Received: 6 May 2023 | Revised: 23 September 2023 | Accepted: 3 October 2023
DOI: 10.1002/prs.12541

PROCESS SAFETY PROGRESS

ORIGINAL ARTICLE

Introduction to grid-scale battery energy storage system concepts and fire hazards

Veronica Goldsmith

Arup, Los Angeles, California, USA

Correspondence
Veronica Goldsmith, Arup, 900 Wilshire Blvd., 19th floor, Los Angeles, CA, USA.
Email: veronica.goldsmith@arup.com

Abstract

As the world continues to enact progressive climate change targets, renewable energy solutions are needed to achieve these goals. One such solution is large-scale lithium-ion battery (LIB) energy storage systems which are at the forefront in ensuring that solar- and wind-generated power is delivered when the grids need it most. However, the perceived hazards of LIBs due to recent events in the United States and Australia pose a risk to their future success. When a battery energy storage system (BESS) has a multilayered approach to safety, the thermal runaway, fire, and explosion hazards can be mitigated. Successful implementation of this approach requires cooperation, collaboration, and education across all stakeholder groups to break down these preconceived notions. Much can be learned from the recent BESS fire and explosion events to inform safer design and operation. These events and their contributing factors share many commonalities with historic losses in the hydrocarbon industry. Fire and process safety engineers who have traditionally worked in the hydrocarbon industry can be of immense value to the BESS industry.

KEYWORDS
alternative energy infrastructure, BESS, energy storage, fire engineering, lessons learned

1 | BATTERIES, POWER, AND THE GRID

The way in which the world generates, transmits, and uses its energy is changing. We have been decarbonizing our electricity networks and transitioning our vehicles to run from petroleum fuels to batteries/fuel cells. Additionally, we are striving to make upgrades and expansions to transmission networks and use energy more wisely.

We are now generating power with wind, solar, and wave technologies, which are variable generation technologies because supply will vary over time based on the weather, daylight, and gravitational forces. When coupled with inflexible generation, such as nuclear which cannot quickly ramp up and down to match changes in energy demand, energy balancing issues ensue. This is because these variable and inflexible generation technologies do not provide the stable output that fossil fuels historically could guarantee. In a system where supply constantly must meet the demand, we are in danger of over-generating when the renewable generation is high and under-supplying when the conditions are less than favorable. This energy balancing challenge is symbolized in Figure 1. It is imperative that this theoretical scale is balanced. Energy storage is a piece of the solution, along with distributed generation and microgrids, which can hypothetically tip the scale.

The risks of imbalance in the electrical grid are significant, most recently highlighted by a severe winter storm in Texas in February 2021, which resulted in the usage of power significantly outpacing production. As shown in Figure 2, this resulted in the Texas energy grid frequency dropping below a safety threshold of 59.4 hertz. Had the frequency stayed below this threshold for 9 min, the entire network would have shut down, as generating units would have tripped, disconnecting from the grid to protect themselves.[1]

There are a number of opportunities for energy storage to be deployed throughout the electricity network. Energy storage is not just limited to large power plants; it can be deployed at many locations along the network. Power generation is being decentralized:

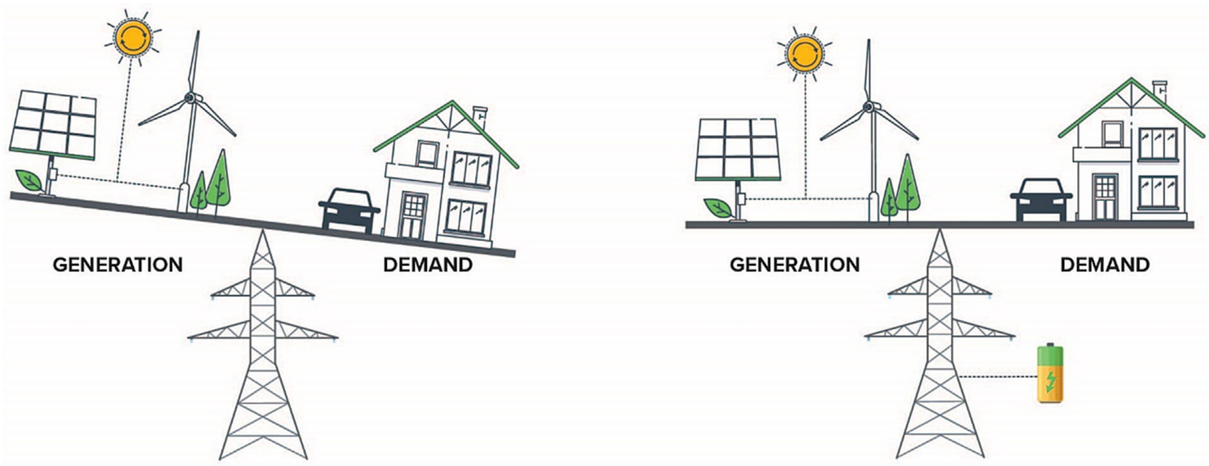

FIGURE 1 The energy balancing challenge.

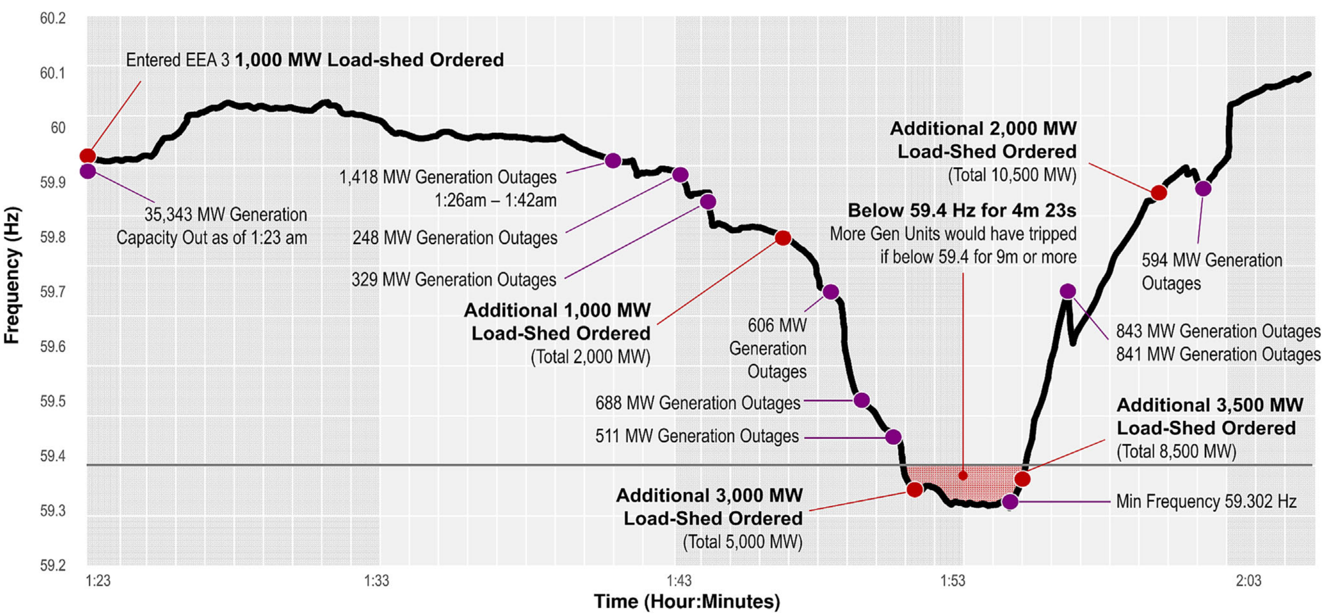

FIGURE 2 Texas 2021—Rapid decrease in generation resulting in frequency drop.[2]

businesses and homeowners are now generating power too. Some electricity companies even allow these users to sell electricity back to the power grid or receive credits through net metering. Businesses can utilize energy storage for reliable or uninterrupted power supply. Energy storage downstream of distribution can relieve peak loads by buying/charging during low demand and selling/discharging during high demand. Along transmission lines, storage can also offer opportunities for grid stabilization.

2 | LITHIUM-ION BATTERIES

One form of energy storage is using lithium-ion batteries (LIBs). The first commercial LIBs were introduced in 1991.[2] What once just powered our personal electronics and power tools is now used to power medical devices, cars, and houses and can bring stability to our power grids. Some benefits of LIBs for energy storage are their high energy density, power density,[3] and efficiency. With increasing demand for LIBs, the prices were reducing until 2022 when a 7% increase[4] was seen due to increase in raw material cost. Lithium carbonate and lithium hydroxide prices saw the greatest rises in 2022.[4]

Over the past 30 years, many types of LIBs have been developed, each chemistry having its trade-offs with respect to thermal stability, specific power, safety, performance, and cost. A LIB typically gets its name from the cathode chemistry. The primary components of a LIB are the cathode, anode, electrolyte, separator, and current collectors. Table 1 outlines various compositions of the first four components. Today's current collectors are made of thin copper and aluminum foils.

TABLE 1 LIB cell component composition.[2,3,5,6]

Cathode	Electrolyte
Lithium cobalt oxide (LCO)	Metal salt (e.g., lithium hexafluorophosphate)
Lithium iron phosphate (LFP)	Dimethyl carbonate
Lithium nickel cobalt aluminum oxide (NCA)	Ethyl methyl carbonate
Lithium nickel manganese cobalt oxide (NMC)	Ethylene carbonate
Lithium manganese oxide (LMO)	Propylene carbonate
	Ethyl acetate
Anode	**Separator**
Carbon	Polyethylene
Graphite	Polypropylene
Lithium titanium oxide (LTO)	Polyethylene terephthalate
Lithium aluminum titanium phosphate	Polyacrylonitrile

Even in a small LIB cell there are safety features incorporated, starting with the cell chemistry. LFP LIBs are considered one of the safest chemistries[7] and currently are the cheapest.[4] During cell manufacturing, a solid electrolyte interface (SEI) is formed when first charged, which creates a protective layer at the anode and prevents electrolyte decomposition.[5,7] Cells can also incorporate pressure relief vents, current interrupt devices (CIDs), protection circuits, and positive temperature coefficient (PTC) components.[3,8] For instance, a CID may operate when the internal pressure is over 1.0 MPa, but it is irreversible. A top vent can relieve pressures over 2.2 MPa, protecting a battery cell from rupturing, but it may not prevent heat transfer to adjacent cells.[8]

3 | THERMAL RUNAWAY

The volatile nature of LIBs has been apparent since the early 2000s when there were many product safety warnings and recalls[2]; hence, the importance of multiple layers of protection in their design. The off-gassing, fire, and explosion incidents can be traced to an event called thermal runaway, which occurs when cascading chemical reactions lead to uncontrollable heating in the cell.

When a cell is stressed by internal or external factors such as short-circuits, overcharging/discharging, crushing, penetrating, or overheating, the temperature in a LIB cell can increase. As the temperature rises, the flammable and combustible constituents in the electrolyte can rapidly vaporize or the $LiPF_6$ can act as a catalyst to decompose the solvent.[9] As gases are produced, pressure in the cell will build until the safety vent opens to relieve the pressure and release flammable vapors.

The SEI can begin to break down at as low as 156 °F (69°C),[3] allowing exothermic reactions between the electrolyte and anode and resulting in flammable off-gases such as ethylene, ethane, and propylene.[5] At approximately 266 °F (130°C), the separator melts, allowing electrolyte–cathode reactions.[3] Decomposition of the metal salt in the electrolyte can occur at 383 °F (195°C)[5] and, if moisture is present, will generate hydrogen fluoride.[2] Once the cell's temperature reaches 302–482 °F (150–250°C),[3] the cell reaches a point of no return where it will continue to generate heat faster than it can dissipate, increasing the overall reaction rate. The onset temperature for thermal runaway varies between LIB chemistries, open-circuit voltages, and abuse types.[2,3]

When flammable vapors and gases produced quickly find an ignition source, then a fire will ensue. When there is a delay in the off-gases finding an ignition source, vapors may have time to accumulate to their lower explosive limit, then a vapor cloud explosion (VCE) can occur.

4 | SCALING UP FOR THE GRID

A grid-scale installation can be of hundreds of megawatts-hours (MWh), and to build such energy capacities requires thousands to millions of LIB cells. The small 2–4 V LIB cells[5,8] are connected in series to increase the voltage and in parallel to increase the capacity and are placed in a casing to form modules. To reduce the thermal runaway hazard, safety features are incorporated at each level. Modules often include supervision circuitry and sensors for temperature and voltage monitoring. They may also have their own battery management systems.[5]

Modules can then be connected in racks and provided with additional safety systems such as fuses, thermal management in the form of liquid cooling systems, vent pathways, and battery management systems if not included at the individual module level. These racks, also called arrays,[10] are then installed in containers with both passive and active protection. Passive protection can include insulated walls and explosion vents designed to NFPA 68 standard on "Explosion Protection by Deflagration Venting." Active protection can include fire and gas detection and exhaust systems designed for cooling or to maintain the container below 25% of the lower explosive limit of off-gases.

Finally, containers, also referred to as units, with ratings of 1–3 MWh, are linked to build up to the required energy capacity. The units are finally connected to auxiliary electrical equipment such as inverters, transformers, breakers, and switchgear to form a BESS.

5 | LEARNING FROM LOSS

Like many industries, much can be learned from loss events. The failure rate of a single lithium-ion cell is <1 in 10 million.[11] However, for utility BESSs that house thousands to millions of cells, the failure rate increases. From 2011 to July 2022, EPRI tracked over 50 utility-scale battery failures across the 12.5 GWh of BESSs globally, which is equivalent to a 1%–2% failure rate across several battery technologies.[12] These events share many commonalities with fire and explosions in more traditional manufacturing and hydrocarbon industries, but on a smaller scale.

5.1 | Surprise, USA: April 19, 2019

Although the hazards of LIBs have been known for a while, the first widely publicized fire event in an outdoor BESS occurred in Surprise, Arizona. The 2 MW/2MWh BESS was first installed to study its ability to complement rooftop solar for a variety of tests. Eventually, after research had been completed, it was used as a load-serving resource,[13] being charged with solar energy during the day and discharging energy into the grid in the evening.

The BESS was one containerized walk-in type unit. It had two access doors. Internally, there were 36 vertical racks separated into two rows with a 1-m-wide hallway. Twenty-seven racks were populated with modules, 14 battery modules per rack. The cells were made with nickel manganese cobalt cathodes. The battery manufacturer also manufactured the modules and a battery protection unit (BPU) which was part of each rack. The system integrator was responsible for outfitting power inverters, HVAC, fire suppression, as well as data capture and monitoring equipment.[13]

On April 19, 2019, at 4:22 p.m., the insulation monitoring device showed insulation fluctuations, suggesting that Rack #15, approximately in the middle of the container, was not electrically isolated.[14] Within about 32 min, Cell #7 in Module #2 of Rack #15 began to exhibit voltage decay, and within 8 s the BMS lost module-level data.[13] Rear temperature readings for Rack #15 began to increase, but then the DC voltage recovered. The AC contactor opened, and an E-stop fault occurred for all racks. Milliseconds later, the air sampling smoke detection system sent out an alarm, thus opening the main breaker, beginning the 30-s countdown for fire suppression and shutting down the ventilation system to seal the compartment, as is typical for clean agent suppression systems. By 4:56 p.m., <2 min after the initial voltage drop, the air temperature measurements began to decrease.[14]

An engineer was dispatched to the site to visually confirm the fire. The fire department was not called until 5:40 p.m. At approximately 5:44 p.m., the BESS's battery backup power capability ended, and data collection and remote communications ceased. The fire department arrived at 5:44 p.m., completely blind to what was occurring within the container.[13] The fire department called for HAZMAT support, which arrived and made first entry into the fenced area at 6:37 p.m. to define a hot zone. They monitored gas concentrations and waited for carbon monoxide and hydrogen cyanide levels around the container to drop. At 8:00 p.m., the team opened the door to the BESS.[15] When the door was opened, gas poured out while the HAZMAT team took a temperature reading of 104 °F (40°C). The gas/vapor mixture was seen to be denser than the air coming in. At 8:03 p.m., an explosion occurred, the blast wave propelling members of the HAZMAT team up to 75 ft from the door they breached.[15] There were thankfully no fatalities, but serious injuries.

There were many factors contributing to this event. The two hypotheses for what started the thermal runaway event are an internal cell defect caused by dendritic growth,[13] or arcing on Module #2.[14] The module architecture led to cascading of the thermal runaway, thereby consuming most of Rack 15. The BESS was outfitted with a total-flooding clean-agent fire suppression system; however, the system was incapable of stopping thermal runaway. Owing to the nature of the suppression system, the ventilation system was turned off to hold the clean agent as per its design; therefore, there was no means to exhaust the flammable off-gases. Lastly, no pre-incident planning was done for the site, and the emergency response plan (ERP) had no guidance on extinguishing, ventilation, or entry procedures for the fire department.[13]

The BESS integrator did not clearly understand the thermal runaway risk of LIBs. They overly relied on the Novec 1230 suppression system, which the manufacturer had advised to standards committees, but it could not prevent or suppress cascading thermal runaway in LIB systems.[13] As a result, safety features were designed that worked against each other.

Both understanding and communicating the hazard to design engineers and emergency responders are an issue that not only plagues the BESS industry but has long been an issue in more traditional manufacturing industries. In 2003, a dust explosion occurred at West Pharmaceutical Services, Inc. in Kinston, North Carolina. Key findings from the Chemical Safety Board (CSB) included not identifying the combustible dust hazard of the polyethylene and zinc stearate from the safety data sheets and not communicating that hazard to their workforce.[16] The 1988 Piper Alpha explosion in the United Kingdom, the largest industry property damage loss of all times, also lacked adequate ERPs causing escalation of the initial incident. Knowledge-sharing among all stakeholders is key to avoiding siloed thinking as pointed out by Marsh.[17] Developing technologies, such as BESSs, can also learn from more mature industries, their losses, and lessons learned.

Since the Surprise, Arizona, event, there have been many improvements to legislation to try and keep up with the rapidly evolving technology. UL9540A, a test method for evaluating thermal runaway in BESSs, has been published, which puts batteries through thermal runaway testing to ascertain valuable information for the design team, including gas composition, lower explosive limits, and temperature onset of thermal runaway.[18] Had this testing been done for the batteries, modules, or unit, it would have exposed the explosion hazard present and potentially shown the need for overpressure vents in the enclosure or a redesign of the ventilation system.

Additionally, the National Fire Protection Association has published a new standard NFPA 855, "Standard for the Installation of Stationary Energy Storage Systems" to provide the minimum requirements for mitigating the hazards of BESSs.[19] The International Code Council[20] has also released updates to the International Fire Code, incorporating similar language as NFPA 855 into Section 1207, "Electrical Energy Storage Systems." Both codes require hazard mitigation analyses, which incorporate a "failure modes and effects" analysis to minimize cascading failures from occurring.

5.2 | Geelong, Australia: July 30, 2021

There is a 300 MW/450MWh BESS project at the Moorabool Terminal Station outside of Geelong, Australia, known locally as the Victorian Big Battery (VBB).[20] On Friday, July 30, 2021, during the initial installation and commissioning of the VBB, a liquid coolant leak in one of the 212 units caused arcing in the power electronics of a module, initiating a thermal runaway.[21]

Around 10:00 a.m., site personnel observed smoke coming from a unit and they electrically isolated the site and called emergency services. By 10:30 a.m., the county fire association (CFA) had set up an 80-ft perimeter, and flames were first observed coming from the roof. High winds, 23–35 mph, tilted the flames, causing direct impingement on the roof of an adjacent unit. By 11:57 a.m., flames were emanating from the adjacent unit. The ERP and facility's subject matter experts instructed the CFA to let the units burn out and only apply cooling water to nearby exposures. Cooling efforts lasted approximately 6 h, and by 4:00 p.m. the flames had subsided. Fire watch continued for almost 3 days after the active fire event ended.[21]

The unit had undergone UL9540A fire testing to establish separation distances to minimize propagation of thermal runaway to adjacent units. However, several factors led to a larger fire than expected. Fisher Engineering, Inc. and the Energy Safety Response Group found that the commissioning procedures had switched off the originating unit via a keylock switch, effectively a lock-out, tag-out. This caused many of the safety systems (e.g., telemetry, fault monitoring, electrical fault safety devices) to be disabled or have limited functionality. Detection of the fire and escalation of thermal runaway were unknown because telemetry data (e.g., temperatures, fault alarms) were not being transmitted to the off-site control facility. Lastly, flames from the originating unit weakened the plastic overpressure vents in the roof of an adjacent unit, allowing a path for hot gases and flames to enter the adjacent unit and cause further damage.[21]

This event reminded the industry that BESS technology is still growing and adapting. American standards, such as NFPA 855 and IFC, are now requiring commissioning and decommissioning plans be submitted for review. In the petrochemical industry, pre-startup safety reviews (PSSRs), detailed written operating procedures, and management of change policies are just a few of the measures put in place to minimize incidents during startup processes. The industry has learned just how cumbersome an operation startup can be. A 2010 study found that 50% of process safety incidents in refineries occurred during infrequent operations such as startup and shutdown.[22] Although the BESS industry now has a legislative push toward written procedures, there is still further room for growth.

The Geelong event also shows the importance of proper equipment siting. Had the accessory electrical equipment such as transformers had more robust thermal protection or were spaced further from the units, the fire department would not have had to utilize approximately 240,000 gallons of water.[21] Had pre-incident planning with the CFA occurred, they would have realized that the closest reliable water source was over 2 km away,[23] and this may have resulted in a closer water storage tank. Poor incident planning was one of the common themes in all four major accidents from 2018 to 2019 in the hydrocarbon industry.[17] History will continue to repeat itself if we do not learn from these lessons and adapt.

5.3 | Moss Landing, USA: September 4, 2021

The power plant in Moss Landing, an unincorporated community in Monterey County, California, repurposed old gas turbine halls to house a 400 MW/1600MWh BESS, known as the Moss Landing Energy Storage Facility.[24] On Saturday, September 4, 2021, a bearing in an air-handler failed, releasing smoke into a turbine hall, which triggered the air-sampling smoke detection system to raise an alarm. Upon the alarm, water was released into a pre-action sprinkler system zone. The energy management system reported no battery modules outside of their temperature limits at the time the detection system raised the alarm, thereby confirming that the batteries were not the source of the smoke.[25]

Pre-action sprinkler systems are often used for electrical installations to minimize the risk of water damage, because typically smoke detection and heat detection, via melting of a sprinkler head fusible link, are needed to spray water on the source. Unfortunately, at Moss Landing, some couplings and pipes in the sprinkler zone failed, resulting in water spraying onto the battery racks. The application of water caused the modules to short-circuit and arc, leading to thermal runaway. This caused more smoke detection zones to raise alarm, releasing water into adjacent sprinkler zones with similar flaws.[25] The local fire department responded to the incident in accordance with the ERP[24] but did not have to provide any active suppression for control or containment. In the end, approximately 7% of modules were damaged.[25]

The incident investigation report found that the entire pre-action system had not undergone pressure testing and that the air-sampling smoke detection system had been programmed incorrectly, leading to the alarm level being significantly lower than designed.[25] Unfortunately, on Sunday, February 13, 2022, another similar event occurred in another turbine hall associated with Phase II of the system.[26] These events highlight the importance of testing and commissioning all safety systems associated with the BESS, even those integrated into a building's design.

The importance of verifying and adequately installing fire systems has been a problem in the hydrocarbon industry in the past. In the 1989 Pasadena, Texas, event, the fire-water pumps failed to perform as a result of damaged electrical cables, a maintenance outage, and fuel shortage. Inspections, fire detection/alarm testing and operability, and fixed fire protection are frequently the cited root causes and contributing factors in the largest loss events in the hydrocarbon industry.[17] Safety is a culture that must occur at all stages of a project and all levels of operation/staff.

5.4 | Moss Landing, USA: September 20, 2022

At the Moss Landing electric substation in California, a 182.5 MW/730MWh BESS composed of 256 units was brought online on April 7, 2022.[27] At 1:30 a.m. on Tuesday, September 20, 2022, the owner became aware of a fire in one of the units.[28] Firefighters first on the scene reported seeing a fire in one unit, but it burned relatively quickly.[29] As a precaution, the North County Fire Department and Monterey County Sherriff's Office issued a shelter-in-place advisory and closed the adjacent highway in the morning.[30] Around 9:00 a.m., the fire chief reported that the unit was no longer flaming but continued to produce a white smoke.[29] By 6:50 p.m., the event was considered fully under control, and all road closures and advisories were lifted.[31]

The BESS owner has noted that the safety systems worked as designed, including disconnecting the BESS from the grid.[28] There were no injuries to on-site personnel and no electrical outages to customers. The United States Environmental Protection Agency (USEPA) and NES Consulting were dispatched to the site to conduct air monitoring. Sampling for concentrations of fluoride and hydrogen fluoride was done around the site beginning September 20 and continued for days after containment. The concentrations around the BESS site were found to be below the detection limits for the sampling method and therefore well below the permissible exposure limits (PELs).[32]

While it is still unclear what caused this thermal runaway event, this event is a great example of stakeholder collaboration and safety systems working to minimize loss.

6 | CONCLUSIONS

BESS technology continues to evolve, balancing the needs for larger energy capacities, lighter weights, and providing additional safety measures. The codes and standards in America are trying to catch up to the technology and have improved greatly over the last 5 years. It is important that the energy storage industry learns from historical events in BESSs and beyond.

BESSs are built with robust multilayered approaches to safety. Reviews across the lifecycle of the technology provide immense value to mitigate their thermal runaway, fire, and explosion hazards. Every site should have a unique approach, as the location, owner's acceptable risk, water supply, fire department, and technology will vary. This could entail starting with cause-and-effect analyses of the BESS design, site-specific risk assessments, or heat transfer analyses to consider safe separation distances for auxiliary equipment and fire departments.

Stakeholder involvement and knowledge-sharing are critical to the successful planning, installation, and operation of a BESS. LIB manufacturers and BESS integrators need to collaborate with engineers and fire departments to agree on design, permitting, and emergency response approaches. Emergency response as well as commissioning and decommissioning plans need to be created and coordinated. The owner needs to determine their acceptable loss criterion. Operators need to ensure the upkeep of maintenance.

At this time, LIB thermal runaway cannot be prevented but the risk is being mitigated through research, innovation, design, and collaboration. The renewable energy industry can learn a lot from more mature hydrocarbon and manufacturing industries and their major accidents. Fire and process safety engineers are uniquely situated to be the conduit and help the energy storage industry through its growing pains.

DATA AVAILABILITY STATEMENT

Data derived from public domain resources.

ORCID

Veronica Goldsmith https://orcid.org/0009-0004-7431-3998

REFERENCES

1. Review of February 2021 Extreme cold weather event – ERCOT presentation. Electric Reliability Council of Texas, Inc, 2021. https://www.ercot.com/files/docs/2021/02/24/2.2_REVISED_ERCOT_Presentation.pdf
2. Larsson F. Lithium-ion battery Safety – assessment by abuse testing, fluoride gas emissions and fire propagation. Paper presented at: Chalmers University of Technology, Goteborg 2017.
3. Kong L, Li C, Jiang J, Pecht M. Li-ion battery fire hazards and Safety strategies. *Energies*. 2018;11:2191.
4. Cheung A, Sekine Y, Stoikou E. *AskBNEF: the rising cost of batteries*. BloombergNEF; Webinar, 2023.
5. Md SM. Experimental study and numerical modeeling of lithium-ion battery thermal runaway behaviour. The University of Sheffield, PhD Thesis. 2018.
6. Kaliaperumal M, Dharanendrakumar M, Prasanna S, et al. Cause and mitigation of lithium-ion battery failure – a review. *Materials*. 2021; 14:5676.
7. Mrozik W, Rajaeifar M, Heidrich O, Christensen P. Environmental impacts, pollution sources and pathways of spent lithium-ion batteries. *Energ Environ Sci*. 2021;14:6099-6121.
8. Xu B, Kong L, Wen G, Pecht M. Protection devices in commercial 18650 lithium-ion batteries. *IEEE Access*. 2021;9:66687-66695.
9. Lamb JL, Orendorff CJ, Roth P, Langendorf J. *Studies on the Thermal Breakdown of Common Li-Ion Battery Electrolyte Components*. Sandia National Laboratories; 2015. SAND2015-6333J.
10. International Code Council. *International Fire Code*. 2021st ed. ICC Publications; 2020.
11. Battery University. *BU-304a: Safety Concerns with Li-Ion*. *Battery University*; 2022. https://batteryuniversity.com/article/bu-304a-safety-concerns-with-li-ion#:~:text=Lithium%2Dion%20batteries%20have%20a,than%20those%20in%20consumer%20products
12. Warren C. A focus on battery energy storage safety. *EPRI J*. 2022. https://eprijournal.com/a-focus-on-battery-energy-storage-safety/
13. Hill D. *McMicken Battery Energy Storage System Event – Technical Analysis and Recommendations*. DNV GL Energy Insights USA, Inc.; 2020. 10209302-HOU-R-01.
14. Swart J, White K, Cundy M. *APS McMicken Progress Report*. Exponent, Inc.; 2020. 1903648.000-0144.
15. McKinnon M, DeCrane S, Kerber S. *Four Firefighters Injured in Lithium-Ion Battery Energy Storage System Explosion – Arizona*. UL Firefighter Safety Research Institute; 2022.
16. U.S. Chemical Safety and Hazard Investigation Board. *Investigation Report Dust Explosion*. Chemical Safety Board; 2004. Report No. 2003-07-01-I-NC.
17. Marsh JLT Specialty. *100 Largest Losses in the Hydrocarbon Industry 1947–2019*. 26th ed. Marsh; 2020.
18. National Fire Protection Association. *NFPA 855 Standard for the Installation of Stationary Energy Storage Systems*. 2023rd ed. NFPA; 2022.
19. Department of Energy, Environment, and Climate Action. Victoria Big Battery. *State Government of Victoria*. 2023. https://www.energy.vic.

gov.au/renewable-energy/batteries-energy-storage-projects/victorian-big-battery
20. Blum A, Bensen T, Rogers P, Grant C, Hough G. *Victorian Big Battery Fire*. Johns Creek: Fisher Engineering, Inc./Energy Safety Response Group. Report of Technical Findings. 2022.
21. U.S. Chemical Safety and Hazard Investigation Board. Safety digest: CSB investigations of incidents during startups and shutdowns. US Chemical Safety Board. 2018. https://www.csb.gov/assets/1/17/csb_start_shut_02.pdf?16301
22. United Firefighters Union of Australia. Inquiry into electric vehicle (EV) adoption in the ACT. Standing Committee on Planning, Transport and City Services: Inquiry Into Electric Vehicle Adoption in the ACT; UFU ACT Branch submission. 2022.
23. Colthorpe A. Investigation begins into overheating incident at world's biggest battery storage facility. *Energy Storage News*. 2021. https://www.energy-storage.news/investigation-begins-into-overheating-incident-at-worlds-biggest-battery-storage-facility/
24. Vistra Corp. Vistra announces investigation findings and corrective actions related to fall 2021 incident at Moss landing energy storage facility. Vistra Corp. 2022. https://investor.vistracorp.com/news?item=217
25. Colthorpe A. World's biggest lithium battery storage facility now completely offline after weekend incident. *Energy Storage News*. 2022. https://www.energy-storage.news/worlds-biggest-lithium-battery-storage-facility-now-completely-offline-after-weekend-incident/
26. Kane M. PG&E Commissions its Moss Landing Elkhorn Battery: 256 tesla Megapacks. *Inside EVs*. 2022. https://insideevs.com/news/590551/pge-moss-landing-elkhorn-battery/
27. Weber H. PG&E says tesla battery was source of power storage site fire. *Tech Crunch*. 2022. https://techcrunch.com/2022/09/20/pge-says-tesla-battery-was-source-of-power-storage-site-fire/
28. Rubin S. Fire at PG&E's Moss landing battery plant causes highway 1 closure, shelter-in-place order. *Monterey County Weekly*. 2022. https://www.montereycountyweekly.com/blogs/news_blog/fire-at-pg-es-moss-landing-battery-plant-causes-highway-1-closure-shelter-in-place/article_3a55239a-38f9-11ed-95ee-1320e1c5ca95.html
29. Monterey County Office of Emergency Services. Moss landing incident. *Monterey County*. 2022. https://www.co.monterey.ca.us/government/departments-a-h/administrative-office/office-of-emergency-services/incidents/power-storage-facility-incident
30. Murray C. Fire at PG&E's tesla battery storage facility in Moss landing under control, authorities lift closures. *Energy Storage News*. 2022. https://www.energy-storage.news/fire-at-pges-tesla-battery-storage-facility-in-moss-landing-under-control-authorities-lift-closures/
31. County of Monterey Health Department, Environmental Health Division. County of Monterey environmental health shares air quality testing information and process during Moss landing fire incident. *Monterey County*. 2022. https://www.co.monterey.ca.us/Home/Components/News/News/9345/1336?arch=1
32. Rubin S. Air quality testing showed no hazards to human health amid battery fire in Moss landing. *Monterey County Weekly*. 2022. https://www.montereycountyweekly.com/blogs/news_blog/air-quality-testing-showed-no-hazards-to-human-health-amid-battery-fire-in-moss-landing/article_5a0ee07a-4125-11ed-a797-c31048cab7a5.html

How to cite this article: Goldsmith V. Introduction to grid-scale battery energy storage system concepts and fire hazards. *Process Saf Prog*. 2024;43(2):357-363. doi:10.1002/prs.12541