of industry-wide codes and standards, and adhering to them proactively, are crucial to addressing the risks of failure modes.

System failure. Risk management of an energy storage installation must also recognize it as a complex system in which failure modes can emerge and combine in unexpected ways. Failures within a complex system can have a multiplier effect on undesirable outcomes that are not well understood simply by summing the risks of individual failure modes. Ex post investigations into actual events and codes and standards address complex system risk to some degree and help us to understand how to mitigate large fires, thermal runaway propagation, and hazardous explosions. But guidance from these investigations and from even the most up-to-date codes and standards must be supplemented with local and site-specific expertise on a specific installation.

Residual risk. A prudent risk management approach accepts that, despite even the best risk management and mitigation activities, failures will happen at unexpected times and in unexpected places. Strategies to address this residual risk include plans to slow and contain fire, thermal runaway, and explosion if they do happen, and fail-safes to avoid cascades into the worst outcomes for people, the environment, property, and reliability.

[2] For example, see failure modes outline in (Chiu et al. 2013).

Safety Events in Context

All electricity infrastructure creates safety risk that needs to be managed through a combination of technology, design, and ongoing maintenance and operating procedures—battery storage systems are not unique in this. But as a relatively new technology and application many states are poised to invest significantly in, safety-related events draw widespread media coverage and public concern. What we know so far is that although these events are rare they can have dramatic impacts on the health of individuals and surrounding communities. These events can also have secondary impacts on the reliability of electricity supply to customers and on ratepayer costs.

At the end of 2019 the U.S. had 163 large-scale battery storage systems installed with 1,000 MW/1,700 MWh capacity with an average system size of 6 MW (EIA 2021). Up to that time only three known major safety-related events occurred, involving only 2% of installations. Those events resulted in destruction of 18 MW/14 MW of battery storage, or only 1–2% in terms of total U.S. capacity. All three situations, however, involved significant emergency response efforts, including one event in the city of Surprise, Arizona that resulted in severe injuries to several responders. All three also occurred about 1–2 years after initial installation of the systems.

Between beginning of 2020 and end of September 2021 large-scale battery storage MW capacity tripled in the U.S.: increasing by 2,200 MW to almost 3,300 MW (EIA 2022). Most of these new installations occurred in 2021. Within that timeframe in 2020 and 2021 another two events occurred at large-scale battery storage systems in the U.S. Relative to prior events, both were apparently minor events and perhaps reflecting evidence of industry improvements in safety risk management. It remains to be seen what unmanaged risks will be revealed at newly installed sites, as well as aging existing sites, over the next few years.

Each safety-related event gives the industry an opportunity to learn and improve battery technology and how we use it. These events drive a great deal of the industry's discussion around how to improve safety best practices and address risk management gaps that are revealed. The next sections summarize historical safety-related events, known and observed impacts, and lessons learned.

Case Studies of Safety Events

This section includes summaries of ten safety-related events with stationary energy storage battery systems in the U.S., plus discussion of events in Australia and South Korea.[3] To collect this information we reviewed technical reports, media and public accounts, and various assessments within the fire safety and energy storage research and policy communities. Our selected case studies include:

- **Kahuku Wind Farm**—August 2012 in Kahuku, Hawaiʻi
- **Elden Substation**—November 2012 in Flagstaff, Arizona
- **Franklin Facility**—August 2016 in Franklin, Wisconsin
- **South Korea**—2017–2018 in various locations
- **McMicken Battery Energy Storage System**—April 2019 in Surprise, Arizona
- **Industrial Warehouse**—June 2021 in Morris, Wisconsin
- **Grand Ridge Energy Storage Project**—July 2021 in Marseilles, Illinois
- **Victorian Big Battery Project**—July 2021 in Geelong, Australia
- **Dallas Energy Storage/Moss 300**—September 2021 in Moss Landing, California
- **Dallas Energy Storage/Moss 100**—February 2022 in Moss Landing, California
- **Valley Center Battery Storage Project**—April 2022 in Valley Center, California
- **Elkhorn Battery Energy Storage Facility**—September 2022 in Moss Landing, California

To understand the implications of each event, we focused on the following questions:

- What were the circumstances?
- Was anyone hurt?
- How much damage was done?
- How was electricity supply reliability affected?
- What were the main contributing factors to the impacts and severity of the event?

[3] For information about other safety events around the world we recommend starting with the Electric Power Research Institute's BESS Failure Event Database (EPRI 2022).

Kahuku Wind Farm—August 2012

Kahuku, Hawaiʻi

First Wind's wind plus storage installation in Kahuku included 30 MW of wind turbines and a 15 MW/10 MWh transmission-sited lead acid energy storage system contained within a 2,500 square foot warehouse. The energy storage system provided continuous voltage regulation, smoothing minute-to-minute wind output. Operations began in February 2011, followed by three incidents involving the energy storage system: one in April 2011, another in May 2011, then again in August 2012.

Due to the August 2012 event, wind farm operations were interrupted and the energy storage system was destroyed. It took over a year to bring the wind farm back online. In the process, First Wind abandoned an expansion project at the site. The energy storage system was replaced with a new Dynamic Volt-Amp Reactive (DVAR) system to provide the needed voltage regulation and the wind farm was brought back online in February 2014.

Image Credit: Jay Armstrong

Figure 2: Event at Kahuku Wind Farm—August 2012.

Emergency responders delayed entering the warehouse building for 7 hours in August 2012 due to safety concerns and awareness of chemical and physical hazards from the prior two incidents at the site. They attempted use of a dry chemical extinguisher and water directly to the site with limited success. Efforts then were focused on containing the observed fire to the energy storage building until it self-extinguished. The fire burned for 13 hours and smoldered for 36 hours, releasing significant smoke in the process. The warehouse building was apparently not designed for the hazard level and parts of it collapsed. No persons were reported harmed. A 2016 hazard assessment for the National Fire Protection Association concluded that, "These fires [at Kahuku wind farm] demonstrate the need for better understanding of ESS fires so that the owner and fire departments responding to these incidents can better prepared in the event of a fire." The event apparently resulted in about $30 million in damage.

Exact cause of the August 2012 fire was not publicized, although first alarm activation and visual evidence indicates fire origination within an inverter cabinet. Cause of the first two fires in April and May 2011 was linked to undersized capacitors contained in the battery system's inverters and led to litigation among the involved parties. The battery developer Xtreme Power had a significant portion of its business in Hawaiʻi and it filed for Chapter 11 bankruptcy protection in January 2014.

Elden Substation—November 2012

Flagstaff, Arizona

Arizona Public Service's (APS) lithium-ion energy storage system at Elden substation was a 0.5 MW/1.5 MWh distribution-sited pilot project installed in 2011 to better understand the benefits of storage including improved renewable integration and distribution system utilization. The battery system included

16 closed cabinets, each containing 28 sealed modules of 24 cells, within a 28’x8.5’x11.5’ container configured to be transportable on a flatbed trailer. The system was installed within the substation fencing.

In November 2012, after about 11 months of operations, the system was destroyed by fire and thermal runaway. The Flagstaff Fire Department observed 10–15’ flames and smoke upon arrival to the site. Responders were initially instructed not to flow water within 50–75’ of the fence housing the substation and they reported not being aware of the specific chemical hazards at the time. Flame lengths grew to an observed 50–75’ during the event. Responder efforts were to prevent fire spread to nearby forested area, extinguish fire, and cool the equipment. One responder experienced chemical exposure upon removal of a safety mask. The fire department cleared and turned the site over to APS after about 1.5 hours.

An in-depth root cause analysis conducted by experts at Performance Improvement International (PII) did not determine exact cause but identified 5 primary factors (“failure modes”) that contributed to the event. Two out of five contributing factors involved component failures initiating the event. PII found (a) severely discharged cells below the minimum voltage threshold (a measure of state of charge) at the origin of thermal runaway, and (b) controller software and system design that allowed and continuously attempted charging of cells below that threshold. The system previously had a “near miss” with thermal runaway due to these two factors in May 2012 and PII found the issues were not resolved at the time.

Another two factors contributed to thermal runaway propagation through the battery system. Hardware design was one contributing factor, including issues with design of the water cooling system, water leakage, insufficient separation of cells, and inability to isolate individual banks. The presence of electric faults was another contributing factor, including material and placement of busbars that caused melting and ground faults that aided thermal runaway.

The fifth contributing factor created delays in responding to the situation. Inadequate monitoring—including no temperature alarm, no status signal on failed relays, no daily checks, and alarms going to unattended stations—prevented situational awareness needed to address component failures more proactively. It should also be noted that the system vendor and utility’s emergency response plan did not prepare first responders enough to understand the specific hazards of the site nor immediate course of action for containing the fire and cooling the equipment.

Image Credit: Arizona Public Service Image Credit: Performance Improvement International

Pre-Event **Post-Event**

Figure 3: Event at Elden substation—November 2012.

Franklin Facility—August 2016

Franklin, Wisconsin

S&C Electric Company (S&C)—an electric power systems engineering and manufacturing company—manufactured and assembled power quality and energy storage systems at its facility in Franklin, Wisconsin.

In August 2016 a fire occurred at the facility involving a partially-assembled system of lithium-ion batteries within its shipping container (Figure 4). The energy storage system's fire suppression and containment system was nonfunctional as it was only partially assembled. Over 20 fire departments were involved, apparently due to the severity of the fire and weather conditions. Smoke was observed upon arrival at the site. One firefighter injury was initially reported although not part of final descriptions of the event. The Franklin Fire Department estimated damages on the order of $3 million.

Image Credit: National Fire Protection Association

During Event

Image Credit: Greentech Media

Type of Storage System Involved

Figure 4: Event at S&C's Franklin Facility—August 2016.

S&C stated the fire began in one of the DC power and control compartments of a battery rack within the energy storage system while the system was under construction. Once the fire started it spread to the adjacent batteries and initiated thermal runaway. Upon arrival, responders reviewed material safety data sheets, applied an alcohol-resistant aqueous film-forming foam per those instructions, then applied water for cooling which did not extinguish but helped limit thermal runaway to within the container. Thermal runaway self-extinguished after a few hours.

S&C's final public assessment of the situation included emphasis on a need for better information and training on fighting battery fires, noting that material safety data sheets are not enough. The company also outlined five elements of their approach to safety:

- Intelligent controls (their battery and power conversion system);
- Protective devices (fuses, AC circuit breakers, DC circuit breakers);
- Fire suppression systems;
- System design (power conversion system, battery components and systems, compartmentalization, and containerization); and
- Container.

South Korea—2017–2018

various locations

Energy storage systems in South Korea have received global attention in part due to the volume of fire incidents reported. The government launched a 5-month investigation in late 2018 and suspended deployment of new energy storage system installations in response to 23 fires in 2017 and 2018. Results of the investigation were announced in June 2019, identifying four primary causes:

- **Inadequate battery protective systems**, e.g., protection against overvoltage and overcurrent
- **Faulty operating procedures** and inadequate management of operating environment, thus exposing ESS to repeated condensation and dryness, leading to accumulated dust inside battery module and broken insulator
- **Improper installation** of energy storage systems
- **Lack of overall control systems** and lack of comprehensive protective and management system in which EMS, PMS, and BMS with different manufacturers were not operated together by a system integration (SI) business

In addition, investigators noted a practice of aggressive daily cycling, from zero state of charge to full state of charge, which is known to severely degrade batteries.

McMicken Battery Energy Storage System—April 2019

Surprise, Arizona

Arizona Public Service's (APS) lithium-ion McMicken energy storage system was a 2 MW/2 MWh distribution-sited project installed in 2017 for the purposes of facilitating new renewables on the grid with voltage regulation and power quality services. The system was installed adjacent to a substation and within its own fencing. The system included 27 racks, each containing 14 modules of 28 cells, within a 50'x13'x12' container the size of a large shipping container.

In April 2019, after about 2 years of operations, the system was destroyed by rapid thermal runaway over the course of 3 hours followed by an explosion. The system's temperature monitor, laser-based Very Early Smoke Detection Apparatus (VESDA), and Novec 1230 clean agent gas fire suppression system reportedly operated and responded as designed. A passerby reported smoke about 45 minutes after VESDA registered an alarm condition and the Surprise Fire-Medical Department was dispatched. At about the same time the battery developer (Fluence) and APS apparently had notified authorities. The first fire engine arrived about seven minutes later (at 5:49 p.m.). The Fire-Medical team observed a toxic smoke emanating from the battery storage facility and called for backup. About 30–40 minutes later the Peoria Fire-Medical Department's HAZMAT team arrived. The HAZMAT team entered the fenced area several times to take readings and assess the situation. About 1.5 hours later (at 8:01 p.m.) they opened the door to the container and an explosion described as "a jet of flame that extended at least 75 feet outward and an estimated 20 feet vertically" severely injured four members of the HAZMAT team. Additionally, four members of the Fire-Medical team plus one officer from the Surprise Police Department were sent to a hospital for overnight observation for chemical exposure. Post-event assessments and cleanup at the site were particularly difficult as the storage system was at a high (90%) state of charge.

Image Credit: DNV GL

Pre-Event

Image Credit: DNV GL

Post-Event

Figure 5: McMicken Battery Energy Storage System event—April 2019.

APS and LG Chem (the battery manufacturer) each commissioned technical analyses on the event which disagreed on the exact origin of thermal runaway. The APS analysis, conducted by DNV GL, found that thermal runaway was initiated by a voltage drop within one faulty battery cell. The LG Chem analysis, conducted by Exponent, rebutted this conclusion and instead found the cause to be a heat source external to the cells. A third analysis, conducted by Underwriters Laboratories (UL), did not address the topic of initial component failure and instead focused on emergency response and applicable design codes and standards. UL also issued a formal response to the DNV GL report to address inaccuracies it saw in DNV GL's description of the development process, scopes, and test methodologies of UL standards.

Beyond event initiation, the DNV GL report identified several factors contributing to event severity:

- **No thermal (or physical) barrier** between cells; module-to-module barriers insufficient
- The **fire suppression system** was designed to contain initial small fires and not to prevent or suppress cascading thermal runaway; no bulk cooling mechanism (such as water).
- Once the clean agent was discharged it took **45 minutes to visually confirm the potential fire** and dispatch emergency responders.
- **Flammable gases** accumulated from thermal runaway with no ventilation.
- **Emergency responders** did not have an extinguishing, ventilation, or entry procedure in the event of cascading thermal runway that would produce significant flammable gases.

DNV GL made several recommendations to address these contributing factors. It also noted a need for a more comprehensive risk management approach that would include input from, and communication among, the battery manufacturer, developer, and procuring utility.

UL's analysis identified several contributing factors related to lack of proactive education and training of emergency responders on battery energy storage system hazards and emergency procedures, limitations in sensory and communications systems for situational awareness, lack of ventilation to prevent an explosive concentration of gases, and a fire suppression system not designed for explosion protection. UL made a number of recommendations to improve situational awareness, and emergency preparedness and response.

This event halted APS' energy storage development opportunities. Two years later, in 2021, APS resumed energy storage development with enhanced safety protocols including:

- System design that anticipates failure; and
- Outdoor placement at least 100 feet away from any occupiable building space (Spector 2021).

In addition, a storage developer working with APS has highlighted the safety benefits of LFP battery systems and the need to increase coordination with first responders (Spector 2021).

Industrial Warehouse—June 2021

Morris, Illinois

In June 2021 significant thermal runaway propagation in batteries stored in an unlicensed solar and storage industrial warehouse led to a dangerous situation for the surrounding community and emergency responders. The site held approximately 100 tons of batteries.

Smoke and flames were observed over the course of about 1.5 days until contained by concrete, and it took weeks for authorities to declare the site fully under control. About 3,000 homes within a square mile southwest of the site were evacuated for 3 days due to large volumes of toxic smoke emanating from the warehouse. The governor issued a disaster proclamation and The Red Cross supplied food and water to the more than 300 first responders from multiple federal, state, and local agencies and organizations.

Image Credit: ABC7 Chicago

Figure 6: Event at an industrial warehouse in Morris, Illinois—June 2021.

The event started mid-day and responders reportedly began applying water spray until they were told the batteries would explode upon contact with water. By that evening responders had obtained and applied large volumes of a dry fire suppression chemical called Purple-K with no apparent effect. By the next evening, responders had consulted with the Illinois Environmental Protection Agency (IL EPA) and others and decided on an unconventional approach to smother the burning and smoking batteries with 28 tons of concrete. The concrete successfully extinguished visible flames and contained the toxic smoke from thermal runaway. Responders described the decision to use concrete as an effort to buy time while they sought advice and expertise from across the nation on how to best handle the situation.

After application of concrete responders and authorities connected with an expert who explained the nature of thermal runaway, why it was not stopped by the concrete, and why it needs to self-extinguish. Responders then focused efforts on the possibility thermal runaway would “break through” the concrete. They dug a trench to contain chemical runoff in case they would need to apply water spray. They continuously monitored the site and air quality until the site was declared under control.

Complexities with post-event cleanup included the need for residents to wipe down all surfaces with soap and water upon return to their homes, similar cleanup of public sites (such as playgrounds) by responders, and the need for contractors entering the warehouse to have appropriate protective equipment. Environmental damages are yet to be determined. According to the IL EPA may include contaminated runoff, air contaminants, and/or hazardous wastes. Two days after the event started the IL EPA referred the responsible party (Superior Battery Inc.) to the Illinois Attorney General’s Office for enforcement. In its referral the IL EPA requested investigation into the cause of the event, site containment and inspection, site cleanup and restoration, and procedures to prevent future events. Superior Battery agreed to begin cleanup in October 2021 and is facing two lawsuits for danger to the public and the environment.

Grand Ridge Energy Storage Project—July 2021

Marseilles, Illinois

Invenergy LLC’s 31.5 MW/12.2 MWh Grand Ridge Energy Storage Project was installed in May 2015 for the purposes of providing market-based regulation services. It was built on the site of an existing 210 MW wind farm, an existing 20 MW solar project, and an existing 1.5 MW/1 MWh energy storage system. The battery utilizes lithium iron phosphate chemistry.

In July 2021 an incident at the site destroyed one out of eighteen storage containers—or about 2 MW of the project. No persons were reported hurt, no environmental damage was apparent, and the incident received very little press. Fire was observed in the morning, and by mid-evening the visible flames were extinguished by responders. Responders were able to access the interior of the container and they applied water spray to cool the equipment. A responder reported the ability to apply water spray due to the battery’s lithium iron phosphate chemistry (as opposed to the batteries involved in the Morris, Illinois incident—we are not aware of any advantages of LFP under water spray compared to NMC). Invenergy has said it is conducting an investigation.

Image Credit: Invenergy

Installation Pre-Event

Image Credit: LaSalle County Emergency Management Agency

During Event

Figure 7: Grand Ridge Energy Storage Project event—July 2021.

Victorian Big Battery Project—July 2021[4]

Geelong, Australia

The Victorian Big Battery Project is a 300 MW/450 MWh transmission-sited project installed at the end of 2021. The site design includes 212 Tesla Megapacks, each about 1.5 MW.

In July 2021 two of the 212 Tesla Megapacks were damaged while the project was in the process of initial energization testing. Smoke was initially observed by a site supervisor, then flames were observed shortly thereafter (Figure 8). When responders arrived they applied water externally to nearby exposure equipment and allowed the reactions to self-extinguish. Responders monitored the Megapack temperatures using thermal imaging cameras and drone technology, and in total it took 3.5 days until thermal runaway self-extinguished and the site was declared under control. Energy Safe Victoria (ESV, Victoria's safety regulator) conducted an investigation over the next two months, concluded the event to be a safe failure, and took a number of actions to prevent recurrence. ESV conditionally allowed Tesla to continue energization testing in September 2021. The testing and commissioning process continued and the site officially began commercial operations in December 2021.

The root cause was identified as most likely a cooling system leak in one of the Megapacks. The leak apparently caused an arc fault in the power electronics during the energization testing period, which created a heat spike that initiated thermal runaway in the battery cells. Immediate situational awareness was obscured by various systems not being fully integrated and operational at the time. The Supervisory Control and Data Acquisition (SCADA) system, which reports real-time battery system information to operators, was not functional as it required 24 hours to fully integrate with the project but the Megapacks operated for testing for only 13 hours. Then, when the Megapacks were turned off, the monitoring systems, cooling system, and battery protection system also turned off.

[4] Ozdemir 2021; ESV 2021; Kolodny 2021; Neoen 2021; Blum et al. 2022.

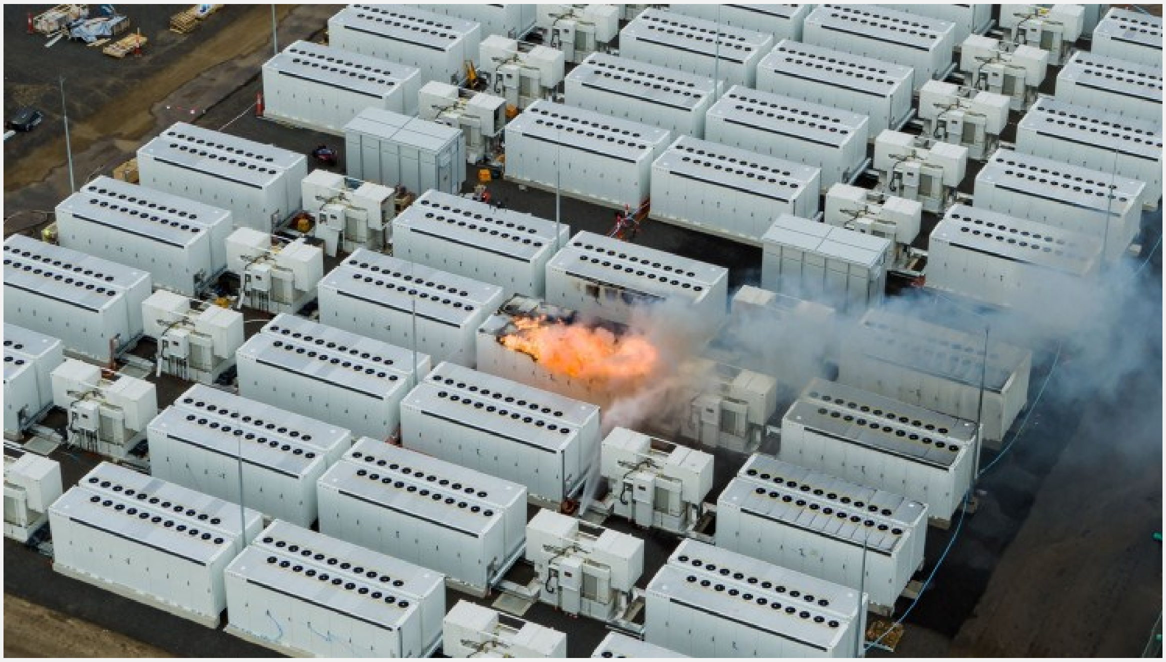


Image Credit: Fire Rescue Victoria

Figure 8: Victorian Big Battery Project event—July 2021.

How thermal runaway spread to an adjacent Megapack was of particular concern as the systems were evaluated under UL 9540A testing methods and their spacings were designed to mitigate inter-pack propagation. ESV required this issue to be addressed in Tesla's investigation. ESV also noted that, "Designers are also working to ensure that Megapacks are engineered to fully mitigate the risk of fire propagation from one unit to another under Victorian climatic conditions," suggesting that propagation to the second Megapack may have been aided by weather factors such as wind, ambient temperature, and/or humidity. An investigation conducted by Fisher Engineering, Inc. confirmed that untested wind speeds were a key contributing factor, reaching up to 36 miles per hour during the event compared to a maximum of 12 miles per hour under the UL 9540A testing environment. In an interview, ESV characterized this situation as a "near miss" when considering an event like this in the context of other times of the year with higher temperatures and stronger winds.

The investigation identified some needed enhancements to procedures, firmware, and hardware. It also noted a clear and effective emergency preparedness and emergency response process involving several parties: the developer (via system designs), facility staff, subject matter experts, and emergency responders. In an interview, ESV shared lessons learned and stressed the importance of (a) regulator engagement in safety review from the time of installation and throughout operations, (b) a better understanding of an installation's technology and its safety risks, and (c) a better understanding of interactions with the surrounding and natural environment.

California's Moss Landing Site

Moss Landing, California

The Moss Landing site hosts several large energy storage installations and has been the hub of a string of safety events in northern California.

The site was developed for a natural gas-fired power plant in the 1950s under the ownership of PG&E. In the late 1990s Duke Energy purchased the site and subsequently invested in a major refurbishment that included retirement of the original units 1–5, construction of units 6 and 7, and construction of two new combined cycle units (for more information see CEC 2000). At the end of 2016, then-owner Dynegy retired units 6 and 7. In 2018, Dynegy Inc. merged with Vistra Energy Corp. and Vistra owns the site as of the time of this report.

In late 2018 the CPUC approved two PG&E contracts to develop energy storage on the Moss Landing site. One RA contract with Vistra is for a 300 MW/1,200 MWh installation. The project is also known as "Phase I of the Moss Landing Energy Storage Facility," "Dallas Energy Storage 1–3," and "Moss 300." One engineering/procurement/construction (EPC) contract is with Tesla to develop a PG&E-owned installation. The project is formally known as the "Elkhorn Battery Energy Storage Facility." In 2020 the CPUC approved another PG&E contract with Vistra for a 100 MW/400 MWh installation known as "Phase II of the Moss Landing Energy Storage Facility," "Dallas Energy Storage 4," and "Moss 100." Moss 300 reached operations in late 2020, and Elkhorn and Moss 100 reached operations in mid-2021.

Each of these installations experienced a safety event over the course of a year (Figure 9). We discuss each event separately in the next few pages. Importantly, each installation reflects a distinct approach to site design. Moss 300 is built inside of a refurbished building that previously housed the retired gas-fired units' turbines. Elkhorn is built outdoors as an array of Tesla Megapacks—similar in design to the Victorian Big Battery Project. Moss 100 is developed within a new structure placed near the two operating natural gas-fired combined cycle units (Figure 10). In 2022 the CPUC approved another PG&E contract with Vistra to expand the site further with a 350 MW/1,400 MWh installation. Vistra has announced plans to continue building westward (inland) with an additional 750 MW/3,000 MWh energy storage in the future.

	Installation Name	MW	MWh	CPUC Contract Approval	Operating Status	Ownership	Safety Event
1	Dallas Energy Storage 1–3 /Moss 300	300	1,200	Nov 2018	Online Dec 2020	Vistra	**Sep 2021**
3	Dallas Energy Storage 4 /Moss 100	100	400	Aug 2020	Online Jul 2021	Vistra	**Feb 2022**
2	Elkhorn Battery Energy Storage Facility	182.5	730	Nov 2018	Online Aug 2021	PG&E	**Sep 2022**
4	*Moss 350*	*350*	*1,400*	*Apr 2022*	*Under Development*	*Vistra*	*n/a*

Figure 9: Battery storage installations and timing of safety events at the Moss Landing site.

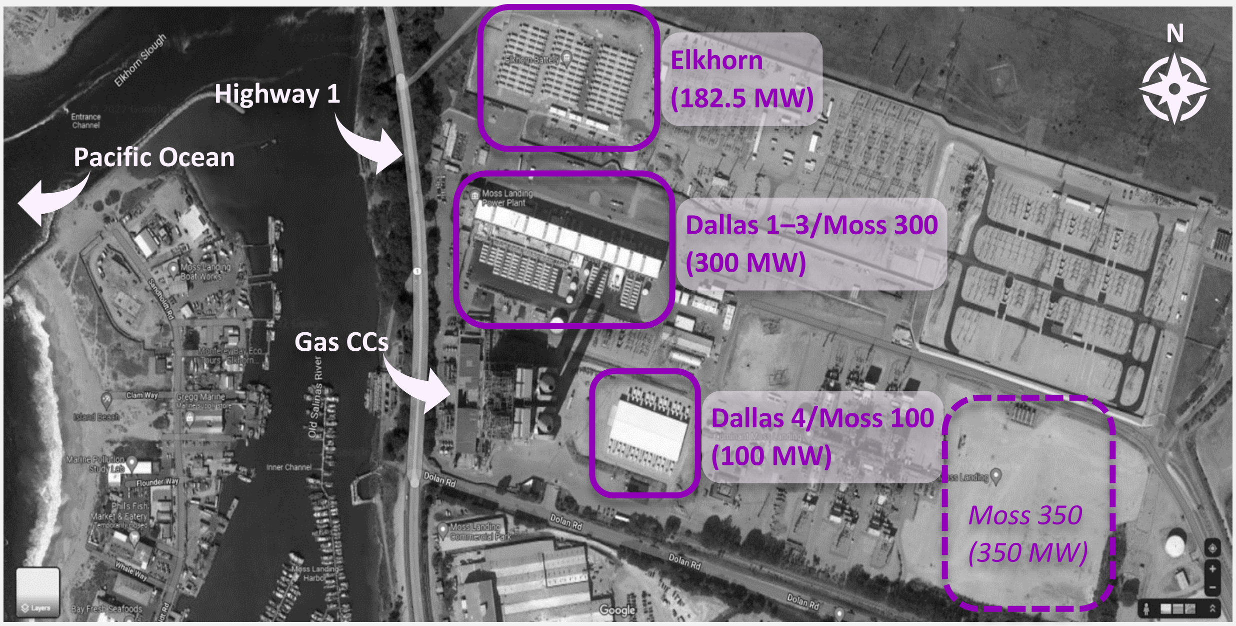


Image credit: Site image from Google Maps; annotated by Lumen.

Figure 10: Configuration of battery storage installations at the Moss Landing site.

Dallas Energy Storage 1–3/Moss 300—September 2021

Moss Landing, California

The Moss 300 installation is a 300 MW/1,200 MWh transmission-sited project owned by Vistra Corp. and installed at the end of 2020. The project includes three 100-MW battery arrays, with a total of 4,539 racks each containing 22 modules (Vistra 2022). The project is located within the Moss Landing site's existing and refurbished two-story turbine hall (Figure 10, Figure 11). The project is contracted by PG&E for local reliability purposes pursuant CPUC proceedings to replace retired natural gas-fired capacity.

Image credit: Vistra Corp.

Figure 11: Moss 300 building exterior and interior.

In September 2021, the North County Fire Protection District of Monterey County responded to a fire alarm at the Moss Landing site (Principi 2021). When they arrived, no fire was present but battery modules in Moss 300 had overheated and were producing smoke. Hazmat and environmental teams were also called to the scene. After inspection of the situation, emergency responders determined that the batteries were not in thermal runaway and the smoke was originating from other materials surrounding the batteries as the batteries overheated. Seven percent of the battery modules were damaged (almost 7,000 modules, or almost 320 racks), along with other facility equipment. No injuries were reported. In February 2022 another similar safety event occurred at Vistra's adjacent Moss 100 site. Vistra reportedly postponed its Moss 300 reenergization until further investigations could be conducted. Vistra did not bring the Moss 300 project (mostly) back online until late June 2022 (Colthorpe 2022)—almost a year after the September 2021 incident.

After a 5-month investigation, in January 2022, Vistra released a statement describing the facility, incident findings, and corrective actions (Vistra 2022). Vistra described the origin of the event as the combination of (a) a source of smoke at or near the facility's air handling unit and (b) due to a programming error, an overly-sensitive Very Early Smoke Detection Apparatus (VESDA) that was prematurely triggered. After the fire suppression sprinkler system activated, hose and pipe leaks sprayed water directly onto battery racks. Water also leaked from the upper floor onto battery racks on the lower floor. This type of water exposure caused short-circuiting and arcing, battery damage, and more smoke—which then let to continued VESDA activation.

Vistra's corrective actions include complete pressure-testing of the water delivery system, installation of a system to monitor for water leaks, VESDA re-programming, installation of smoke detectors in all air handling units, and sealing gaps in the facility's upper floor.

This incident at Moss 300 highlights the challenges with water as an effective fire suppressant but a potential risk with energized equipment. The Moss 100 event also highlights the sudden and significant impact safety events have on the electricity grid's resources: from a safety codes and standards perspective, and in terms of emergency response, this event was a safe failure. However, Moss 300 was on outage almost an entire year, including during the time of the year when California has the greatest need to move solar generation from daytime to avoid solar curtailments (spring) and during September when the grid is most stressed and in need of resources to help meet peak demand.

Dallas Energy Storage 4/Moss 100—February 2022

Moss Landing, California

Moss 100 is a 100 MW/400 MWh transmission-sited lithium-ion battery system installed in July 2021. The battery system is situated within a new standalone structure on the Moss Landing site (Figure 10, Figure 12). The project is contracted by PG&E for system reliability purposes pursuant to the CPUC's integrated resource planning proceedings.

In February 2022, the North County Fire Protection District of Monterey County again responded to an emergency call at the Moss Landing site (Principi 2022). No fire was found at the scene. This time, emergency responders found the Moss 100 fire suppression system was activated and spraying water. Vistra shut down the facility pending investigation and repairs, then brought it back online in late June 2022 along with the Moss 300 project—5 months after shutdown. No injuries from the incident were reported.

At the time of this report, the exact cause is not yet publicly clear. A Vistra statement (Vistra 2022) and news reports indicate that the cause may be similar or the same as the September 2021 safety event at Moss 300. Something triggered the facility's smoke detection equipment which was apparently overly sensitive due to a programming error. Then, apparently (but to be confirmed): the fire suppression system activated and sprayed water, water contacted the batteries due to water hose leak(s), which then caused the batteries to overheat, and surrounding materials released smoke as they melted/scorched.

Like the Moss 300 safety event, this incident at Moss 100 highlights the challenges with water as an effective fire suppressant but a potential risk with energized equipment. The Moss 100 event also highlights the sudden and significant impact safety events have on the electricity grid's resources: from a safety codes and standards perspective and in terms of emergency response this event was a safe failure. However, Moss 100 was on outage for 5 months, and in the time of the year when California has the greatest need to move solar generation from daytime to avoid solar curtailments (spring).

Image credit: Vistra Corp.

Figure 12: Moss 100 building exterior.

Image credit: Terra-Gen.

Figure 13: Valley Center Battery Storage Project.

Valley Center Battery Storage Project—April 2022

Valley Center, California

Terra-Gen's 140MW/560MWh lithium-ion installation came online in March 2022. The facility is designed as an outdoor array of containers (Figure 13). The project is contracted by SDG&E for system reliability purposes pursuant to the CPUC's integrated resource planning proceedings.

In April 2022 fire crews responded to a small electrical fire at the site (Roadrunner 2022). The fire triggered the battery system's fire suppression system which then extinguished the fire. The event was contained to one battery module and no injuries were reported. Further details on the cause of the electrical fire are not publicly available. Although light on data, we included this case study as an example of how properly-functioning fire suppression systems, which are designed to contain initial small fires, play an important role in mitigating safety risks.

Elkhorn Battery Energy Storage Facility—September 2022[5]

Moss Landing, California

The Elkhorn Battery Energy Storage Facility is a 182.5 MW/730 MWh transmission-sited project installed in August 2021. The facility is designed as an outdoor array of 256 Tesla Megapacks (Monterey County 2022c)—similar to the Victorian Big Battery Project. Along with Moss 300, the project is contracted by PG&E for local reliability purposes pursuant CPUC proceedings to replace retired natural gas-fired capacity.

[5] Most event information from Monterey County 2022a; Monterey County 2022b; Monterey County, 2022c; Monterey County, 2022d; KSBW8 2022.

On September 20, 2022 a fire was detected at about 1:30 a.m. and fire crews arrived shortly thereafter. Fire crews followed a pre-planned strategy, based on their training, to not attempt to extinguish the thermal runaway and to instead focus on protecting surrounding structures with water spray. The fire was extinguished in 5 hours by about 6:30 a.m., then the thermal runaway process continued and released gas (including hydrogen fluoride) into the surrounding community.

Local officials then issued a shelter-in-place advisory and closed nearby roads including Highway 1 in both directions (Figure 10). Residents were told to shut windows and turn off ventilation systems. The surrounding area was monitored for toxic gas levels. The shelter-in-place and road closures were ended at 6:50 p.m. on the same day. The fire was contained to one megapack and no injuries were reported.

Cause of the fire and thermal runaway are unknown publicly as of the time of this report. We included this case study as an example of an effective fire response strategy, and of the importance of communication and knowledge-sharing with the community and local officials.

News reports we reviewed indicated community confusion and concern about the nature and impacts of the toxic gas release. This highlights some challenges in knowledge transfer of safety events to local authorities and their communities. Community impacts from gas release of lithium-ion batteries in thermal runaway reached the national stage over a year prior (June 2021) with the industrial warehouse event in Morris, Illinois. Many important safety lessons were learned in that event that can be helpful to California communities.

Image credit: David Paul Morris/Bloomberg

Facility pre-event

Image credit: KION 46 News Channel

Community gas release during event

Figure 14: Elkhorn Battery Energy Storage Facility—September 2022.

Known and Observed Impacts

Based on these case studies we observe the following known and observed negative impacts of under-managed, under-mitigated, or residual safety risk:

- **Emergency responders and staff**—injury from fire or explosion; chemical exposure (air or contact) such as from released hydrogen flouride (HF) and phosphoryl fluoride (POF3) gases (*see* Larsson 2017).
- **Communities**—chemical exposure, chemical runoff, displacement from homes due to evacuation, shelter-in-place, temporary shut-down of local economy, fears of known and unknown risks.
- **Environment**—release of contaminants of concern, chemical runoff from emergency water spray such as hydrofluoric acid, and fire propagation.
- **Electricity infrastructure**—loss or partial loss of battery system and attached equipment.
- **Other property**—loss or partial loss of surrounding and adjacent structures.
- **Reliability of electricity supply**—outage or permanent loss of storage capacity, outage of other onsite electricity supply (e.g., wind turbines) during event and recovery period.
- Cost, time, and hazards of **post-event investigations and cleanup**.

It should also be noted that the more extreme events create some public backlash and have hindered storage market growth as ex post investigations and risk assessments take place. After the event at McMicken in 2019, for example, Arizona Public Service paused on its energy storage deployment plans for two years. Earlier in 2018, South Korean regulators deployment of new energy storage system installations in response to more than 20 fires in 2017 and 2018.

Lessons Learned from Safety-Related Events

Ex-post studies and assessments of safety-related events provide valuable information on specific failure modes and circumstances leading to catastrophic situations. This information has shaped development of safety codes and standards and other best practices. In addition, we observe several themes in lessons learned from safety-related events that continue to guide efforts to improve safety:

- A **need for more comprehensive and complete proactive risk assessment**—This was explicitly addressed in DNV GL's report on the McMicken event, but also apparent in the emergency response process of other events (DNV GL 2020). DNV GL noted that manufacturers, developers, operators, and utilities each have unique information on known and possible safety risks; and that they all need to communicate ahead of time to develop an assessment that combines their knowledge into a complete set of known, possible, and unknown hazards.
- Relatedly, a **need for more proactive coordination with emergency responders**—In nearly every safety-related event emergency responders were presented with very limited information on the hazards of the situation on-the-spot. They are consequently required to manage an emergency situation in which they don't have a full picture of what the hazards are, are not fully aware of the limitations of dry chemical suppressant, are not clear on when/where/how to apply water, and are not sure of when or how to approach or enter the structure. Emergency response plans are

needed that include proactive communication and training for both staff and emergency responders on relevant risks, what emergency events may look like, and how to handle them.

- **Need for integrated system supervisor with complete situational awareness at all times**—Installations designed to operate too remotely and/or with various detection and management systems monitored by multiple separate parties inhibit fast and efficient emergency response. A single integrated platform and/or coordinator for all operating and monitoring systems is needed. Also, events point to a need for situational awareness even when the batteries are offline.
- Codes and standards have evolved rapidly to address many types of component and system-level risks, but within limits. **Risk management activities beyond meeting codes and standards are needed** in order to address secondary impacts like reliability of storage and co-located electricity supply, and to establish broader multi-party coordination and communication protocols such as emergency response plans.
- **Events in other jurisdictions don't reflect some California-specific and local risks and implications**—such as local environmental extremes, grid outages during a heat wave or extreme wildfire weather and how that might affect the storage system, fire propagation from and to the storage system in certain locations, and water supply constraints.

Best Practices and Next Steps

This section summarizes best practices and next steps, drawing from lessons learned from safety-related events; efforts by federal, state, and local agencies; and other efforts by stakeholders and industry experts to enhance safety practices.

We divide risk management and mitigation activities into four components:

- Risk assessment
- Emergency preparedness
- System and site design
- Operations, diagnostics, and maintenance

Risk Assessment

The industry has learned a great deal through experience and ex post investigations about how specific failure modes can manifest, how design and operations can affect fire and thermal runaway propagation risks, and the range of severity of impacts on people and equipment. These events and experiences provide valuable information to guide development of best practices in safety.

As a result, best practices are trending towards more comprehensive proactive (ex ante) risk assessments of battery storage installations. *Who* should conduct an ex ante risk assessment, *why*, and *scope of risks* to assess depend on stakeholder perspective, and defining this perspective and its objective is important for an effective risk management strategy.

We focus on the type of risk assessment of ratepayer-funded installations involving the CPUC and utilities with the dual objective to minimize harm to people, communities, and the environment, and to maximize reliability and quick recovery in the event of a storage component or system failure. We propose the following risk management objective from this perspective:

Safety risk management objective: minimize harm to people, communities, and environment, and maximize reliability and quick recovery in the event of a component or system failure

In a complex system many sources and combinations of failures can contribute to risks. **Underlying battery chemistry and technology**, its inherent safety risks and failure modes, and how sensitive it is to fire and thermal runaway propagation is a key consideration. It is standard practice for manufacturers to provide material safety data sheets and/or emergency response guides which document a battery's chemical hazards and safe handling procedures.

More than a dozen codes and standards have been developed to identify and address safety risks of other **individual components of a battery installation** beyond the batteries themselves, including inverters, capacitors, battery management systems, and energy management systems. Going further, about a half dozen additional codes and standards identify and address risks of various **components assembled into an installation**. These include guides for ventilation and thermal management; for electrolyte spill containment and management; for installation, maintenance, and operations; and for managing electrical, fire, and shock hazards.

To assess risks more holistically at a **complete energy storage system** level (e.g., storage container and all contents and attachments), Underwriters Laboratories developed a test method (UL 9540A) for observation and evaluation of behavior of a replica system in an actual thermal runaway situation. This is a destructive lab test in which thermal runaway is instigated then observed—at the cell level, module level, unit/rack level, and installation level. A favorable test outcome, or "safe" failure, is essentially thermal runaway that self-extinguishes without significant propagation, flaming, or explosion. Less favorable outcomes provide guidance for additional risk mitigation and management that may be needed to meet fire codes and other safety objectives.

Codes and standards for an **entire built environment** (including immediate area and structures surrounding the storage container) identify and address various electrical, fire, and building safety risks. Projects that trigger review under the California Environmental Quality Act (CEQA) undergo additional risk assessment that helps to translate component- and system-level failures into risks to the surrounding people and environment. Tests results under UL 9540A, for example, can be assessed against a specific site plan and local environment in order to determine whether or not something like a fire wall needs to be built to provide extra protection to the surrounding area.

Next Steps for Risk Assessment

In many of the case studies we reviewed it is unclear to what extent the full spectrum of safety risks were assessed in advance and, if they were, how broadly these risks were communicated to all parties involved in risk mitigation and management. These experiences indicate a benefit to both the real-time battery system supervisors and their regulators having a more comprehensive understanding of how a specific battery systems' electrical and thermal stability can fail, types of hazards that can result, and potential secondary impacts on electricity system reliability and ratepayer costs.

One important next step in risk assessment of the utilities' energy storage procurements is to inventory and better understand each individual installation's safety risks. National and international codes and standards identify many—but not all—of the risk factors we observe in actual safety-related events.

Some **local or site-specific factors** may require additional consideration beyond codes and standards. Tests under UL 9540A, for example, are performed within a controlled environment where heat and gas release can be measured. Notably in the Victorian Big Battery Project event flames propagated to a second adjacent Tesla megapack despite the product having been subject to tests under UL 9540A. In its assessment of the event the Australian regulator, Energy Safe Victoria, emphasized a need for designers to consider Victorian climatic conditions to mitigate fire propagation.

Events like the Victorian Big Battery Project and industrial warehouse in Illinois highlight the dangers of gaps in 24/7 real-time situational awareness—even with the batteries offline. Thermal runaway and subsequent fire and propagation is a vulnerability of some batteries regardless of operational status of the battery system. Some additional consideration beyond codes and standards may be needed to better understand **grid or battery system outage as a failure mode**, how the outage might coincide with external stressors (such as a heat wave or high wildfire threat), how the outage affects monitoring and thermal management equipment, and consequences to fire and thermal runaway propagation risks.

Risks to grid reliability and ratepayer costs will certainly require additional consideration beyond codes and standards. After destruction of its battery system in 2012 the Kahuku Wind Farm was shut down for over a year until replacement equipment could be installed. After its September 2021 safety event the

Moss 300 facility was shut down for almost a year, coming (mostly) back online in June 2022 (Colthorpe, 2022). This type of impact on the operability and reliability of energy storage systems and any onsite generation could materially affect ratepayers, but it is not a risk factor considered within the scope of codes and standards. Complete and permanent destruction of the storage system under UL 9540A, for example, would be considered a favorable test outcome as long as flames, gas and chemical release, and explosion are sufficiently contained in that situation.

It should also be noted that **codes and standards are evolving rapidly** as the industry climbs the learning curve of energy storage safety. Safety measures at a new battery system installation could conceivably become out-of-date within months. Older, pre-2018 systems are almost certainly out-of-date with current best practices. Furthermore, consistency in interpretation of codes and standards may be a challenge. It will be up to storage system owners and their regulators to update their understanding of safety risks accordingly and determine if continued status quo operations are acceptable, if retrofits or updates are needed, or if decommissioning would be the best course of action. Although built to safety standards at the time of its installation in 2014, the design of SCE's Tehachapi was severely out of step with codes and standards by 2020 (SCE, 2021). The cost to retrofit to meet current codes and standards was a major factor in the decision to retire the facility in 2021 (SCE, 2021).

Once risks are identified and known, **proactive communication of those risks to all parties involved** is clearly an urgent and essential area for improvement across the industry. Nearly every safety-related event reveals major communication barriers that undermine risk mitigation and management efforts. Poor communication with local authorities and emergency responders is the most visible example of this to the public eye. In several safety-related events, responders were forced to assess risks on the spot by assembling information from various sources including materials safety data sheets, battery system supervisors, outside experts, and responders' own experience with fire and hazardous materials. Less visible is the essential communication among the many parties involved in developing and managing a battery system. In its investigation of the McMicken event, DNV GL observed that a more comprehensive ex ante risk management approach could have been achieved with better communication among the battery manufacturer, developer, and procuring utility on the key risks each party was aware of (DNV GL 2020). DNV GL suggested this knowledge transfer could be facilitated using a Johari window technique to reveal blind and hidden risks (DNV GL 2020).

Emergency Preparedness

No one can fully control or predict when or where a battery system failure mode leads to fire and thermal runaway propagation. Emergency preparedness is a mitigation strategy that assumes fire and thermal runaway propagation will happen, with a more focused objective of setting the stage for fast and efficient real-time mitigation of harm to people, communities, and environment. The more severe an emergency, the more mitigation objectives narrow to the most important goal: to protect the lives and health of people. Actual safety-related events have provided valuable information on where gaps in emergency preparedness lie and how they can be addressed.

Site designs are improving to include better situational awareness tools, egress for staff or other persons onsite, access for emergency responders, structural integrity to withstand extreme conditions, and physical buffers to protect surrounding buildings and landscape. Updates to codes and standards and their applications in recent years include enhancements to firefighting, preparedness for explosive gases and vapors, spill control, smoke detection, and signage. It has also become increasingly clear that site design and installation must include the input of local emergency responders who are experts in their community's terrain and weather patterns. Dr. Paul Christensen, a professor of electrochemistry at Newcastle University whose research focuses on lithium-ion battery fires and safety, summarizes this point: "If the design is approved, and then the fire and rescue service are brought in—that's the wrong way around." (Kolodny 2021) He also recommends:

- A monitoring system that provides internal visibility (e.g., within the storage container) at any time;
- Enough clearance for responders to maneuver around a system and direct a hose if needed; and
- Water access including onsite hydrants and capped pipes into the storage container to allow flooding with an external hose if needed (Kolodny 2021).

These guidelines are consistent with observations and activities of other experts in the field. Various monitoring systems need to be accompanied by staffing and process strategies for 24/7 situational awareness—whether the storage system is online or offline and under a variety of grid and environmental conditions. Depending on battery chemistry and technology, battery system designs may need to be modified in order to allow safe application of water in an emergency.

Proactive and robust emergency training and coordination among battery system operators, supervisors, and emergency responders is another area where the industry is adapting and innovating quickly. Best practices in managing safety risks acknowledge that all parties involved in real-time emergency response need to be trained on types of possible failures and hazards, how to identify them and assess the overall situation, and what course of action to take in different situations. Knowledge-sharing on the characteristics of thermal runaway, how it is different from fire, and its chemical and explosive hazards has been an area of particular focus. Emergency responders likely have significant experience with fire and/or chemical hazards, but they may have never seen or managed thermal runaway. In many of the safety-related events we observe fire responders put significant time and effort into attempting to extinguish thermal runaway like a fire, putting themselves at risk in the process.

Next Steps for Emergency Preparedness

As with risk assessment, national and international codes and standards are being continuously improved and they provide valuable guidance. But gaps remain particularly in consideration of certain installation-specific factors as well as communication among many parties to develop a coordinated risk management approach.

The most urgent and fruitful next step in emergency preparedness is for battery system owners and supervisors, their regulators, and state and local emergency responders to coordinate in a battery system **safety knowledge exchange**, then formalize that exchange through an established training program and updates to state and local requirements for battery systems (e.g., city fire code, permitting review process). In New York, for example, the New York State Energy Research and Development Authority (NYSERDA) developed training webinars and a guidebook for local governments including model (boilerplate) law for storage system requirements, a model permit application, a model inspection checklist, and information on how battery system safety is incorporated into state fire and building codes. They also provide technical assistance to local authorities.

Deep investigation into the McMicken event revealed that very little information was communicated to responders, forcing them to improvise in a dangerous situation. Timelines of other safety-related events indicate a similar problem at other sites. In addition to this general knowledge exchange, each installation must have an **emergency response plan** that is readily available in an actual emergency and that provides enough information to responders for quick situational assessment and best course of action. The plan should include information on how to identify and address thermal runaway specifically. It may be helpful to consult with the emergency responder community on the most useful elements of an emergency response plan from their perspective. A widely vetted emergency response plan could then be used as a model for other installations.

System and Site Design

Ideally, system design is informed by an initial risk assessment that points to specific design needs, such as ventilation for hazardous gas buildup. It should also be informed by an emergency preparedness strategy that identifies useful design-related emergency tools such as perimeter clearance and placement of fire hydrants. Although still in development, best practices in energy storage safety have made significant progress towards this type of integrated risk management strategy and that is what we highlight here.

A battery system contains many design elements and we do not discuss them exhaustively in this paper. But as the industry learns lessons from safety-related events a few design elements have become central to the discussion of best practices.

Lithium-ion NMC has thus far been the dominant **chemistry for battery storage systems**, but cost and supply chain issues with cobalt, plus rare but dramatic safety failures and scares, have driven developers and electricity system planners to consider alternative chemistries. After the event at McMicken in 2019 Arizona Corporation Commission (ACC) Commissioner Sandra D. Kennedy found utility-scale energy storage based on certain lithium-ion chemistries to “not [be] prudent and create unacceptable risks.” The letter suggested consideration of other technologies such as liquid flow, liquid metal, zinc air, nickel iron, and magnesium batteries—and consideration of non-battery storage. In 2021, Tesla announced plans to switch its Megapack chemistry from NMC to LFP (Plautz 2021). Wood Mackenzie projects NMC market share in global stationary energy storage to drop from 60% in 2020 to 30% in 2030, and for LFC to grow from 15% to 35% (Wood Mackenzie 2020).

If NMC is the chemistry of choice, its inherent safety risks can be addressed by **increasing physical and thermal barriers** between cells, modules, and/or racks. This reduces energy density and may increase costs but is crucial to slow or contain thermal runaway once initiated. Self-contained installations placed outside with sufficient perimeter clearance helps to protect surrounding structures and landscape. If the installation is placed within an existing building or structure, such as a warehouse, it may need additional physical separation.

The industry has pushed to improve **operating tools and fail-safes** in response to safety-related events. Battery management systems should be able to detect and fully isolate deteriorated or malfunctioning cells. Energy management systems should be tuned to avoid operational extremes that risk rapid cell damage (such as extreme charge discharge ramps, depth of cycle, states of charge). Battery and energy management systems should be able to talk to each other in order to better recognize and address potential issues—such as thermal runaway risk as a function of temperature and state of charge (Rosewater 2019).

Monitoring and situational awareness equipment are essential to address a failure mode quickly before it cascades into fire or thermal runaway propagation. This equipment includes temperature monitors and smoke detection equipment like a laser-based Very Early Smoke Detection Apparatus (VESDA). Other gas monitoring equipment may be needed to detect thermal runaway absent fire. Several safety-related events revealed the need for internal camera systems to visually confirm possible fire quickly and remotely without endangering staff or emergency responders. Depending on the system type and local climate a temperature control system (such as HVAC) and/or additional environmental monitoring such as humidity or fine particle sensors may be needed.

The purpose of a **fire suppression and response system** has caused some confusion around safety-related events, mainly tied to confusion around the distinction of fire versus thermal runaway. Installation of a fire suppression and response system is standard practice and essential for control of fire within a system—hopefully before thermal runaway can initiate (fire can trigger thermal runaway). Once thermal runaway is initiated, however, fire extinguishing agents and techniques will not stop it. In practice, thermal runaway is only contained by (a) the physical and thermal barriers that were put in place as part of the system and site design and (b) if it can be safely applied, large volumes of water to cool the reaction. Accordingly, system and site designs that include **extra water supply** and a layout to safely apply water spray or flood the storage system are emerging as a best practice (Kolodny 2021). Designs with proper **ventilation** to prevent buildup of flammable gases such as via Pacific Northwest National laboratory's IntelliVent have become part of best practices (PNNL n.d.).

Containerized systems placed outdoors on a concrete pad, away from occupiable spaces, fenced, and with sufficient space for emergency responders to maneuver has become a standard site design for utility-scale storage. The site should include a fluid collection system for emergency response efforts to contain any potential chemical runoff. Appropriate signage is needed to warn staff and responders of various hazards. State and local fire and building codes may need to be updated to address the safety of a system placed indoors, even if the system is containerized.

Next Steps for System and Site Design

Next steps in system and site design safety best practices largely follow gaps in risk assessment as previously discussed. Lessons learned from safety-related events point to the need for designs to **better address local or site-specific factors, grid or battery system outage as a failure mode, and secondary risks to reliability and ratepayer costs**.

Large-scale systems trend towards containers placed outdoors but for **customer-sited installations** the best approach is not as clear. Safe placement and installation depends on a number of factors including local environmental conditions and it requires close scrutiny by local fire and permitting authorities. It also requires input from developers and installers to ensure rules are feasible and do not create major barriers to storage adoption. This process can be complex. The New York City Buildings Department and New York City Fire Department worked with stakeholders for several years to develop codes for indoor placement that fit both safety objectives and available technology (St. John 2017; St. John 2020). In general, any indoor placement—even in a garage—potentially restricts air flow and endangers the surrounding structure, property, and/or nearby people in the event of fire or thermal runaway. On the other hand, outdoor placement in unfavorable climate conditions like a hot, dusty, desert-like environment can pose its own risks. In 2017 Standards Australia drafted safety rules in a best practices guide (AS/NZS 5139) that would essentially ban indoor installation of lithium-ion battery systems (Colthorpe 2017a; 2017b). After significant backlash from stakeholders Standards Australia re-worked and finalized the rules in 2019 to allow indoor installation with certain protections like use of cement sheeting when adjacent to occupied space, clearance from appliances and room egress, and exclusion from certain hidden enclosed spaces and habitable rooms (Podder 2021).

The industry has identified **better integration of the many management and control systems** operating an energy storage system as a key area of needed improvement. Better integration means management and control systems that talk to each other, that incorporate inputs from **situational awareness monitors**, that communicate with an integrator software that performs higher-level system optimization functions, and that reports comprehensive status and operational data to system supervisors. As the industry makes technological advances in this space it would be prudent for both new and existing energy storage systems to utilize best in class software to the extent feasible. One potential advancement, for example, is in machine learning-based **predictive maintenance**. The software would utilize all historical system data and look for complex statistical relationships to proactively alert system supervisors of potential issues needing inspection. A key component to this and other integrator solutions that rely on a complete picture of the energy storage system will be **improved data collection and retention** of the system's data.

For an existing system, we recognize that migrating to new IT systems is a difficult process and that it requires testing to ensure the new system is working as designed. Similar issues arise with **compliance with rapidly-changing codes and standards** in general. Energy storage owners, regulators, and permitting authorities will need to monitor codes and standards developments and have a decision-making framework for allowing status quo operations, or requiring a retrofit versus retirement assessment of energy storage systems that no longer meet the latest safety guidelines.

Large utility-scale battery systems may need to be **tested and designed to address grid or battery system outage as a failure mode** in order to minimize (a) delays in responding to failures, and (b) secondary risks to reliability and ratepayer costs. The system should be designed to provide 24/7 situational awareness even in a grid or storage system outage situation. If the grid is functioning normally but the storage system is on outage, the configuration should be designed to minimize downstream outages of co-located electricity supply (such as solar or wind).

Operations, Diagnostics, and Maintenance

Best practices are trending towards hardware and software solutions to improved operations, diagnostics, and maintenance in system designs. But even with the best information technology in place, system design alone cannot address the need for 24/7 oversight and routine checks by knowledgeable and experienced persons.

An energy storage system can include many different detection and management tools, such as temperature and smoke detection, fire suppression, battery management, power control, energy management, and site management. These systems can potentially be monitored by different parties. Best practices trend towards **providing supervisory staff with a more complete picture** of what is going on with the system. Beyond technological solutions this includes a streamlined communication and decision-making process. It also needs to include training on the types of risks involved and types of situations that could occur, and training on an emergency response plan.

The industry has learned a great deal in the past few years about how different **operating use cases and operating practices** affect battery cell degradation and safety risks. Experiences in South Korea, for example, highlighted the need to avoid overcharging and aggressive cycling. Those experiences also demonstrated the need to consider and manage the day-to-day operating environment. Warranty or operating contract terms may set preferred operating parameters as a starting point. Battery system operators may also set their own preferred state of charge operating range (to avoid very low and very high states of charge) or ramping and cycling operating limits.

Routine visual inspections and equipment tests are a standard practice. In California, for example, the County of Santa Clara Development Services Office developed a field inspection checklist for residential battery storage systems in 2015 that has been held as a model for the state. In 2017 the CPUC's Safety and Enforcement Division (SED) collaborated with stakeholders to develop an inaugural safety assessment checklist (CPUC SED 2017). The checklist includes an emergency plan; regular inspections of equipment by companies or utilities; and inspections of interconnection equipment, structure, detection and protection systems, fans and cooling equipment, electrical, battery module, and hazardous materials policy by SED inspectors.

<u>Next Steps for Operations, Diagnostics, and Maintenance</u>

Data collection and retention is becoming increasingly important as system monitoring, management, and control tools advance and as operating use cases become more sophisticated. Experts at Sandia National Laboratories emphasize the importance of data acquisition systems that include remote access and 30 or more days of on-board memory (for example *see* Schenkman 2020). Larger data reservoirs will likely be needed as systems become more predictive. Relatedly, regular **software and firmware updates** are becoming increasingly important, including tests and checks to ensure the updates installed and are performing correctly (for example *see* Fioravanti et al. 2020).

As discussed earlier in system and site design, **predictive maintenance tools** using machine learning models are on the technological frontier. These models would utilize all historical system data and look for complex statistical relationships to proactively alert system supervisors of potential issues needing inspection.

Routine inspections by local or state authorities will need to consider the increasing importance of software and firmware in energy storage operations, diagnostics, and maintenance.

Key Observations

Energy storage safety is a complex risk management issue that involves many parties.

Historically, major safety-related events involved about 2% of large-scale battery storage installations in the U.S., occurred within 1–2 years of installation, and destroyed about 1–2% of its capacity.

In 2021 and 2022, safety events in California are increasing along with the state's acceleration of large lithium-ion battery installations.

The definition of energy storage system "safety" from an electricity regulator's perspective considers both direct impacts (e.g., harm to humans, the environment, or surrounding communities) and impacts on the reliability and resilience of electricity supply.

Lithium-ion batteries are unique from other electricity supply resources in their ability to rapidly decompose through a fire-like and extremely hazardous process called thermal runaway.

Public and industry confusion over the difference between fire and thermal runaway is a major source of misinformation on appropriate management of lithium-ion battery safety risks.

Although large volumes of water spray can help limit thermal runaway propagation, thermal runaway is best addressed proactively through energy storage system design and site configuration.

Lithium-ion chemistries differ in their vulnerabilities to thermal runaway. The industry is trending away from the more sensitive NMC chemistry and towards the more stable LFP chemistry.

Risk management of complex systems must consider multiple layers of risk, including: points of failure, failure modes, system risks, and residual risk.

Case studies of safety-related events demonstrate a range of failure modes and situations, offer valuable information on known and observed impacts, and point to themes in lessons learned.

Risk management and mitigation activities include four components: risk assessment; emergency preparedness; system and site design; and operations, diagnostics, and maintenance.

California's next steps in risk assessment are to investigate (a) **local or site-specific factors** that heighten or change risk profiles, (b) **grid or battery system outage** as a failure mode, (c) **risks to grid reliability and ratepayer costs**, (d) procedures for keeping the storage fleet up with **codes and standards**, and (e) methods for **improving communication and knowledge-sharing** among all parties involved.

California's next steps in emergency preparedness are to build a robust and ongoing **safety knowledge exchange** and ensure **emergency response plans are well vetted within that safety community** including local officials and emergency responders.

California's next steps in system and site design mirror next steps in risk assessment, including steps to (a) ensure designs **better address local or site-specific factors, grid or battery system outage as a failure mode, and secondary risks to reliability and ratepayer costs;** (b) **improve battery management systems, control systems, and learning from historical system data;** and (c) consider **retrofit versus retire** options for systems that no longer meet codes and standards.

California's next steps in operations, diagnostics, and maintenance include improvements in **data collection and retention, software and firmware upkeep, and predictive maintenance**.

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