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Lithium ion battery energy storage systems (BESS) hazards

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Abstract

There has been an increase in the development and deployment of battery energy storage systems (BESS) in recent years. In particular, BESS using lithium-ion batteries have been prevalent, which is mainly due to their power density, performance, and economical aspects. BESS have been increasingly used in residential, commercial, industrial, and utility applications for peak shaving or grid support. As the number of installed systems is increasing, the industry has also been observing more field failures that resulted in fires and explosions. Lithium-ion batteries contain flammable electrolytes, which can create unique hazards when the battery cell becomes compromised and enters thermal runaway. The initiating event is frequently a short circuit which may be a result of overcharging, overheating, or mechanical abuse. During the exothermic reaction process (i.e., thermal runaway), large amounts of flammable and potentially toxic battery gas will be generated. The released gas largely contains hydrogen, which is highly flammable under a wide range of conditions. This may create an explosive atmosphere in the battery room or storage container. As a result, a number of the recent incidents resulted in significant consequences highlighting the difficulties on how to safely deal with the hazard. This paper identifies fire and explosion hazards that exist in commercial/industrial BESS applications and presents mitigation measures. Common threats, barriers, and consequences are conceptually shown and how they would be identified in a hazard mitigation analysis (HMA). Mitigation measures that can be implemented to reduce the risk of a fire or an explosion are discussed. The presented information is intended to provide practical information to professionals and authorities in this fairly new industry to assure that prevention and mitigation strategies can be effectively implemented and that the regulatory requirement of the HMA can be met.

Introduction

A battery energy storage system (BESS) is a type of system that uses an arrangement of batteries and other electrical equipment to store electrical energy. BESS have been increasingly used in residential, commercial, industrial, and utility applications for peak shaving or grid support. Installations vary from large scale outdoor sites, indoor sites (e.g., warehouse type buildings), as well as modular systems. Containerized systems, which are one form of a modular design, have become a popular means of integrating BESS projects efficiently. In this paper, the primary focus is placed on containerized or modular BESS.

BESS project sites can vary in size significantly ranging from about one Megawatt hour to several hundred Megawatt hours in stored energy. Due to the fast response time, lithium ion BESS can be used to stabilize the power gird, modulate grid frequency, provide emergency power or industrial scale peak shaving services reducing the cost of electricity for the end user. BESS are typically designed to output for one to 4 h. This is governed by the charge rate (C-rate). A 1C charge rate means that a fully charged battery rated at 1Ah should provide 1 A for 1 h. The same battery discharging at 0.5C provides 1 A for 30 min. Generally, lithium ion batteries perform best for fast charge rates. This makes it attractive to use BESS for short-term peak compensation and frequency control to minimize the chance of power outages. However, high powered and rapid charge cycles result in electrical transients that can generate heat quickly. This is generally true when the batteries approach a high state of charge (SOC) when charging and or a low SOC when discharging. This phenomenon may also be amplified with battery degradation. In other words, additional heat may be generated towards the end of the lifetime of the battery cell. Overheat is not beneficial to the safety, performance, and lifespan of lithium ion batteries. Hence, thermal management is of great importance. The desired range of optimal operating temperatures is often narrow and can be difficult to maintain, especially during electrical transient. In general, an optimal cooling control strategy keeps the battery cell temperature somewhere between 15 °C and 35 °C (Chen et al., 2016). This requires a reliable and well-performing cooling system that either directly cools the battery cell/modules or cools the enclosure in which the battery packs are installed. Allowing a lithium ion battery to perform outside its intended operating temperature range can have detrimental effects on safety possibly leading to fire or explosion.

To operate efficiently, grid supporting BESS (also called “in front of the meter” applications) are installed within close proximity or at sub-stations. Behind the meter BESS can be installed close to where the end-user needs the power. For example, behind the meter BESS are seen next to electric vehicle (EV) charging stations to provider a booster function or next to buildings that take advantage of the peak shaving capability and increased power resiliency. Hence, large scale BESS are often installed near additional electrical infrastructure and smaller scale BESS may be installed near buildings. In both installation cases, there are secondary aspects to the fire and explosion hazard, which deals with the protection of people and property. In the following, available technical guidance, hazard analysis methods, as well as fire and explosion hazard prevention and mitigation for BESS are discussed.

A brief review of the lithium ion battery system design and principle of operation is necessary for hazard characterization. A lithium ion battery cell is a type of rechargeable electro-chemical battery in which lithium ions move between the negative electrode through an electrolyte to the positive electrode and vice versa. Lithium-ion battery cells are a family of cells that consist of an anode (negative terminal) and a variety of different types of cathodes (positive terminal) and electrolytes. The anode and cathode serve as host for lithium ions. Lithium ions move from the anode to the cathode during discharge and are intercalated into the cathode (i.e., inserted into voids within the crystallographic structure). The ions reverse direction during charging. For a basis of understanding, a single lithium-ion cell (or battery) in a commercial/industrial application has typically an operating voltage that ranges approximately from 3 V to 4 V. Lithium ion batteries will voltages outside of this range also exist.

The anode and the cathode are separated by the so-called separator, which is a thin film made of polyolefin, for example. This film can break down if the cell overheats. The typical electrolyte is based on organic solvents which are flammable and volatile. A dissolved lithium salt provides the media for lithium-ion transport within the electrolyte. The cell can have different “form factors”, which are mainly cylindrical, prismatic or pouch. Layers of electrodes are stacked into the cell housing. Hence, the basic functional electrochemical cell contains an assembly of electrodes, electrolyte, separators, container, and terminals. A subassembly of a group of cells is called a module, which are connected either in a series and/or parallel configuration within a unit. A unit consists of a frame, rack or enclosure that consists of a functional BESS which includes the aforementioned components and subassemblies such as cells and modules, but also a Battery Management System (BMS), ventilation devices and other ancillary equipment.

BESS are installed in different forms and sizes of enclosures. This paper focusses primarily on small modular building or containerized applications as these are currently the most popular considering the number of installations. Containerized BESS are often installed in standard shipping containers that come in the ISO standard sizes ranging from 8 feet to 53 feet in length, with a width and height of approximately 8 feet each. Certainly, custom built container systems exist as well, which have sizes outside of the ISO specification. Generally, a metal container is convenient to use as a BESS enclosure. These types of enclosures are readily available, economical, and of non-combustible construction. The enclosure can be outfitted in the manufacturers’ shop and shipped to the project site as a turnkey system.

The figure below provides an example layout for an air-cooled BESS container. The overall dimensions of this container are 40 feet long, 8 feet wide, and 8.5 feet high. This design is a walk-in unit and contains two rows of battery racks. Only one row is shown as the figure is an axial slice through the center axis. The container is partitioned to include a separate auxiliary room where heating, ventilation, and air conditioning (HVAC) and communication equipment is installed. Two HVAC ducts provide cooling airflow to the batteries. There are a total of 22 battery racks, each having 12 modules. The total energy capacity of the ESS container is 4.29 MWh. This type of BESS container is then typically equipped with smoke detection, fire alarm panel, and some form of fire control and suppression system. Explosion control measures would be required for this type of system which will be explained in detail further down. The container material is steel with a thickness of 3 mm.

According to recent lessons learned on BESS fire prevention and mitigation published by the Electrical Power Research Institute (EPRI) in June 2021, over 30 large-scale BESS globally experienced failures that resulted in destructive fires over the past four years (Long, 2021). These events are also tracked in the publicly accessible BESS Failure Event Database (EPRI, 2022). Most events had in common that the lithium ion batteries installed in the BESS where somehow driven to vent battery gas and transition to thermal runaway, which is a process that releases large amounts of energy. Thermal runaway is strongly associated with exothermic chemical reactions. Under a variety of scenarios (i.e., short circuit), the stored chemical energy is converted to thermal energy. The typical consequence is cell rupture and the release of large amounts of flammable and potentially toxic gases, which can lead to fire and explosion.

A notable event that led to a shift in the industry in terms of hazard mitigation at BESS occurred on April 19, 2019, at a BESS unit owned and operated by Arizona Public Service Company. The facility, which was of modular building design (similar aspect ratios and size as of a large containerized system), experienced a thermal runaway event. The BESS was equipped with a clean agent suppression system but was not provided with deflagration venting or explosion prevention systems (i.e., the requirement for explosion control was not satisfied). The fire department responded and took no immediate action due to a lack of information concerning the system and the event. While a HAZMAT team attempted to enter the BESS to survey the scale of the event, an explosion occurred, seriously injuring the firefighters. The “McMicken” Event Technical Analysis and Recommendations report (Arizona Public Service, 2020) identified five contributing factors that led to the incident:

- Internal failure in the battery cell initiated thermal runaway.
- The clean agent fire suppression system was incapable of stopping thermal runaway.
- The facility lacked thermal barriers between battery cells; this lack of barriers allowed the thermal runaway event to cascade to adjacent cells.
- Without a means to ventilate the enclosure, the flammable off-gases from the batteries concentrated.
- The emergency response plan did not include extinguishing, ventilation, or entry procedures.

Since 2017, at least 27 BESS fires were reported in South Korea. Twenty-three of the BESS fires were recorded in 2018. As a result of these events, the South Korean Ministry of Industry formed a committee to investigate the high number of fires at BESS. A five-month investigation produced a report released in June 2019. The report outlines the following key factors that contributed to the high fire frequency (MOTIE, 2019).

- A lack of battery protection systems to identify and stop short circuits.
- Insufficient management of the operating environment (e.g., dust, humidity, temperature swings)
- Poor installation quality
- Lack of integrated BESS monitoring and control systems.

Section snippets

Codes and standards

The following codes and standards are currently considered by the industry for the installation of BESS and the hazard mitigation analysis for those systems. Once a BESS exceeds 600 kWh in energy capacity, a hazard mitigation analysis (HMA) that can help identifying additional mitigation measures is typically required.

2021 International Fire Code (IFC), Chapter 12, Electric Energy Storage Systems:

- The 2021 edition of the International Fire Code provides prescriptive requirements and identifies…

…

Hazard analysis

An evaluation of potential energy storage system failure modes and the safety-related consequences attributed to the failures is good practice and a requirement when industry standards are being followed. It was established above that several national and international codes and standards require that a hazard mitigation analysis (HMA) is performed. Consequences and failure modes must be evaluated that include thermal runaway condition in a single module, array, or unit, for example. Only…

Prevention and mitigation measures

Prevention measures should be directed at thermal runaway. This is by far the most severe BESS failure mode as demonstrated in the introduction to the hazard mitigation analysis. If it cannot be stopped, fire and explosion are the most severe consequences.

The battery management system (BMS) provides the primary thermal runaway protection and is one of the most important barriers. This is why BESS safety standards, such as NFPA 855, require that the BMS is evaluated together with the batteries…

Conclusions

This paper provided an overview of BESS fire and explosion hazards. In a time of increased development and deployment of BESS installations, it could be laid out that more incidents have been occurring. Several of these incidents experienced significant consequences in the form of fire, explosion, and first responder hospitalizations.

A technology overview was provided which was then paired with an introduction to hazard analysis. A hazard analysis in the form of an HMA is a frequent requirement …

Author contribution statement

All authors contributed to the paper. The lead author submitted the original paper, handled the comment resolution, and revised the paper.…

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.…

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Investigation of the compressed air energy storage (CAES) system utilizing systems-theoretic process analysis (STPA) towards safe and sustainable energy supply

2023, Renewable Energy

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Renewable energy attracts increasing attention from both industry and academia under the context of carbon neutrality. For wind and solar energy, the strong dependence on natural processes results in the imbalance between energy production and real demands. Energy storage technologies, e.g., Compressed Air Energy Storage (CAES), are promising solutions to increase the renewable energy penetration. However, the CAES system is a multi-component structure with multiple energy forms involved in the process subject to high temperature and high-pressure working conditions. The CAES system is a complex process flowsheet consisting of charging and discharging process. The process should be optimized to achieve the best

thermodynamic and economic performance. Under the optimal design conditions, it might lead to severe consequences once a failure occurs, e.g., harm to humans, the environment, and assets. Limited attention and scarce available information have been paid to the CAES system risk management yet. Hence, this paper applies the System-Theoretic Process Analysis (STPA), which is a top-down method based on system theory, to identify the CAES system safety hazards. The results are expected to provide a preliminary guideline for practitioners regarding the safety and reliability of the CAES system. As a result, a more reliable CAES system can contribute to a more flexible energy system with more efficient and economic utilization of fluctuating renewable energy.

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