THE ULTIMATE GUIDE TO FIRE PREVENTION IN LITHIUM-ION BATTERY ENERGY STORAGE SYSTEMS

HOW TO PREVENT THERMAL RUNAWAY WITH ELECTROLYTE VAPOR GAS DETECTION

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The stationary Battery Energy Storage System (BESS) market is expected to experience rapid growth. This trend is driven primarily by the need to decarbonize the economy and create more decentralized and resilient 'smart' power grids.

Lithium-ion (Li-ion) batteries are one of the main technologies behind this growth. With higher energy density, faster charging and longer life than traditional batteries, they provide significant benefits to BESS operators.

Without appropriate safety measures in place, though, Li-ion batteries may pose a serious fire hazard, which is often a consequence of thermal runaway.

This guide examines some of the main risks associated with Li-ion-based stationary, utility-scale BESSs. It looks at why electrolyte solvent vapor early detection is the optimum fire safety technology to help prevent thermal runaway in BESSs.

The guide analyzes the far-reaching consequences that BESS fires can have. It explains why neither existing fire safety standards and regulations nor traditional fire detection and suppression technology are fit for purpose.

The final section of the guide examines the findings of rigorous testing of electrolyte vapor early detection compared to other fire detection and suppression technologies in different BESS fire scenarios.

WHY ARE LI-ION BATTERY CELLS A FIRE HAZARD?

Li-ion BESSs: a growing market

Stationary BESSs are a key component of the ongoing transition to a more energy efficient, resilient and reliable power grid. Energy storage installations around the world are projected to reach a cumulative 411 gigawatts (or 1,194 gigawatt-hours) by the end of 2030, according to the latest forecast from research company BloombergNEF (BNEF). That is 15 times the 27GW/56GWh of storage that was online at the end of 2021.[1] Li-ion batteries account for the majority of BESSs worldwide.

The price of Li-ion battery packs decreased steadily over the past decade.[2] Despite a recent price increase,[3] Li-ion batteries may cost as little as $58 per kilowatt hour by 2030.[2] Li-ion is becoming a viable utility-scale alternative to traditional energy storage technology such as pumped-storage hydropower.

One major advantage of BESSs is that they can be deployed almost anywhere. This is key to enabling the ongoing transition to smart grids[4] and microgrids[5] that, increasingly, rely on decentralized, renewable power generation.

BESSs serve three main purposes

- **Peak shifting**: batteries charge during off-peak times and discharge during peak times.
- **Renewable integration**: batteries stabilize renewable power availability, which is naturally intermittent, by charging when power is available and discharging when it drops.
- **Frequency regulation**: batteries charge when grid frequency rises and discharge when it decreases.

Fire risks associated with Li-ion batteries

There are advantages to deploying Li-ion technology in grid-scale applications. Despite their benefits, using Li-ion batteries can come with risks. The main reason for this is that these batteries feature a highly-flammable, organic electrolyte and store significant amounts of energy.

Thermal runaway is an exothermic reaction that causes the Li-ion battery's internal temperature to rise and may eventually ignite the electrolyte. If the electrolyte catches fire, it may lead to catastrophic fires, which can be extremely hard to extinguish.

" A single failing cell can quickly overheat the surrounding cells, causing them to go into thermal runaway "

Unless they are constantly kept within specific environmental conditions and electrical parameters, Li-ion cells are prone to failing. This can lead to a process known as thermal runaway.

Thermal runaway events can easily escalate into dangerous and damaging fires. A single failing cell can quickly overheat the surrounding cells, causing them to go into thermal runaway in their turn.

The four stages of battery failure

Battery failure happens in four stages. Understanding each of these will ultimately help BESS operators to prevent thermal runaway.

1. BATTERY ABUSE

This could be electrical, thermal or mechanical abuse and what starts a potential fire event.

Electrical abuse is caused by exceeding the battery voltage limits during charge or discharge.

Thermal abuse is caused by the operational temperature exceeding the temperature limits of the batteries, due to overcharging or overheating.

Mechanical abuse is caused by physical or mechanical damage such as a crush, indentation or puncture.

2. ELECTROLYTE SOLVENT VAPORS (OFF-GAS)

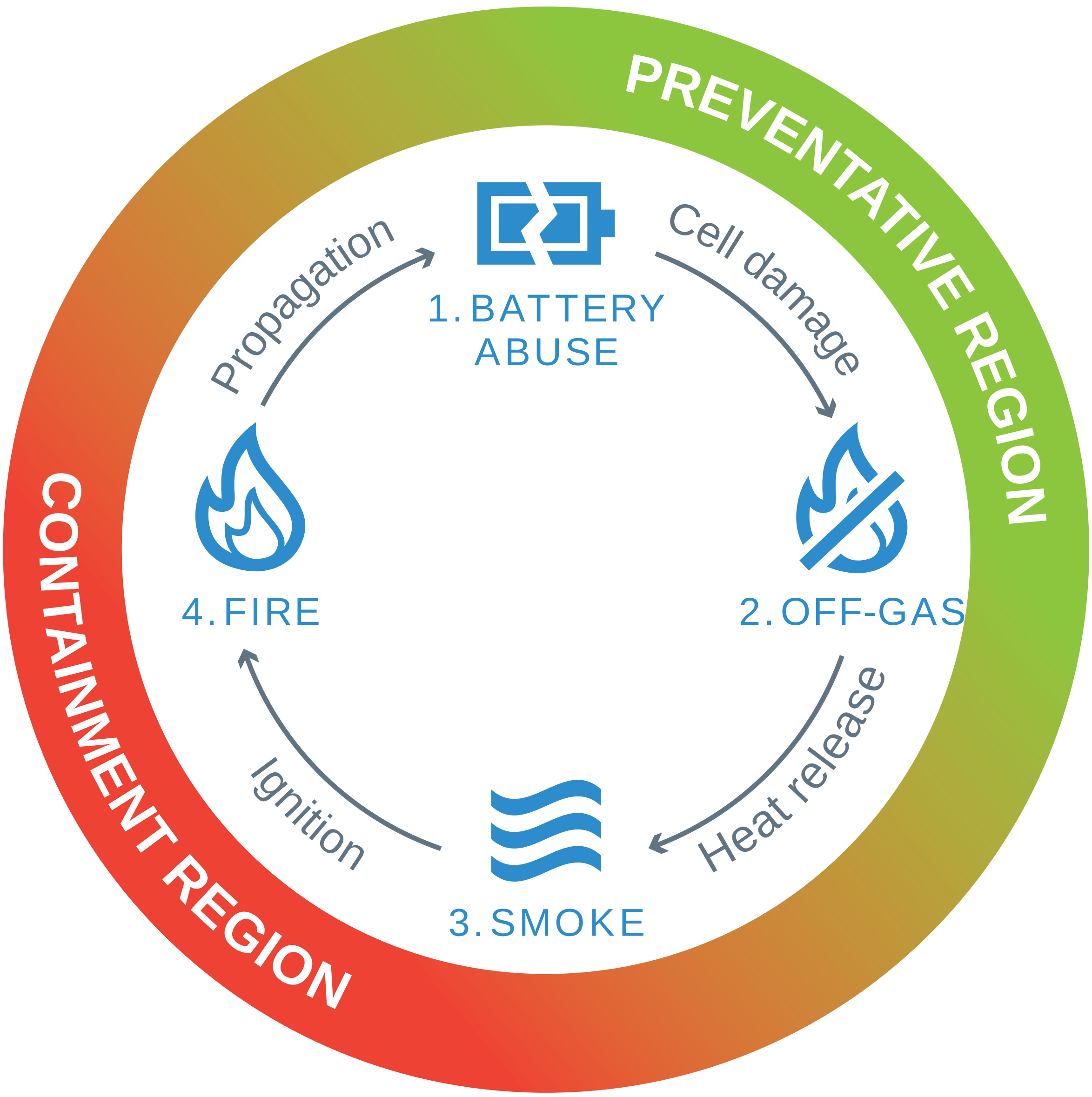
If the abuse factor continues, more of the liquid electrolyte will continue to convert to electrolyte solvent vapors, including diethyl carbonate, dimethyl carbonate or other carbonate species used in electrolyte solvents. This will cause an internal pressure build-up inside the battery.

3. SMOKE

As gas continues to be generated, the internal pressure continues to rise. Eventually, it will melt down and rupture the separator, causing the release of smoke. At this stage thermal runaway is imminent and can no longer be prevented.

4. FIRE

When a battery catches fire, this is what is often referred to as thermal runaway. A single cell can cause severe thermal abuse to surrounding cells, meaning that a total system failure can result from a single cell failure.



BESS FIRES IN NUMBERS

The full extent and impact of fire incidents involving stationary Li-ion-based BESSs remains largely unknown due to limited research in this field. Li-ion battery fires, due to their potential to spread quickly and cause significant damage have made headlines on numerous occasions in recent years.

" At least 50 failure events occurred in utility-scale sites globally between 2018 and 2022.[6] "

Here are some examples of major BESS fires recorded around the world in recent years:

- 23 fires involving BESSs were recorded in South Korea between 2017 and 2018.[8]
- In 2019, an explosion occurred at a container filled with more than 10,000 energized Li-ion battery cells, part of a utility-scale BESS near Phoenix, Arizona (USA). Four firefighters suffered serious injuries. The cause was the build-up of combustible gases that ignited immediately when firefighters opened the container door letting oxygen in.[9]
- In 2020, a 20MW BESS in Liverpool, England, suffered a major fire that started in one of the containers. It took several hours for firefighters to extinguish the fire, with smoke reaching nearby residents.[10]

" Fire safety is becoming "an issue of growing severity and stakes" now that Li-ion battery technology is moving to larger, utility-scale applications, from single cells to modules and packs."[7]

CONSEQUENCES OF BESS FIRES

Li-ion BESS fires present unique challenges, which can potentially put first responders, workers and members of the public in harm's way.

A study from the Underwriters Laboratories (UL) Firefighter Safety Research Institute noted several key challenges associated with BESS fires:[9]

- Explosive nature of the gases and vapors released during thermal runaway;
- Vapor cloud formation and dispersion;
- Dynamics of deflagrations and blast wave propagation; and
- Ineffectiveness of fire suppression

The consequences of thermal runaway fires can be far reaching. Increasingly, BESSs are key to microgrids. This means they are likely to be located near the buildings they power, from factories to schools. Building occupants may therefore be exposed to toxic gas leaks, fires and even explosions caused by thermal runaway. Fire tests of unconfined Li-ion batteries have demonstrated that cell explosions can cause projectiles to travel up to 40 meters (133 feet),[11] potentially causing damage to neighboring areas.

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The social and economic consequences of such incidents should not be underestimated. Increasingly, microgrids and smart grids rely on BESSs to deliver uninterrupted power to communities around the world. A battery fire can bring an entire BESS site to a halt. It may lead to added pressure on the grid, or worse, power cuts, which typically come with major disruption and huge financial costs. Research from the Royal Academy of Engineering estimated that nation-wide outage of one or two hours could cost the UK economy millions of pounds.[12] BESS fires can also disrupt telecommunications. For example, a recent BESS fire at a South Korean data center brought down a messenger service used by 90 percent of Koreans, and disabled various banking, payment, and travel apps.[13]

Another outcome of fire incidents may be fines and other legal consequences for BESS operators, especially if injuries occur. In South Korea, BESS operators were forced to suspend all new installations in 2019 following several fire events and two of the main operators recorded losses of $100 and $125 million, respectively.[14]

The reputational damage suffered by both BESS manufacturers and operators can also be potentially significant with long-lasting financial consequences.

FIRE SAFETY CODES, STANDARDS AND REGULATIONS IN ESS APPLICATIONS

There are different standards and regulations mandating minimum fire safety requirements for stationary BESSs. These norms may vary from region to region.

The adoption cycle of these norms can be slow, taking a minimum of three years on average. This means the standards might be behind the curve in terms of advancements in fire safety technology or methods. Fire codes, standards and regulations should be regarded as a starting point to build upon with additional solutions.

Some important norms to consider are:

- Li-ion battery cell-related standards such as UL 1642 / IEC 62133
- Module-related standards, such as UL 1973
- Rack-level standards, such as UL 9540 / IEC 62619
- System-level regulations such as NFPA 855 / IFC Chapter 12

Compliance with these norms is generally seen as a minimum requirement for market entry in many countries.

One of the latest and most important standards to bear in mind is UL 9540A. It is mandated by NFPA 855[15] and involves large-scale fire testing of BESSs. The test is a four-step process:

1. A cell is forced into thermal runaway
2. The cell is inserted into its module and forced into thermal runaway
3. The module is inserted into the battery rack and forced into thermal runaway
4. A rack within a fully functional system is forced into thermal runaway

The purpose of this test is to evaluate the system's mechanical design and how it responds to thermal runaway.

There are also many guideline documents published, particularly in Europe, including:

- Euralarm's guidance document, "Integrated Fire Protection Solutions for Lithium-ion Batteries"[16]
- The UK's Fire Industry Association (FIA)'s "Guidance on Li-ion Battery Fires"[17]

Insurers also produce guidelines for loss prevention. FM Global has a series of data sheets for this purpose, one of which is dedicated to Electrical Energy Storage Systems.[18] This document describes loss prevention recommendations for the design, operation, protection, inspection, maintenance, and testing of BESSs that use Li-ion batteries.

For more information and the latest standards, regulations, and guidance read THE INSURER'S GUIDE TO FIRE SAFETY COMPLIANCE IN BATTERY ENERGY STORAGE SYSTEMS.

WHY ARE BATTERY MANAGEMENT SYSTEMS, TRADITIONAL DETECTION TECHNOLOGIES AND FIRE SUPPRESSION METHODS NOT ENTIRELY EFFECTIVE IN BESSs?

Battery Management Systems

Battery Management Systems (BMSs) are an essential part of a large-scale energy storage system. They are designed to monitor voltage, current, and temperature as well as to prevent abuse to the batteries. Relying on them as the only layer of defense against thermal runaway is not enough.

One of the main limitations of a battery management system is the inability to resolve single cell temperatures or voltages. Even with temperature sensors on every cell, there could be hot spots that go undetected. Additionally, faults can occur in utility-scale BESSs with hundreds of thousands of Li-ion battery cells and sensors.

Detection technologies

Traditional detection technologies; such as smoke and fire, or carbon monoxide and hydrogen monitoring can also be part of a comprehensive safety solution. It is important to note that these approaches are not effective until thermal runaway has already occurred.

Smoke and fire are not present until a cell has reached thermal runaway. Additionally, carbon monoxide and hydrogen are not dependably present until thermal runaway and are often not present in large enough concentrations to be detectable until several cells have failed.

In other words, all these solutions are reactive to thermal runaway instead of proactive. Even if a single cell has reached the point where it starts emitting smoke or fire, it may already be too late to prevent it from spreading to surrounding cells.

According to the UL Firefighter Safety Research Institute study from 2020, there are challenges associated with gas detection in energy storage systems,[9] including:

- Sensor position relative to the battery gas vent
- Cross-sensitivity issues
- Interference with extinguishing agents
- Compartment volume and geometry
- Confinement of flammable gases within equipment
- Air movement patterns
- Stratification of gases

Fire suppression systems

Suppression is a BESS' last line of defense against fire. It becomes vital when all preventative measures fail.

Yet, according to a recent study published last year in the Journal of the Electrochemical Society, none of the main suppression methods are proven as entirely effective in containing BESS fires.[7]

- **Smothering**: as oxygen is often already present in battery components, this method has little effect
- **Cooling**: using a continuous water mist to cool the battery is a more effective tactic but can cause short circuits, propagating thermal runaway further
- **Chemical suppression**: conventional fire extinguishers are unable to arrest thermal runaway and can only suppress open flames outside the battery; additives have proven more effective but can produce hydrogen fluoride (HF) at high temperatures, which is extremely toxic and corrosive

In addition, the study found that, even after initial suppression, there is a high risk of reignition as the exothermic chemical processes inside the cells may continue.

A DNV study from 2019 analyzed different suppression systems, assessing their effectiveness in a Li-ion-based BESS application. It found that there was no 'silver bullet' solution while some fire suppression systems and methods were yet to be fully tested, as the table below illustrates.[19]

Fire suppression system	Suppression method	Flame extinction	Long Term Heat Absorption	Short Term Heat Absorption	Reduce Gas Temp in room	Gas Absorption in room
Sprinkler	Total flooding	Medium capability	Medium capability	Low capability	High capability	No or very low capability
Hi-fog	Total flooding	High capability	Medium capability	Low capability	High capability	High capability
NOVEC 1230	Total flooding	High capability	No or very low capability	Medium capability	Medium capability	No or very low capability
FIFI4Marine	Direct Injection	High capability	High capability	High capability	Not evaluated	Not evaluated
Direct Water Injection*	Direct Injection	High capability	High capability	High capability	Not evaluated	Not evaluated

High capability — Medium capability — Low capability — No or very low capability

* Not expected or recommended to be used in practice for high voltage applications, due to the risks of short circuit and hydrogen production. The method is presented as a flame extinction and heat absorption capability reference.

Table 1: Fire suppression systems' capability matrix (source: DNV[19])

WHAT IS ELECTROLYTE VAPOR DETECTION?

Electrolyte vapor detection is an application-specific gas monitoring solution for Li-ion batteries that gives BESS operators indication at the earliest presence of electrolyte solvent vapors. Li-ion batteries go through two stages of gas release, the first being when the cell starts venting and the second when thermal runaway occurs.

Understanding when a cell starts venting gas is critical. It enables the prevention of thermal runaway, ultimately avoiding destructive fires.

Electrolyte solvent vapor detection solutions are designed to a BESS' specific characteristics, including geometry, volume, cell type, spatial layout, and air flow patterns. A distributed network of gas sensors immediately detect even when a single cell starts venting electrolyte vapors. In this way, BESS operators receive the earliest indication of failure and can intervene to prevent thermal runaway. As the detector's monitor connects to the BMS via a fire alarm control panel, it can automatically instruct the system to immediately isolate the affected battery rack, containing the fire threat. The monitor can also communicate with the BMS to automatically initiate ventilation, increase cooling, or trigger fire suppression. As BESS sites are often unmanned and located in remote areas, this automated response can buy BESS operators critical time to intervene.

" Electrolyte vapor detection solutions are designed to a BESS' specific characteristics "

The latest detection systems are out-of-the-box solutions designed to simplify installation and maintenance, minimizing costly time on-site in remote BESS facilities. The location and number of sensors is optimized to deliver the earliest detection using the least number of sensors, providing an economical but effective solution to customers. Additionally, having a design that suits BESS' characteristics addresses the challenges that UL has pointed out regarding gas detection in BESSs.

How can electrolyte vapor detection help prevent thermal runaway and fire?

A recent study by DNV[19] put different technologies to the test to assess their response times and, ultimately, their effectiveness in detecting early signs of thermal runaway:

- Lower Explosion Limit (LEL) sensors
- Electrolyte vapor specific sensors
- Cell voltage sensors.

Testing was performed at both cell and multi-cell levels using different chemistries and form factors and under different failure modes. Cell and rack/module testing results were used as input to calibrate Computational Fluid Dynamics (CFD) models, which were then used to evaluate a wider range of configurations.

The test demonstrated that electrolyte vapor detectors displayed higher sensitivity, accuracy and responsiveness than the two tested technologies. As illustrated in the table below, neither LEL sensors nor voltage sensors were able to activate until after thermal runaway had already started. By contrast, the electrolyte vapor detector activated, on average, only 10 seconds after electrolyte vapors started to be released, and more than six minutes before thermal runaway started to take place.

	Electrolyte Vapors Release	Electrolyte Vapors Sensor	Thermal Runaway	Cell Voltage	LEL Sensor
Average time of occurrence relative to thermal runaway (seconds)	-381	-371	0	+7	+28

Table 2: Average responses from different sensors and indication mechanisms tested in cell level tests (source: DNV[18])

Testing also showed how shutdown measures combined with off-gas detection were effective in preventing thermal runaway. By electrically isolating the battery system once electrolyte vapors were detected, the cell temperature ceased to increase. Ultimately, the test demonstrated the effectiveness of a correct mitigating action at the earliest indication of gas presence.

Further testing conducted by Xtralis in 2021 corroborated the DNV report investigation, comparing Li-ion Tamer with aspirated smoke detection (ASD) and aspirated gas detection (AGD) technologies. Tables 3 and 4 show that Li-ion Tamer was the fastest and most effective in detecting the early signs of a thermal runaway providing the BMS with a 25-minute warning.

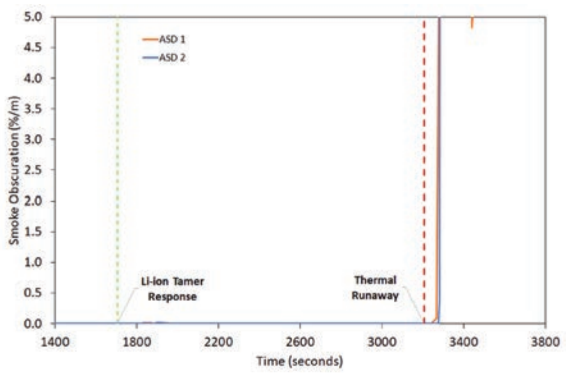

Table 3: Li-ion Tamer and ASD response (Thermal Runaway noted by perforated red line) (Source: Xtralis)

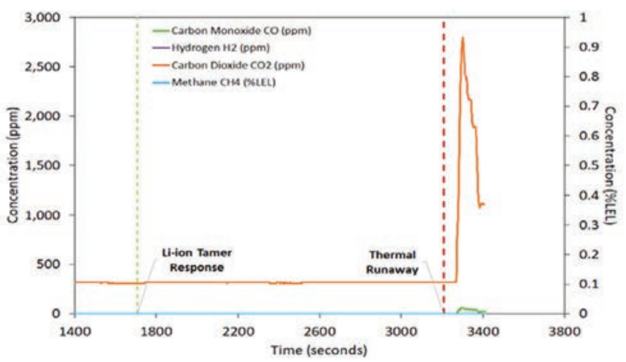

Table 4: Li-ion Tamer and Gas Detectors (AGD) response (Thermal Runaway noted by perforated red line) (Source: Xtralis)

CONCLUSION

Li-ion battery-based energy storage has and will continue to have a major role to play as the transition to a greener economy accelerates. This battery technology is ideally placed to meet the growing demand for decentralized power that lies at the heart of an increasingly smart grid.

This guide examined the main fire risks that are associated with Li-ion batteries within stationary BESSs. If undetected, thermal runaway can pose a serious threat to people and property alike and the consequences can be far reaching.

Yet, BESS fires remain an under-investigated risk that deserve greater attention. As utility-scale energy storage becomes commonplace, a more comprehensive, international regulatory framework is also needed. More up-to-date standards and regulations are key to giving BESS manufacturers and operators around the world the guidance they need to ensure higher levels of fire safety.

Electrolyte solvent vapor detection is a critical solution which enables customers to not only have access to the earliest indication of failure but also serve as a barrier to potential catastrophic failure and thermal runaway. By implementing electrolyte vapor detection, BESSs can continue to meet the needs of a green energy economy and world and serve as a reliable technology for utilities around the world.

For more information on how to install and use electrolyte solvent vapor detection effectively, download our LI-ION TAMER RACK MONITOR DESIGN GUIDE here.

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We protect highly valued assets and infrastructure belonging to the world's top governments and businesses.

To learn more, please visit us at www.xtralis.com

[1] BloombergNEF, *Global Energy Storage Market to Grow 15-Fold by 2030*, October 12, 2022 [Accessed May 22, 2023]
[2] BloombergNEF, *Lithium-ion Battery Pack Prices Rise for First Time to an Average of $151/kWh*, December 6, 2022 [Accessed May 22, 2023]
[3] Statista, *Lithium-ion battery pack costs worldwide between 2011 and 2030*, January 5, 2023 [Accessed May 23, 2023]
[4] SmartGrid.gov, *The Smart Grid* [accessed December 16, 2020]
[5] Energy.gov, *How Microgrids Work*, June 17, 2014 [accessed December 16, 2020]
[6] EPRI, *BESS Failure Event Database*, August 17, 2022 [Accessed May 22, 2023]
[7] Journal of the Electrochemical Society, *Meta-Review of Fire Safety of Lithium-Ion Batteries: Industry Challenges and Research Contributions*, August 17, 2020, Laura Bravo Diaz et al [accessed December 14, 2020]
[8] BusinessKorea, *Second Probe Blames Faulty Batteries for ESS Fires*, February 7, 2020, Michael Herh [Accessed December, 16 2020]
[9] UL Firefighter Safety Research Institute, *Four Firefighters Injured In Lithium-Ion Battery Energy Storage System Explosion – Arizona*, July 28, 2020, Mark B. McKinnon et al [Accessed December 17, 2020]
[10] Energy Storage News, *Fire at 20MW UK battery storage plant in Liverpool*, September 16, 2020, Andy Colthorpe [Accessed December 14, 2020]
[11] Fire Protection Research Foundation, *Hazard Assessment of Lithium Ion Battery Energy Storage Systems*, February, 2016, Andrew F. Blum et al [accessed December 17, 2020]
[12] Royal Academy of Engineering, *Counting the cost: the economic and social costs of electricity shortfalls in the UK*, 2014 [accessed January 21, 2021]
[13] DCD, *SK's Li-ion batteries blamed for data center fire behind Kakao outage*, October 20, 2022, Peter Judge [Accessed on May 23, 2023]
[14] S&P Global, *Burning concern: Energy storage industry battles battery fires*, May 24, 2019, Garrett Hering [Accessed December 14, 2020]
[15] NFPA Journal, *A handful of highlights of NFPA 855, the new standard for the installation of energy storage systems*, May 1, 2019, Brian O'Connor [Accessed December 17, 2020]
[16] Euralarm, *Integrated fire protection solutions for Lithium-ion batteries*, February 2022 [Accessed on January 23, 2023]
[17] FIA, *Guidance on Li-ion Battery Fires*, January 2021 [Accessed on May 23, 2023]
[18] FM Global, *5-33 Electrical Energy Storage Systems*, July 2020 [Accessed on January 23, 2023]
[19] DNV-GL, Technical Reference for Li-ion Battery Explosion Risk and Fire Suppression, 2019