An EPRI White Paper

CARNEGIE ROAD ENERGY STORAGE SYSTEM FAILURE RESPONSE, RECOVERY, AND REBUILD LESSONS LEARNED

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1 INTRODUCTION

In the early morning hours of September 15, 2020, an explosion occurred at the Carnegie Road energy storage site, followed by a fire that consumed one of three energy storage enclosures. The owner (Ørsted) and the supplier/maintenance provider (NEC) immediately began an investigation of the incident. In December 2020, EPRI was integrated into the investigation team to advise on battery technology hazards in a supporting role to Ørsted.

This report conveys the lessons learned from the Carnegie Road energy storage system (ESS) failure event, including aspects of emergency response, root cause investigation, and the redesign and rebuild process. EPRI was engaged by the system owner, Ørsted, following the failure event to provide support and guidance as experts in ESS design and safety. This report is not the full summary of the engagement nor a complete root cause analysis (RCA). Rather, this document highlights and conveys the general information about the failure event and the subsequent process to educate the industry on lessons learned and facilitate the development of best practices.

Through industry monitoring efforts, EPRI has established a battery ESS (BESS) Failure Event Database[1] as a resource to the industry to further document and understand the nature of BESS failures in the industry. This work has highlighted the need for further understanding of the nature of the failures as well as the challenges associated with response, redesign, and rebuild.

The findings communicated within this report are not meant to assign or convey fault or attribute blame. Rather, the intent is to make clear the areas of design difficulty and challenges encountered in the context of the increased industry knowledge of energy storage fire safety design and event response that has occurred in the years since this system was designed and commissioned.

2 CARNEGIE ROAD ENERGY STORAGE SYSTEM DESCRIPTION

2.1 Site

The Carnegie Road BESS was first energized in December 2018 and commissioned in May 2019. The BESS is located in Liverpool, UK and interconnected to the Scottish Power Energy Networks at 33 kV. It includes three containerized battery enclosures within the site footprint (see Figure 1).

[1] EPRI's BESS Failure Event Database: https://storagewiki.epri.com/index.php/BESS_Failure_Event_Database.

Figure 1
Carnegie Road energy storage site image; source: https://orsted.com/en/media/newsroom/news/2019/01/orsteds-first-standalone-battery-storage-project-now-complete

2.2 Specifications

The Carnegie Road BESS design, installation, and commissioning were led by NEC. Ørsted procured and continues to operate the system, using maintenance contracts with NEC. The system is designed to charge and discharge energy up to 20 MW capacity for up to 30 minutes, primarily operated for the National Grid Firm Frequency Response (FFR) service.

Among the three enclosures, the ESS houses 126 racks totaling 2,142 LG Chem JP3 lithium ion (nickel-manganese-cobalt [NMC]) modules. The racks are divided into 14 "zones" (or power blocks) with 2 zones per inverter. Each inverter is 3.2 MVA, supplied by WSTECH. Container 1, where the failure incident occurred, houses five zones and 45 total racks. The total usable energy capacity of the system at the beginning of life is 11.25 MWh at the point of interconnection (AC). Specifications are listed in Table 1.

Table 1
Carnegie Road BESS specifications; source: NEC

DESCRIPTION	20 MW 11.25 MWH GSS	NOTE
Nominal DC Energy	13.45 MWh	Module DC nominal energy rating at beginning of life (BOL): installed modules x module DC rated energy
Useable Energy Capacity	11.25 MWh	33 kV AC at 20 MW rate at BOL. Includes DC/AC losses up to the point of interconnection (POI).
Nameplate Power Capability	20 MW	At 33 kV AC, 0.95 power factor (PF), 1.0 per unit (pu) voltage
Point of Interconnection	33 kV AC	
Maximum Charge Rate	20 MW	From 0% to 100% state of charge (SOC)
Maximum Discharge Rate	20 MW	From 100% to 0% SOC

2.2.1 Battery Racks

Each battery rack contains 17 modules, a fuse assembly panel, and a rack battery management system (BMS) (see Figure 2). Although the modules are supplied by LG Chem, NEC supplies and manages the BMS. Each rack is designed for 112.1 kWh (DC) of energy storage.

2.2.2 LG Battery Replacement Program

Several weeks before the Carnegie Road BESS thermal event, Ørsted was informed by NEC of a battery replacement program by LG, which affects several battery packs in all three containers. This replacement program was planned to replace batteries with potential issues as part of a broader recall program. The failure event occurred prior to the start of the replacement program, which was scheduled for Q4 2020.

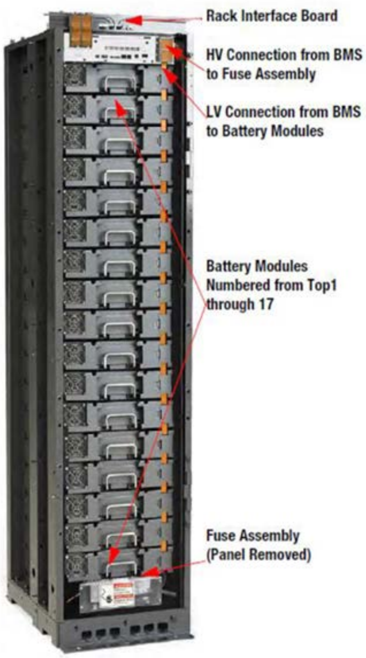

Figure 2
NEC battery rack and LG module configuration; source: Merseyside Fire & Rescue Service

3 FAILURE INCIDENT

At 12:49 am on September 15, 2020, fire crews were alerted of "an incident at an electrical unit on Carnegie Road, Old Swan." Five fire engines arrived on scene at 12:57 am and "found a large grid battery system container well alight."[2]

3.1 Timeline

Table 2 presents an abbreviated timeline of the failure incident provided by the Merseyside Fire & Rescue Service.

3.2 Post-Event Status

The failure occurred in Container 1 of 3. Figure 3 shows bowing of the container walls because of pressure buildup within, dislocation of the air conditioning units that were attached to the top of the container, and severe charring from the fire. The doors on both ends of the container had been blown open, seen in Figure 4. The door exiting to the yellow metal stairs had been torn off the hinges, further illustrating how powerful this explosion was. Bowing, sagging, and melting of the interior components are the result of extreme temperature exposure. Pools of hardened aluminum were found at the base of the racks and below the container, suggesting that the fire temperatures exceeded 660°C (1221°F).

[2] Merseyside Fire & Rescue Service—Latest Incidents: https://www.merseyfire.gov.uk/media-centre/latest-incidents/energy-unit-fire-old-swan/.

Table 2
Abbreviated timeline of events leading up to the explosion and its suppression

DATE	TIME	DESCRIPTION
15-09-2020	00:29	Alarm for module temperature above the maximum safe level[3]
15-09-2020	00:31	Smoke alarm triggered; rack powered off[3]
15-09-2020	00:49	First call received by MFRS Fire Control[4]
15-09-2020	00:52	Appliances mobilized to large explosion near the Fisheries, Lister Drive[4]
15-09-2020	00:57	First appliance in attendance[4]
15-09-2020	01:34	Station manager advised of call from Ørsted Energy, Denmark[4]
15-09-2020	01:55	Station manager declares a hazmat incident[4]
15-09-2020	02:19	Entire site goes offline; high-volume pump requested[3,4]
15-09-2020	02:39	Level 1 welfare requested[4]
15-09-2020	02:46	Station manager requests Fire Control to inform Environment Agency of possible HF in water runoff[4]
15-09-2020	03:27	From group manager, water tests show a reading of 8 to 9 pH[4]
15-09-2020	03:39	From Ørsted Energy in Denmark, monitoring CCTV, informed Fire Control that FFs must not enter battery containers[4]
15-09-2020	06:43	Watch manager now Incident Commander 2 pumps required and now for remainder[4]
17-09-2020	10:44	STOP[4]

Figure 3
Aerial photo of Carnegie Road BESS after incident (left) and side view of Container 1 (right); source: MFRS

[3] Merseyside Fire & Rescue Service. (2022). *Fire Investigation Report 132-20 Incident Number 018965 Ørsted BESS, Carnegie Road.* https://www.merseyfire.gov.uk/about/access-to-information/freedom-of-information-foi/foieir-requests/.
[4] Merseyside Fire & Rescue Service. (2022). *Significant Incident Report Incident no. 018965 Ørsted BESS, Carnegie Road*. https://www.merseyfire.gov.uk/about/access-to-information/freedom-of-information-foi/foieir-requests/.

Figure 4
Image of doors blown open (source: NEC) and inside the container; source: MFRS

Containers 2 and 3 were largely undamaged as a result of the fire service's deliberate action to put water on Container 2, as directed in the emergency response plan (ERP). Ørsted worked with the fire service to develop the ERP in summer 2020, prior to the failure event. Some discoloration can be seen at the top of Container 2 and the HVAC systems were damaged beyond repair, but the batteries appeared unharmed.

4 LESSONS LEARNED

Involvement in the investigation, root cause analysis (RCA), redesign, and rebuild provided many lessons learned that are important to communicate to the broader industry. Many aspects of the process and challenges associated with post-incident recovery were unexpected. Through documentation and communication of these lessons learned along with the process followed, the industry may have more well-rounded expectations post-incident recovery and pre-event planning.

4.1 Failure Event and Response

The dynamics of the failure event itself highlighted the increased knowledge within the industry since the system was commissioned and the limited pre-planning and expectations that were the historic industry norm.

NEC monitored each battery zone, rack, and/or module. On the day of the incident, the first system alarms went off at 00:29 and signaled issues with both temperature and voltage within a specific battery rack. By 00:31, a fire system warning was set off and all battery racks in the affected zone were turned off. Seconds later, communication with the BESS was lost and no further telemetry data were able to be collected from the affected rack. At 00:39, CCTV captured an explosion within the Carnegie Road BESS facility and the facility was disconnected from the grid. As the fire burned, the BMS lost communication with the other battery zones, disabling further telemetry and alarms.

Upon arrival, the fire service was unaware what the Carnegie Road BESS facility was. The watch manager initially communicated that a "large refrigeration unit" was on fire. Several minutes later, the watch manager informed crews that the site was a large grid battery system. The fire was later declared a "fire containing hazardous materials" because of the presence of the lithium ion batteries. Subsequently, the Environment Agency and Bureau Veritas—a third-party scientific advisor for MFRS—was notified of the incident. A hazardous materials environmental protection officer (HMEPO) was requested for the site, who then advised on the potential hazards of burning lithium ion batteries, including the possibility of hydrogen fluoride (HF) in the smoke plume. However, the fire service did not take air samples to measure HF or other hazardous emissions because the wind was blowing in the opposite direction of residential buildings at the time of the incident. Instead, MFRS informed the surrounding community of the potential hazard, and residents were warned to keep doors and windows closed—but no evacuations were prompted because there were no residences near the site. The surrounding area is primarily commercial, and most buildings were vacant at the time of the incident.

The HMEPO also identified the potential for HF presence in the firefighting water runoff. Unfortunately, the amount of water needed to manage the fire could not be contained, but fire crews were diligent in taking regular pH measurements of the runoff and found no acidity. It is not well understood what potential hazardous chemicals and particulates are present in battery firefighting water and their effects on the surrounding environment and community.

As mentioned, Ørsted and MFRS had worked together to develop an emergency response plan (ERP) prior to the fire incident. Unfortunately, the information about the site and proper emergency response actions was not disseminated to local fire crews, resulting in lack of preparedness and confusion when the first crews arrived on-site. It was not until the event was escalated within MFRS that a senior officer was able to instruct fire crews on the proper response strategy, saving Container 2.

Lack of preparedness or awareness on how to fight lithium ion battery fires is a sentiment that seems to be echoed by fire departments across the globe. They were not aware of the nature of the facility, the related hazards, and the proper response. Regular engagement with first responders throughout the construction, commissioning, and operation of the system is important for education and training. First responders must understand the potential hazards and come prepared with proper personnel protective equipment (PPE) and monitoring equipment to keep themselves, the local community, and the environment safe. Anecdotally, EPRI has heard of firefighters responding to structure fires unaware of the presence of lithium ion batteries and handling batteries without high-voltage gloves, boots, or other protective gear. The health effects from lithium ion battery fire exposure are also not well understood, but EPRI has heard of firefighters developing temporary respiratory aggravation and skin rashes.

4.2 Investigation

An investigation of the Carnegie Road BESS incident commenced immediately after the fire was extinguished. The investigation included a safety evaluation and hazard mitigation analysis conducted internally by Ørsted and an RCA conducted collaboratively between Ørsted and NEC. These exercises informed the eventual rebuild design and subsequent risk assessment of the proposed replacement system.

Safety evaluations rely on a group of multidisciplinary experts asking "what if" questions and comparing observations of project features (for example, requirements, design characteristics, operational procedures, or physical status) to conditions presented in incident reports, previous experiences, or other lessons learned. For example, the fire protection experts employed for the evaluations have experience in hazardous material fire events. Some have more specific experience with lithium ion BESS design (and fires), while others have more experience with other technologies and facility types.

EPRI found that aligning safety evaluation expert experience to specific site attributes can be instrumental in these hazard mitigation analysis (HMA) processes. When familiar with the site-specific configurations and conditions, experts eased the data discovery and site review process by anticipating and prioritizing issues, reducing the iterations and total time required. This is expected to help avoid confusion or gaps in the assessment.

Another dynamic to consider is the differing priorities for the organizations collaborating on the HMA as well as different levels of access to information and expertise within those organizations. Regarding the Carnegie Road post-incident investigation, there were challenges through the HMA process to achieve completeness and final conclusions.

The RCA used established and well-known methodologies to investigate the cause of the failure, which is important for achieving agreement of technical detail and clarity in communication. Some of the more pragmatic efforts of routine meetings with review of relevant details, plans, and new findings ensured that even organizations with competing interests could have an agreed-upon set of information that was being produced during the RCA. Root cause determination of a lithium ion battery fire is extremely difficult because most of the evidence is destroyed. In the Carnegie Road BESS case, cell internal failure was identified as a potential contributor to failure, but there is no certainty that cell internal failure was the primary cause of failure. Although it is possible to piece together a narrative based on the reported sequence of events and data acquisition, confirming how thermal runaway was initiated is challenging. Therefore, it was recognized that portions of the redesign and rebuild of the Carnegie Road ESS could be approached without a final root cause determination and considering how to properly manage the observed aftermath of thermal runaway and propagation.

The investigation took 11 months to complete because of two main factors: the COVID-19 pandemic and the lack of experience in responding to this type of incident. Regarding COVID-19, travel restrictions made it difficult to convene a group of experts and contractors who could walk the site and analyze the system and its components. Many meetings were held virtually, especially between Ørsted and the NEC team, which was based in the United States. Teams that were integral to the installation and then recovery of the system could not experience the extent of the damage firsthand, which adds complexity when troubleshooting. Ultimately, the results of the investigation would have been the same had there not been a global pandemic, but the investigation timeline would have likely been significantly shorter.

In addition, the Carnegie Road BESS failure was a first-of-a-kind event in the UK. There were many unknowns and no clear guidance on how to proceed. Out of an abundance of caution, the investigation team agreed on a no-entry strategy to avoid putting people at risk. All assessments, measurements, and samplings were conducted from outside the container.

4.2.1 RFI

One critical piece of collaboration was the request for information (RFI) tool. EPRI, Ørsted, and NEC curated a log of information documented in an RFI tracker spreadsheet. The RFI listed numerous requests including the design intent of the BESS, test data of the battery modules, performance data of the BESS, information from the event, and post-event analysis conducted at the site.

EPRI reviewed the collected data in the context of the HMA to develop and test several theories. Root cause theories included internal cell failure (defect), thermal abuse, electrical abuse, mechanical abuse, other abuse, and non-battery fire. Historical review of site-specific data and documentation prior to the failure did not produce clear direction for cause of failure. EPRI also reviewed data from the NEC AEROS site controller from the target rack and adjacent racks during the day of the event.

4.2.2 Hazard Mitigation Analysis

Based on the design documents, failure event details, and information found during the RCA, a detailed HMA was developed to capture and communicate how specific hazards identified were addressed or where more investigation was needed in the system design.

Multiple safety evaluation processes exist, such as process hazard analysis (PHA), failure modes and effects analysis (FMEA), hazard mitigation analysis (HMA), layer of protection analysis (LOPA), and fault tree analysis (FTA). Each serves different goals to assess the safety of a site or project. During this investigation, EPRI chose to use the report *Energy Storage Integration Council (ESIC) Energy Storage Reference Fire Hazard Mitigation Analysis*[5] as the starting point. This report identifies possible concerns of fire and thermal runaway propagation as well as gaps in suitable defense measures (or mitigation barriers). The method still relies on focused observation and interpretation of the effectiveness of different barriers to appropriately characterize the gaps in safety.

This HMA was used as a reference throughout the RCA process and fed into and coordinated with other methodologies used, including fault-tree and fishbone diagrams.

4.3 Post-Event Recovery

As mentioned, the post-event recovery spanned nearly one year. This was partially a consequence of the COVID-19 pandemic and inexperience in responding to and recovering from this type of incident in the UK. As a result, coordination among the requisite teams to perform the deenergization, decommissioning, and investigation was difficult. Cobalt Energy—an Engineering, Procurement, Construction (EPC) Contractor and LTSA provider—was asked to assist the recovery effort.

Loss of telemetry and alarms was especially problematic during response and decommissioning of the system. It was difficult to establish the state of charge in Container 1, and so it remained unclear whether the system remained energized, how much stranded energy may have been in the container, and whether there was an electric shock or arcing hazard that would put work-

[5] ESIC. (2019). *Energy Storage Reference Fire Hazard Mitigation Analysis*. https://www.epri.com/research/products/000000003002017136.

ers at risk. Assessing the burn patterns on the interior and exterior of the container indicated that it seemed feasible that the lower modules could have suffered less damage and retained some charge because the bottom of the container appeared to be less affected by the fire.

February 2021 was when "first entry" was made into Container 1 by camera. Several holes were cut through the walls of the container to assess container construction and provide camera access into the container to better understand the damage and potential hazards and investigate possible extraction methods for removing the battery racks. In March 2021, access points were established so that crews, dressed in PPE, could approach the container and assess the conditions inside. Crews saw no evidence of arcing in the container. However, it became increasingly clear that racks would need to be cut apart to be removed. The amount of solid molten metals and plastics bonding the racks would have made it impossible to disassemble the system without the assistance of power tools. Furthermore, space in the container was limited, and physically separating the container into more manageable pieces seemed to be the best path forward.

Disassembly and removal of Container 1 commenced in May 2021. The container was cut into three sections and craned into a staging area where further investigation of the system could occur. This allowed a more comprehensive assessment of the container and target rack without risk to health and safety. Retrieval of the batteries for further inspection was difficult because they were extremely brittle and not easily separated. Some sections of the modules needed to be sawed apart and removed from the racks. See Figure 5.

Figure 5
View of Container 1, Section 1 being removed (source: SAFE Laboratories and Engineering Corp.)

4.4 Redesign and Rebuild

The rebuild was originally expected to be installed by July 2021. However, as of February 2023, the Carnegie Road site rebuild has commenced and is expected to be fully commissioned in summer 2023.

Following the fire incident, NEC wanted to move forward with a like-to-like replacement of Container 1 to get the system back online within months, in parallel with the failure investigation. In contrast, Ørsted wanted to modify the system to improve safety and prevent a reoccurrence. This led to some contractual complexities.

Discussions of the redesign and rebuild had been concurrent with the failure investigation. However, the investigation findings were necessary to perform a risk assessment of the proposed rebuild. NEC and Ørsted worked through the redesign and rebuild process in consultation with the UK Health and Safety Executive. The failure at Carnegie Road and the process to rebuild illuminated the lack of codes and standards for BESSs within the UK. There were several discussions of how BESSs are classified and what codes are applicable prior to the redesign process.

One specific area of concern was properly considering the principles of the Dangerous Substances and Explosive Atmospheres Regulations (DSEAR) in the proposed ESS rebuild. Compliance with DSEAR requires an employer to assess risks, eliminate risks ("or reduce them as far as is reasonably practicable"), implement control measures, mitigate risks, prepare emergency response plans and procedures, and provide information, instruction, and training for employees.[6]

Ørsted engaged NEC over several weeks with Ørsted's own risk assessment of the proposed rebuild. This risk assessment included an evaluation of hazards, effects, consequences, affected parties, control measures, and residual risk considerations for the following categories of potential threats:

- Non-cell failure thermal issues
- Controls failure
- Cell internal failure
- External/environmental risks
- Electrical risks
- Risks to people performing work activities

[6] Health and Safety Executive. *DSEAR in detail.* https://www.hse.gov.uk/fireand-explosion/dsear-background.htm#whatdsear.

Because cell internal failure was identified as a potential contributor to the fire incident at Carnegie Road, discussion focused on effective control measures to mitigate against cell internal failure. However, detecting and correcting an internal defect of a closed battery cell is practically impossible post-production. Imaging techniques can be used in quality control, but they can be expensive and are not common practice for battery manufacturers and suppliers. Engineering safety into the system design is the most feasible approach for controlling an incident resulting from cell internal failure. The addition of the deflagration panels, gas detection, and water suppression in the system rebuild is intended to reduce and control risks as far as is reasonably practicable.

There has been a shift in system design across the industry since the Carnegie Road BESS was installed in 2018. Older system designs tended toward a single ISO container lined with battery racks along the walls, leaving a small accessible alley through the container—similar to the Carnegie Road BESS. Deflagration panels, venting, gas detection, and so on can be retrofitted into many of these older systems. Some newer system designs use smaller, modularized cabinets with a few racks of batteries. These cabinets are accessible from the outside, so personnel are not confined inside a container when performing their duties. The system layout also limits damage because of thermal runaway and allows a more targeted first responder approach in the event of a fire.

Although newer designs like the one described above may improve overall site and system safety, it requires more land area and may increase construction costs because of the multiple components. In the case of Carnegie Road, the existing site layout limits the extent of the redesign because the infrastructure and balance-of-plant components were already installed. A more extensive redesign would have required additional labor and investment to accommodate a new site layout, further delaying the site's operation and market participation.

The rebuild—which includes new battery modules, deflagration controls, and explosion controls—was agreed upon between Ørsted and NEC in December 2021. However, severe supply chain constraints have significantly impacted project timelines. The expected operation date of the rebuilt system is Q2 2023.

4.5 Advancements in Codes, Standards, and Industry Knowledge

The Carnegie Road BESS was designed to meet the requirements of the initial 2017 National Fire Protection Association (NFPA) 855 *Standard for the Installation of Stationary Energy Storage Sys-*

tems draft. A few high-profile failure events since the publication of that draft have further illuminated the need for greater industry knowledge of BESS safety. NFPA 855 has since been revised and was published in 2020. Applicable codes and standards are necessary for the safe and reliable deployment of energy storage technologies, but the process for development and publishing of these standards lags the fast-paced evolution of the energy storage industry and market. Furthermore, the communicated urgency to meet various clean energy targets does not align well with the time needed to conduct the research needed to adequately understand BESS safety and design while ensuring seamless integration into the grid and ensuring reliability.

Multiple standards-making bodies and organizations understand the need and urgency for applicable codes and standards as well as tools that the industry can use to promote and enhance system safety in parallel with rapid deployment. NFPA and UL have both released energy storage installation standards that are regularly reviewed and updated. EPRI regularly provides guidance and resources for industry stakeholders to assist in navigating through this ever-changing industry. EPRI has published guidance on ESS procurement, testing, operations, and decommissioning. EPRI's BESS safety-specific resources include white papers and reports on thermal runaway and associated explosion and environmental hazards, the BESS Failure Event Database,[7] and an explosion hazard calculator.[8] Resources under development through EPRI's Fire Protection and Mitigation research include battery fire plume modeling, design trade-off analyses, emergency response plans and other first responder resources, a database for technologies that improve system safety, and more.

5 CONCLUSIONS

The overall process from failure event through system rebuild highlights the historically limited industry understanding of these incidents and how important clear communication of event details and design features is to both incident response and safety design trade-offs, rebuild, and planning for future incidents. As mentioned, the Carnegie Road system failure was a first-of-a-kind event in the UK, which offers many lessons learned for the UK, Europe, and across the globe.

The initial communication by the fire service's watch manager that a "large refrigeration unit" was on fire raises concern over first responder preparedness. Ørsted had worked with the fire service to develop an ERP months before the failure incident, making them both aware of the system and trained for an emergency. The communication error at the time of the event was rectified, and the fire service responded appropriately to the incident. However, in a scenario in which the fire service was not trained or included in system planning, development, and deployment, first responders may be seriously injured if responding without proper PPE or putting a direct stream of water on an electrical fire because the incident type was not properly communicated.

There are little data on the environmental, health, and safety effects of exposure to a battery fire or water used in firefighting. These are areas of ongoing research and development. Research suggests that HF can be found in the battery smoke plume and firewater, as directed by the HMEPO. Having a containment or mitigation plan can help protect residents, bystanders, and the environment from the potentially harmful effects of exposure.

Post-event recovery was particularly challenging in this case because of a lack of visibility and guidance on how to safely approach and disassemble a damaged system with an unknown amount of stranded energy. There is no clear solution for discharging stranded energy in a controlled manner, especially in damaged systems with exposed energized materials. Having a post-incident plan can educate and guide recovery teams, maintain a safe working environment, and provide a potential schedule for project recovery.

The root cause analysis was inconclusive but suggested that cell internal failure was a potential contributor to the battery system fire. Detecting and correcting an internal defect of a closed battery cell is practically impossible post-production, and it is extremely difficult to prevent or control a related failure when the defect is unknown. Visiting the cell manufacturing facility and reviewing the quality control practices is an option for trying to mitigate cell manufacturing defects. A more feasible approach to mitigating an internal cell failure is to engineer safety into the broader system, including BMS control, gas detection, ventilation, suppression, and the inclusion of deflagration panels to direct any explosive forces up rather than out.

In hindsight, many contributing factors are apparent—none of which is fundamentally new to the fire protection discipline or particularly difficult to address with engineering controls. This report serves to increase awareness in the industry in applying known mitigations against hazards that are now recognized.

[7] EPRI. *BESS Failure Event Database.* https://storagewiki.epri.com/index.php/BESS_Failure_Event_Database.

[8] EPRI. (2021). *Battery Storage Explosion Hazard Calculator v1.0*. https://www.epri.com/research/programs/053125/results/3002021076.

EPRI PREPARED THIS REPORT.

About EPRI

Founded in 1972, EPRI is the world's preeminent independent, non-profit energy research and development organization, with offices around the world. EPRI's trusted experts collaborate with more than 450 companies in 45 countries, driving innovation to ensure the public has clean, safe, reliable, affordable, and equitable access to electricity across the globe. Together, we are shaping the future of energy.

CONTACT INFORMATION

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EPRI RESOURCES

EPRI members interested in engaging in and supporting this effort should contact EPRI for further discussion.

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