ASSESSMENT OF FIRE AND EXPLOSION HAZARDS IN LARGE-SCALE BATTERY ENERGY

STORAGE

SYSTEMS INTENDED FOR NAMIBIAN GREEN HYDROGEN PROJECTS

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ENERGY SYSTEMS ISE

Abstract

The integration of large-scale battery energy storage systems (BESS) is a pivotal component in advancing Namibian green hydrogen projects, aimed to promote sustainable energy solutions. But there are serious fire and explosion risks associated with the use of Battery Energy Storage Systems, particularly those that use lithium-ion technology. These risks are intensified by the chemical instability of lithium-ion cells and operational challenges associated with large-scale systems. This research investigates the specific risks and failure modes associated with BESS, aiming to provide safety solutions and guidelines for their broader application in renewable energy projects. The study begins with a comprehensive literature review, identifying the primary causes of fires/explosions in lithium-ion batteries, leading to thermal runaway, like electrical faults, and mechanical damage. It also examines various battery chemistries and their respective safety profiles, alongside an analysis of global case studies to draw lessons for Namibia. Fault Tree Analysis (FTA) and statistical tests were employed to pinpoint critical failure mechanisms, with emphasis on factors such as system design, battery age, and operational states during failure events. The study creates a thorough risk assessment model that emphasizes the risks that come with large-scale battery energy storage (BESS). This model evaluates critical factors such as thermal runaway, mechanical stress, and system design. Additionally, study explores potential mitigation strategies, including advanced battery management systems, robust fire suppression mechanisms, and the use of alternative battery technologies to improve overall system safety. By addressing the inadequate safety guidelines, deficiencies in Battery Management Systems (BMS), and failure mode analysis in various operational states, this study provides critical insights and recommendations for enhancing the safety protocols and the regulatory framework for BESS in Namibia's Green Hydrogen projects. The findings aim to contribute to the safe and efficient deployment of BESS, thereby supporting Namibia's transition to a sustainable energy future.

Key words: BESS, Hazards, Explosion, Fire and Battery.

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List of Abbreviations and Accronyms

ABC – Class A, Class B and Class C

BESS – Battery Energy Storage Systems

BMS – Battery Management Systems

BTM – Battery Thermal Management System

$\mathbf{CO_2}$ – Carbon Dioxide

DC – Direct Current

df – Degree of Freedom

DoD – Depth of Discharge

ESS – Energy Storage System

FTA – Fault Tree Analysis

GOF – Goodness-of-fit

GW – Gigawatt

GWh – Gigawatt Hour

IEC – International Electrotechnical Commission

IEEE – Institute of Electrical and Electronics Engineers

ISO – International Standard Organization

kW – Kilowatt

kWh – Kilowatt-hour

LIB – Lithium-ion Battery

$\mathbf{Li^{+}}$ - Lithium-ions

$\mathbf{LiCoO_2}$ - Lithium Cobalt Oxide

$\mathbf{LiFePO_4}$ – Lithium-ion Phosphate

$\mathbf{LiMn_2O_4}$ – Lithium Manganese Oxide

LMO - Lithium Manganese Oxide

$\mathbf{LiNiMnO_2}$ – Lithium Nickel Manganese Cobalt Oxide

MWh – Megawatt Hours

MTTF – Mean Time to Failure

MTTR – Mean Time to Repair

NFPA – National Fire Protection Association

NMC - Lithium Nickel Manganese Cobalt Oxide

NREL – National Renewable Energy Laboratory

PBAs – Prussian Blue Analogs

PCS -Power Conversion System

PV - Photovoltaics

SEI – Solid Electrolyte Interface

SIBs – Sodium-ion Batteries

SOC – State of Charge

SOH – State of Health

UL – Underwrites Laboratories

UN – United Nations

UPS – Uninterruptible Power Supply

LFL – Lower Flammability Limits

UFL – Upper Flammability Limits

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Dedications

This thesis is dedicated to all renewable energy enthusiast and the renewable energy industry at large.

Declarations

I, Laudika Lifoshiwana John, hereby declare that this study is a true representation of my original research and that no part of this work has been submitted for a degree at any other higher education institution.

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Laudika Lifoshiwana John

Chapter 1: Introduction

1.1. Background of the study

Due to technology breakthroughs and environmental concerns, the use of renewable energy sources, such wind and solar, has increased dramatically in recent years. Battery Energy Storge Systems (BESS) have emerged as a practical solution to the intermittency of solar and wind resources by storing the harnessed energy from them [1]. Using specially designed batteries, such as lithium-ion batteries, which are a huge technological advancement, or lead-acid batteries, which are their predecessors, a battery energy storage system (BESS) is a state-of-the-art device that stores electrical energy for later use. Hannan et al [2] reported several characteristics of BESS, such as reliability, adaptability, controllability, and environmental friendliness, potentially making BESS an important player in the fight against global warming.

Serious accidents and BESS failures which lead to fires and explosions, death, property damages and system downtime (energy production losses) have been reported [3-5]. For example, a 25 MWh Li-ion battery explosion in a Shopping Centre in China led to two deaths and injury of a firefighter [4]. BESS fire in South Korea's electric utility KEPCO and similar accidents in Arizona (USA) led to property damages worth tens of millions of USD [5, 6]. Various fault conditions, such as electrical malfunctions, overcharging, over discharging and particulate/moisture contamination, have been described as possessing the potential to induce an elevated temperature within a lithium-ion cell which in turn, may cause degradation and breakdown of the cell separator, leading to thermal runaway and potentially fire [7, 8]. Lithium-ion batteries have significant challenges compared to the technology of lead-acid batteries, such as internal short-circuit which is caused by the damage of the separator due to the formation of dendrites at the anode, acceleration of internal chemical reactions caused by high temperatures and others. Furthermore, environmental conditions like low temperatures lead to a decrease of the battery's capacity, while high temperatures lead to acceleration of internal chemical reaction and reduce battery life span [1, 5, 9]. An interesting alternative technology with a high Technology Readiness Level (TRL) are sodium-ion batteries just coming on the market. They show advantages in terms of environmental friendliness, but safety assessments are not yet fully completed [10].

Projects of the Green Hydrogen Initiative of Namibia intend to utilize large-scale BESS installations. Because of their noteworthy qualities of high energy density and high round-trip efficiency, lithium-ion batteries are suggested to be used in the Green Hydrogen Export Projects [5]. Large-scale system installation poses special safety issues because of the high energy density and possible hazards associated with battery technology, especially with lithium-ion battery (LIB) energy storage systems (BESS) [5].

Understanding and mitigating the various hazards associated with large scale Lithium-ion BESS is essential for their safe deployment [5]. The lack of local safety regulations on the implementation of large-scale BESS presented operational challenges to the Namibian Power Corporation (NamPower), who is currently in the process of launching the Omburu BESS Project, with the capacity of 58 MW / 75 MWh [11].

1.2. Statement of the problem

There are significant numbers of Lithium-ion BESS accidents reported worldwide [3, 5, 6, 12]. There is strong evidence that accidents or failures cannot be solely attributed to predictable factors such as aging of the BESS. System failure can stem from internal causes, such as system design or processes, or external causes, like natural phenomena or human factors, or a combination of random events. No risk assessment studies that we are aware of have been conducted for large-scale BESS in Namibian local conditions, and there exists an inadequate amount of safety recommendations for the implementation of large-scale BESS locally.

1.3. Objectives of the study

The aim of this study is to provide recommendations for mitigation and prevention of fire and explosion hazards associated with BESS.

To achieve this aim, it is necessary to:

- Conduct a comprehensive literature study to gather data on BESS fire and explosion accidents and their causes.
- Conduct comprehensive study of Safety Standards and Scientific literature on thermal runaway propagation.
- Determine any possible dangers or hazards related to the design, construction, operation and upkeep of extensive BESS installations.

- Perform risk assessment for analyzing safety designs in battery energy storage systems; Prepare tailor-made safety recommendations for BESS in local conditions.

Chapter 2: Battery Basics

An essential part of contemporary renewable energy infrastructures are lithium-ion battery energy storage systems [5, 6, 9]. However, the underlying causes of fires and explosion in these systems are inherently linked to the chemical nature of lithium-ion batteries. These hazards can be aggravated by various factors such as thermal runaway, electrical faults, and mechanical damage [5]. Additionally, environmental conditions such as high ambient temperatures, poor ventilation, and physical impacts can further increase the risk of thermal instability [13]. Understanding these causative factors is essential for developing effective risk mitigation strategies to ensure the safe deployment and operation of large-scale BESS.

The intrinsic risks of BESS are divided into three categories: Electrical, Environmental, and Mechanical [5]. Internal and exterior short circuits, as well as overcharge and overdischarge, are Electrical risks. Mechanical hazards are caused by vibrations, shocks, or impacts that can occur during the transportation process, or by puncturing by hard objects [5]. Age primarily causes the battery or cells to deteriorate, increases the internal resistance while environmental hazards are those imposed by the change in temperature beyond manufacturer's recommended range, changes in altitudes, fog, pressures, floods, presence of salt etc. [3, 5, 6, 8, 9, 14].

2.1. Battery Cell Technology

Lithium-ion batteries are available in different chemistries, each with distinct advantages and challenges. Despite their reputation for stability, extended cycle life, and safety, lithium iron phosphate ($LiFePO_4$) batteries usually have a lower energy density than other lithium-ion batteries [15]. The term "energy density" describes how much energy a battery can hold in relation to either its mass (gravimetric energy density) or volume (volumetric energy density) [16]. Lithium Cobalt Oxide ($LiCoO_2$) batteries, mostly used in electronics, offer high energy density but suffer from safety issues, including thermal runaway and capacity degradation due to cobalt's instability [17].

Lithium Nickel Manganese Cobalt Oxide ($LiNiMnO_2$ or NMC) batteries balance energy density, lifespan, safety, making them popular for electric vehicles, however, they can be expensive due to the use of cobalt and nickel [17].

Lithium Manganese Oxide ($LiMn_2O_4$ or LMO) batteries provide good thermal stability and are cost-effective, but they have a shorter lifespan and lower capacity [17]. Each type's propensity for issues such as capacity fade and thermal runaway stems from its chemical composition and structural stability. $LiCoO_2$ is particularly prone to overheating and degradation, whereas $LiFePO_4$ offers better thermal stability but at the cost of lower energy density. These distinctions guide their specific applications and ongoing research efforts aimed at optimizing both performance and safety [15, 17].

The main elements of LIBs are the cathode, electrolyte, anode, and separator. Lithium ions must reversibly intercalate between the anode and cathode during cycles of charge and discharge for LIBs to function [9, 16]. The charge and discharge reactions are as follows:

Charge process:

$$\text{Cathode: } LiCoO_2 \rightarrow Li_{(1-x)}CoO_2 + xLi^+ + xe^-$$

$$\text{Anode: } C_6 + xLi^+ + xe^- \rightarrow Li_xC_6$$

Discharge process:

$$\text{Cathode: } Li_xC_6 \rightarrow C_6 + xLi^+ + xe^-$$

$$\text{Anode: } xLi^+ + xe^- + Li_{1-x}CoO_2 \rightarrow LiCoO_2$$

Usually, graphite makes up the anode while lithium metal oxides like Lithium Iron Phosphate ($LiFeO_4$) or Lithium Cobalt Oxide ($LiCoO_2$) makes up the cathode [16]. A lithium salt, such as $LiPF_6$ dissolved in an organic solvent serves as the electrolyte, facilitating ion transport. A microporous separator keeps the anode and cathode apart, preventing short circuits [9]. The State of Charge (SOC) which shows the amount of energy available and impacts battery health, and the charge and discharge rates (C – rates), which affect temperature and material stress, are important operating metrics [9, 18]. Battery performance is temperature-dependent, with high temperatures accelerating degradation and increasing thermal runaway risk, while low temperatures reduce efficiency [9, 13]. Battery Management Systems (BMS) and thermal management systems are essential safety mechanisms for monitoring and regulating voltage, state of charge (SOC), and temperature in order to prevent failures [18]. The foregoing components' failures, either collectively or separately, may have a detrimental impact on LIB safety [9].

2.2. Sodium Ion Cell Technology

Sodium is viewed as the ideal replacement for lithium in the emerging post-lithium battery era [19]. This is due not only to its abundance and lower cost, but also to its similar physicochemical properties to lithium, instead of using lithium ions (Li^+) as charge carriers, it uses sodium ions (Na^+) as charge carriers. These similarities enable the use of existing knowledge from lithium-ion batteries (LIBs), thereby speeding up the development of sodium-based batteries [20, 21]. Sodium ion batteries (SIBs) face unique challenges, such as lower specific energy compared to lithium-ion batteries, cycling life, and specific power, primarily due to larger size and heavier weight of sodium ions compared to lithium ions. SIBs are considered safer than lithium-ion batteries, with less risk of thermal runaway and less environmental impact [19, 20].

Using alumunium as the current collector on the anode side and cathode materials free of cobalt and nickel helps reduce the cost of sodium-ion batteries because sodium and aluminium do not form an alloy [22]. Unlike lithium, aluminum remains stable and does not dissolve in the electrolyte at 0V, making it practical to store and transport SIBs in a fully discharged state. Research has indicated that the desodiated $Na_{0.5}CrO_2$ cathode demonstrates greater thermal stability than $LiFePO_4$ in nonaqueous electrolytes under elevated temperatures [22]. Furthermore, Na-ion pouch cells show a much slower self-heating rate compared to commercial $LiCoO_2$ pouch cells, and their thermal runaway reactions release less energy. This points to SIBs being a potentially safer alternative to lithium-ion batteries. However, the larger and heavier sodium ions exhibit poorer kinetic behavior during the insertion process, which may accelerate the degradation of host materials and trigger exothermic reactions over time [22].

When defining the energy density and overall performance of SIBS, cathode materials are crucial. The commonly used cathode materials include transition metal oxides, which offers a high theoretical capacity and working voltage [19]. The structure allows for sodium ions to intercalate, with different phases (O3, P2, P3) based on oxide layer stacking. Polyanionic compounds that are known for structural stability and good capacity retention but lower discharge capabilities. Similar to polyanionic chemicals, Prussian Blue Analogues (PBAs) provide stability and capacity retention [19]. Hard carbon from biomass is a promising, cost-effective anode materials for sodium-ion batteries due to its high specific capacity [19, 20].

The lower Lewis acidity of sodium complexes causes the solid electrolyte interphase (SEI) in sodium-ion batteries to be more soluble, which implies that insufficient electrode coverage may cause unintended side reactions and increase heat generation [22]. Furthermore, a lot of the cathode materials for SIBs that have been described have low electrical and ionic conductivity, which can impede thermal dissipation. These materials include oxides, polyanions, organics, and Prussian blue analogues. Nonaqueous liquid electrolyte are still the SIBs today because of their effective mass transfer at the electrode-electrolyte interface, strong ionic conductivity, and broad electrochemical stability window. However, this also raises potential safety concerns [22].

Despite the advantages, SIBs still face significant technological hurdles, including the need for further development of cathode and anode materials to enhance performance and stability [19]. Recycling and end-of-life treatment for SIBs pose economic and environmental challenges. Current recycling strategies include pyrometallurgy and hydrometallurgy, with preference of pyrometallurgy to minimize sodium evaporation [19]. The usage of Hexacyanoferrate cathodes that consist of 50 wt% cyanide anions, poses a significant safety risk due to the possible release of highly toxic cyanide gases [23].

2.3. Battery Modules and Systems

An essential component of the battery energy storage system, the battery management system (BMS) establishes the connection between the battery pack and external devices and controls the battery's rate of use [24, 25]. Typically, integrated circuits, electronic cards, and additional hardware components are used to build BMSs [25, 26]. Battery Management Systems track various parameters, charge and discharge current, charge and discharge voltage, and temperature [25, 27, 28]. Additionally, by working with the power electronics to control power flow, BMS is essential to guaranteeing the battery's safe and efficient operation. It enforces strict limits on both charging and discharging to prevent conditions like overcharging, deep discharge, or current surges, all of which could potentially damage the battery or shorten its lifespan. Additionally, the BMS manages temperature regulation by reducing power output (deration) at high temperatures to prevent overheating, and by limiting the charging current at low temperatures to avoid damaging the battery when it is too cold. In extreme situations, such as during overvoltage, undervoltage, or unsafe temperatures, the BMS can trigger a hard cutoff to protect the battery and prevent hazardous conditions [26, 27, 29].

The four primary types of BMSs can be distinguished by their management model and hardware circuit structure: Modular BMS, Distributed BMS, Main Controller-Subcontroller Type BMS, and Centralised BMS [25, 28]. A cable harness connects the centralized BMS to the cells, which are housed within a single assembly. A data link connects each of the several identical cards that make up a modular BMS, with one card serving as the master [28]. However, the Main Controler-Subcontroller Type BMS consists of a separate master unit that handles computation and communications, as well as several similar cards that each measure the voltage of a set of cells [28]. A card that is physically attached to each cell measures the voltage (and temperature) of the non-centralized type. A data link connects the cells to a controller that controls communications and processing [28].

Air cooling, heat pipe cooling, phase change material cooling, and liquid cooling are the many types of cooling media that are employed in battery thermal management systems [13, 24].

Air cooling is widely used for battery cooling due to its simple design, affordability, and ease of maintenance. This method uses either natural wind or forced airflow from fans to transfer heat away from the battery pack. Natural convection is simple and low-cost, but it relies on unpredictable natural winds, leading to poor heat dissipation. On the other hand, forced convection is more efficient and easier to manage, making it a common choice for cooling lithium batteries [13, 24]. However, even forced convection often results in inadequate heat dissipation and uneven battery temperature distribution requiring concerted efforts to optimize forced-air cooling systems for enhancement of temperature uniformity and overall cooling performance. Cell layout and airflow channel design are the main areas of recent advancements in forced air-cooling BTMs [13, 24]. Figure 1 shows the airflow design and cell arrangement for air cooling in batteries.

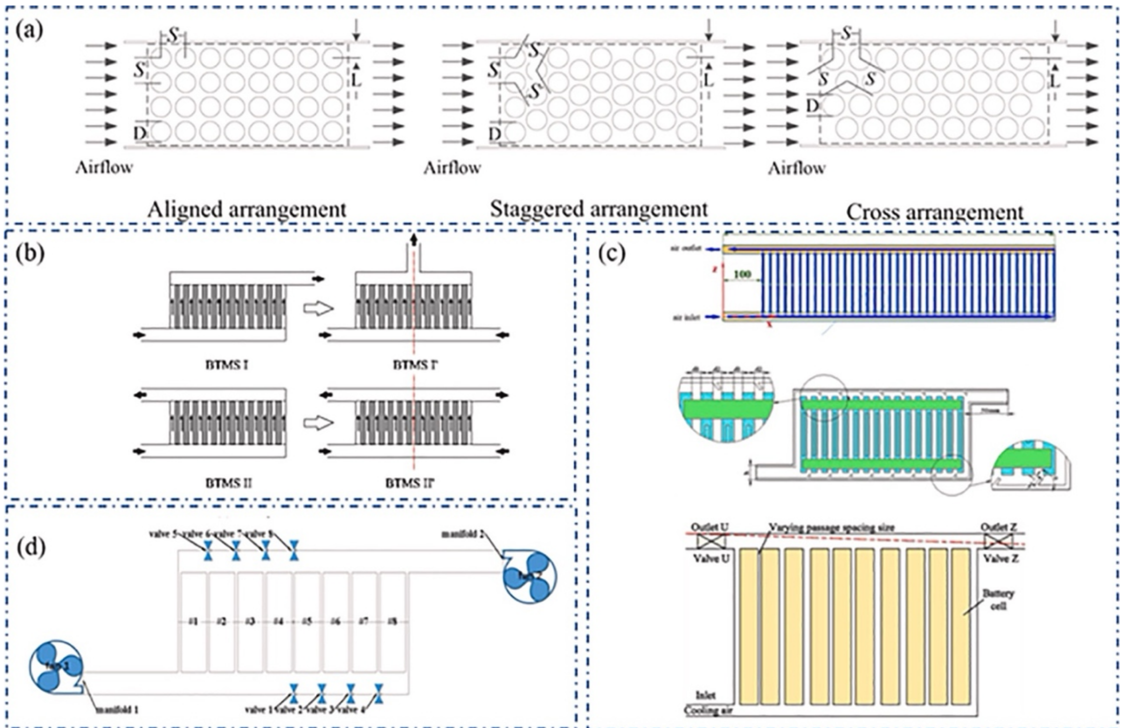


Figure 1. shows the airflow design and cell arrangement for air cooling in batteries. (a) aligned, staggered, and crossed batteries arrangements; (b) Symmetrical arrangement of batteries; (c) U -, Z – and J – shaped channels; (d) Z – passage with additional vents and reciprocating airflow [24].

In BTMs, battery configurations that are staggered, aligned, and crossed under air cooling have different effects on cooling efficiency. In an aligned arrangement, battery cells are placed in straight rows and columns, ensuring that each cell is directly in line with others both horizontally and vertically [24]. This set up allows for uniform airflow over the cells, resulting in consistent cooling and temperature uniformity across the battery pack [24]. In a staggered arrangement, battery cells are placed in an offset pattern similar to a brick wall, which can disrupt airflow patterns and lead to more complex cooling dynamics [24]. While this layout may improve flow distribution in some scenarios, it often results in less uniform temperature profiles compared to the aligned arrangement [24]. Lastly, in a crossed arrangement, cells are placed diagonally from one another where rows and columns intersect, creating varied airflow paths that might enhance cooling in certain areas but can also lead to uneven cooling and temperature gradients across the batter pack [24]. Symmetrical battery arrangements consist of different configurations of BTMs, whereby, cooling airflow is directed in opposite directions. This set up aims to balance temperature distribution across battery cells. U-shaped designs guides airflow in a U-pattern for controlled heat removal, while the Z-shaped designs allow for more uniform airflow, potentially reducing temperature gradients and the J-shaped designs are variations used to optimize cooling efficiency. There are also other Z-passage designs with additional vents that incorporate extra vents and reciprocating airflow to improve cooling performance by redistributing airflow, preventing overheating in certain areas of the battery pack [24].

Compared to air cooling, liquid cooling technology offers superior heat dissipation because of its heat conductivity. Liquid cooling systems provide more efficient cooling, faster temperature reduction, and greater flexibility in maintaining stable maximum temperatures and minimizing temperature difference within the battery [13, 24]. According to Youfu Lv et. al. [24] there are two types of contact between a battery and the coolant: non-contact liquid cooling and direct contact liquid cooling [13, 24]. The battery pack is immersed in the coolant in direct-contact liquid cooling systems, guaranteeing complete contact and greatly enhancing temperature homogeneity and heat dissipation. Silicon oil, fluorinated hydrocarbons, and hydrocarbon oil are examples of common coolants [13, 24]. Although this method offers excellent cooling performance, its application is limited by the large space required, stringent waterproofing, insulation, and sealing requirements, and high manufacturing and maintenance costs [24]. In indirect liquid cooling, the liquid coolant flows through pipes often embedded in a cooling plate, transferring heat via thermal interface material [24]. Indirect cooling reduces the risk of coolant leakage and makes it easier to maintain and replace the cooling medium without disturbing the battery cells. However, it is less efficient in heat transfer and has a slower response to temperature changes [24]. Researchers have recently optimized coolant characteristics, coolant channels, and cold plate architectures to improve the efficiency of indirect liquid cooling systems. Water, ethylene glycol solution are the main coolants utilized in these systems [13, 24].

2.4. Battery Systems and Sizing

Proper sizing is crucial for ensuring that the system can meet energy demand effectively, when designing battery systems for storing energy from wind and solar sources [30]. The key factors to consider in battery sizing are Energy Capacity (kWh), Power Capacity (kW), Depth of Discharge (DoD), Efficiency, Cycle Life, Autonomy [30]. Energy Capacity entails the total amount of energy the battery can store. It also determines how long battery can supply energy during low generation periods. Power Capacity determines how much power can be delivered by the batteries at a given moment. On the other hand, DoD is the proportion of the battery's overall capacity that is usable. Higher DoD allows for more usable capacity but may reduce battery life. The ratio of the energy stored to the energy retrieved is called efficiency. Higher efficiency, on the other hand, results in less energy being lost during storage. Cycle life of the battery represents the number of charge and discharge cycles the battery can undergo before its capacity significantly degrades. The service life of a battery is affected by the rate and depth of discharge-charge cycles and the higher the DoD, the shorter the life of the battery. Autonomy is about the duration the battery can supply energy without being recharged. It is crucial for ensuring energy supply during extended periods when there is low renewable generation.

2.5. Battery Hazards

Recent years have seen an increase in interest in lithium-ion batteries because of their great potential for effective energy storage, particularly given their present use in electric vehicles [9]. These systems have many benefits, but because of their high energy density and flammability of components, particularly in Lithium cobalt oxide ($LiCoO_2$), they present serious fire and explosion risks [18].

When a battery malfunctions during operation, the electrodes can generate heat due to various internal failures like internal short circuit, dendrite formation, electrolyte decomposition and impurities or manufacturing defects [9, 24]. This heat generation can become uncontrollable, leading to a dangerous condition known as thermal runaway [6, 9]. When the heat generated inside the battery is greater than the pace at which it can be released into the environment, thermal runaway happens, causing the battery's temperature to rise quickly [9, 24]. This temperature rise can cause the battery's internal components to react chemically, further increasing the heat output [6, 13]. During thermal runaway, the electrolyte being at high temperatures, releases flammable gases that react with battery components and increase heat output [18, 24]. Exothermic interactions between the anode and cathode materials raise the temperature and accelerate further breakdown [6, 13]. Additionally, the separator escalates heat generation by breaking down and losing its ability to insulate the electrodes, allowing direct contact between the cathode and anode, which results in short circuits. This contact further generates heat, intensifying the thermal runaway process [6, 9, 24].

The combination of these processes creates a self-sustaining reaction where the heat produced accelerates the chemical reactions, leading to even more heat production [9]. If left unchecked, this can cause the battery to reach temperatures high enough to ignite the flammable gases produced, resulting in fires or explosions [13]. The subsequent fire can then propagate within the system, igniting neighboring cells and causing widespread damage [24].

Fire behavior of the battery can be outlined as follows: battery swelling, initial jet flames, consistent burning, subsequent jet flame with stable burning, another cycle of jet flame with stable burning, mitigation, and extinguishing [31, 32]. The quantity of jet flames may vary depending on the state of charge (SOC) of the batteries [31, 32]. Figure 2 illustrates fire test that were carried out on the batteries with the 100% SOC by Ping et al. [31].

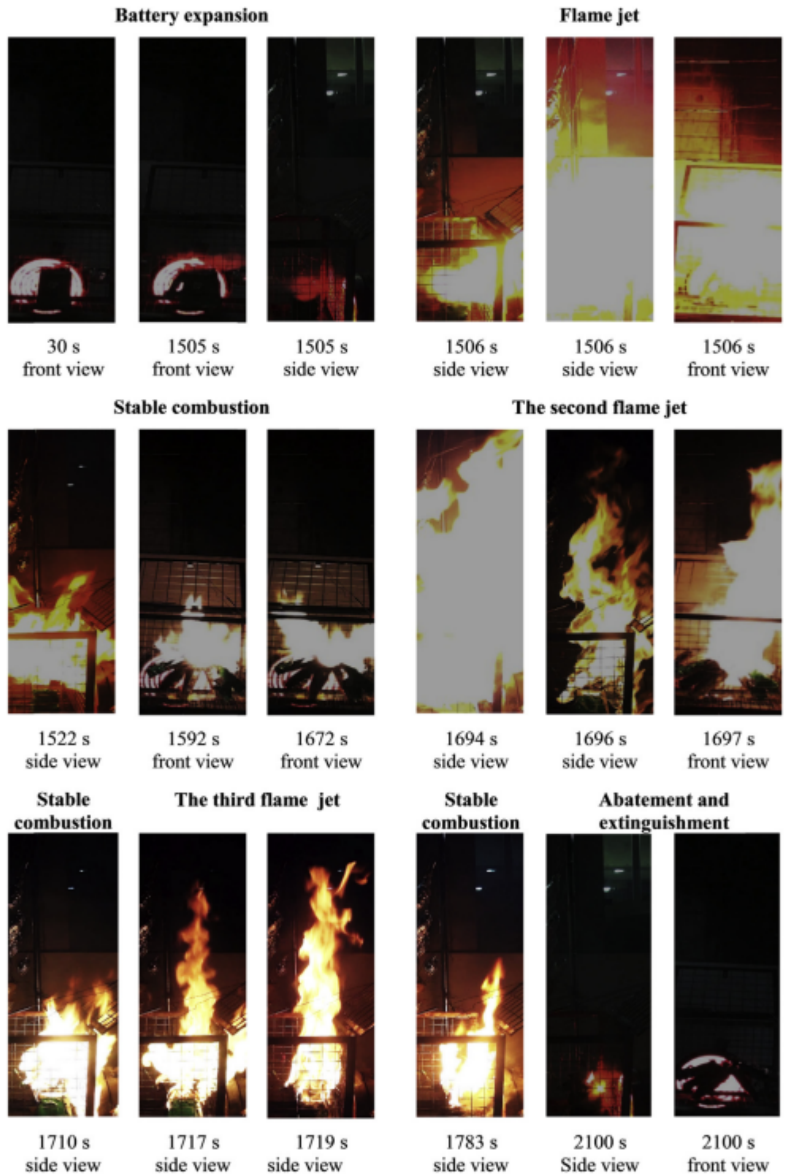


Figure 2. The combustion process in the 100% SOC battery's full-scale burning tests. (With permission from author). This images show different stages of thermal runaway, including: battery expansion (30s - 1505s), jet flames (1506s), stable combustion (1522s – 1672s), second jet flame (1694s – 1697s), third jet flame (1710s – 1719s), stable combustion (1783s) and lastly the abatement and extinguishing at 2100s [31].

Jet flames occur when the battery emits a hissing sound and expels large amount of electrolyte as white vapor. If the vapor encounter an ignition source or reaches its autoignition temperature, it can ignite, producing an intense jet flame [31, 32]. However, off-gassing can also occur without immediate ignition, depending on the concentration. Batteries at full charge (100% SOC) are more likely to undergo severe thermal runaway and explosive reactions, but this not always the case. High energy content means there is more potential for violent reactions, leading to substantial damage. While batteries at 50% charge still contain a significant amount of energy, the risk of thermal runaway is relatively lower compared to the 100% SOC. The damage will be severe but generally less catastrophic than at full charge. Batteries at 0% SOC have the least amount of energy, reducing the risk of severe thermal events, however they can still suffer considerable damage due to internal chemical degradation, especially if exposed to high temperatures or mechanical stress. Even at 0% SOC, side reaction such as electrolyte decomposition or degradation of electrode materials can continue, potentially leading to internal short circuits. But it is less dramatic in terms of explosive potential [31]. Figure 3 shows the battery damage ratio based on the SOC of the battery.

Figure 3. (a) 50 Ah LiFePO_4/graphite battery before the full-scale burning test; (b) 100% SOC, (c) 50% SOC and (d) 0% SOC batteries after full-scale burning tests. (With permission from author) [31].

According to Ping et al. and Fredrik et al. [31, 32], the flame temperature can rise to 1500 ℃, with the maximum temperature happening in an area about 100 mm from the battery. The normal spacing between cells or modules is not met by this distance. The possibility of burning nearby batteries is therefore quite high if a battery or battery module ignites.

Another significant issue compromising the safety of lithium-ion batteries is lithium plating in the anode, which is mostly brought on by heat and electrical abuse [9]. Lithium plating occurs when a battery is excessively charged. Lithium plating can trigger the formation of lithium dendrites that disrupt the solid electrolyte interface (SEI) layer and the separator [9, 24]. Conversely, over-discharging can cause the collapse of the graphite structure in the anodes, dissolution of copper and subsequent copper dendrite growth [9, 24]. Additionally, overheating may lead to shrinkage or melting of the separator membrane as shown in Fig. 3 [13, 24]. These factors collectively contribute to the internal short circuits within the battery. Once an internal short circuit occurs, it generates heat rapidly, leading to the release of flammable gas from the electrolyte and significant thermal decomposition [24]. Due to high energy density and confined spaces in which lithium batteries operate, the heat and flammable gases produced during thermal runaway cannot dissipate sufficiently quickly which leads to further escalation of battery temperature. The battery is vulnerable to combustion or explosion if the temperature rises above the safety level [24]. The temperature threshold for lithium-ion batteries refers to the critical temperature at which the battery can start to experience significant degradation, thermal runaway, or other safety issues [24]. This threshold can vary depending on the specific type of lithium-ion battery, its chemistry, design, and application [24]. The operational temperature range is the general temperature threshold; most lithium-ion batteries can function safely in the of $-20°C$ to $60°C$ temperature range [18]. However, the optimal performance is usually between $20°C$ to $30°C$. For long-term storage, lithium-ion batteries should be kept at storage temperature in the range $-20°C$ to $25°C$. Elevated temperature during storage can lead to capacity loss and increased self-discharge rates [18]. Temperature range for charging: lithium-ion batteries may normally be safely charged between $-0°C$ to $45°C$. Charging outside this temperature range can cause lithium plating, which can lead to battery damage or failure [18]. Thermal runaway threshold is typically around $70°C$ to $100°C$. The battery may catch fire or explode as a result of this uncontrollably high temperature [18, 24, 33].

Figure 4. An example of a melting separator.

Battery Energy Storage System safety is not exclusively dependent on the State of Charge [32]. The battery's State of Charge and State of Health are also important considerations. SOH is a key parameter used to measure and describe the current condition of a battery relative to its ideal, (as-new) state [32]. SOH of a battery describes the difference between a battery at hand and a fresh battery and considers cell aging. It is often expressed as a percentage, with 100% indicating a battery that is functioning optimally and as intended by the manufacturer, while lower percentages indicate various levels of degradation or diminished performance as shown below in equation (1).

$$SOH\% = 100\frac{Q_{max}}{C_r}, \qquad (1)$$

Whereby, $Q_{max} -$ is the maximum charge available of the battery, $C_r -$ the rated capacity.

SOH, or relative residual capacity, is determined by dividing the current C/5 discharge capacity by the starting C/5 discharge capacity [32]. Equation (2) provides the C – rate, which is a measurement of the rate of discharge in relation to the maximum battery capacity.

$$C_{rate} = \frac{I}{\frac{C_{batt}}{1\,h}}, \qquad (2)$$

When the battery's C – rate is C/5, it means that it will be charged or drained over a 5-hour period. Frederik et al. [32] have shown that batteries with diminished SOH are at higher risk of overheating during charging or discharging because of heightened internal resistance. Furthermore, as the battery's SOH diminishes, its probability of failure rises [32].

2.6. Explosions and Fire

Battery Energy Storage Systems (BESS) present unique fire and explosion risks due to the electrochemical nature of lithium-ion and other battery technologies. The potential for thermal runaway, gas venting, and ignition sources within confined enclosures necessitates a thorough understanding of fire and explosion dynamics [5].

Flammability limits define the concentration range of flammable gases in the air within which combustion can occur. In BESS applications, key gases such as hydrogen, carbon monoxide, and various hydrocarbons may be released during thermal runaway events [18, 34]. The lower and upper flammability limits (LFL and UFL) of these gases influence the likelihood of ignition. For example, hydrogen has an LFL of 4% and a UFL of 75%, making it particularly hazardous in enclosed battery compartments. Additionally, gas accumulation in confined spaces increases the risk of combustion, requiring appropriate ventilation and monitoring systems [18, 34].

Several ignition mechanisms can trigger a fire or explosion in BESS, including electrical faults, mechanical damage, overheating, and electrolyte decomposition. Electrical faults such as short circuits and overcharging can cause localized heating and potential ignition. Mechanical damage, including physical impacts or deformation of battery cells, may expose reactive materials [5]. Overheating and thermal runaway can result from excessive heat generation within a cell, leading to self-sustaining reactions, venting, and eventual ignition. Electrolyte decomposition is another critical factor, as many battery electrolytes are highly flammable and can vaporize under high temperatures, forming explosive mixtures with air [18, 34].

Fire and explosion dynamics in BESS are influenced by the nature of released gases and the conditions within the storage environment. The combustion behaviour can manifest in two primary forms: deflagration and detonation. Deflagration is a combustion process that propagates through a medium at subsonic speeds [18, 34]. In BESS, deflagration can occur when flammable gas mixtures ignite, creating pressure waves but not necessarily leading to destructive explosions. Detonation, on the other hand, is a more violent combustion process where the reaction front transitions to supersonic speeds, producing shockwaves and significantly more destructive force. Though less common in BESS, certain gas mixtures, particularly hydrogen-rich environments, can result in detonation under specific conditions [18, 34].

2.7. Summary of Chapter 2

A thorough explanation of the fire and explosion risks connected to large-scale battery energy storage systems (BESS) is provided in Chapter 2, especially as it relates to their use in Namibia's green hydrogen projects. The assessment emphasises the inherent dangers associated with lithium-ion batteries' chemical makeup, which makes them essential parts of contemporary renewable energy systems.

Key findings from the literature indicate that the primary causes of fires and explosions in lithium-ion BESS include thermal runaway, electrical faults, and mechanical damage. These hazards are further intensified by environmental conditions such as high ambient temperatures, poor ventilation, and physical impacts. A deep understanding of these causative factors is essential for developing effective risk mitigation strategies to ensure the safe deployment and operation of BESS in large-scale renewable energy projects.

The evaluation divides the hazards into three categories: environmental, mechanical, and electrical. The main causes of electrical risks include internal and external short circuits, overcharge, and overdischarge. Mechanical hazards arise from vibrations, shocks, or impacts during transportation or due to puncturing by hard objects. Environmental hazards are influenced by conditions beyond the manufacturer's recommended range, such as extreme temperatures, altitudes, and exposure to salt, fog, too much sand, or floods.

The examination of various lithium-ion battery types, such as Lithium Manganese Oxide (LMO), Lithium Nickel Manganese Cobalt Oxide (NMC), Lithium Cobalt Oxide (LiCoO_2), and Lithium Iron Phosphate (LiFePO_4), underscores the trade-offs between energy density, safety, and cost. Each type's susceptibility to thermal runaway and capacity degradation in linked to its chemical and structural properties, guiding their specific applications and ongoing research aimed at optimizing performance and safety.

Furthermore, the review addresses the environmental impact and cost issues associated with lithium, suggesting sodium as a potential alternative due to its abundance and similar physicochemical properties. This shift could leverage existing lithium-ion battery knowledge, expediting the development of sodium-based batteries.

Chapter 3: Review of Incidents and Measures

3.1. Case Studies

Many incidents using battery storage systems have been documented globally, leading to significant losses in terms of human life, property damage, and energy production losses in terms of density, safety, and cost [5, 14, 32].

The choice of specific BESS accident cases for analysis is critical to ensure relevance and applicability to the conditions in Namibia. Namibia's hot and arid climate can influence the performance and safety of BESS, so selecting cases from regions with similar climatic conditions, such as Australia and parts of the United States, helps in understanding how high ambient temperatures and low humidity impact battery safety and performance. Because of their high energy density and efficiency, lithium-ion batteries are likely to be implemented in Namibia. The selected cases offer insights into potential dangers and Namibian-specific mitigation solutions [11, 35, 36]. These cases include large-scale BESS used in grid stabilization and renewable energy integration, which is the expected use case in Namibia, allowing for better risk assessment and planning [11, 35]. The incidents occurred in countries with established safety and regulatory frameworks for BESS, from which Namibia can benefit by identifying gaps and improving local standards to prevent similar accidents [11]. Analyzing these cases provides insights into common failure modes, such as thermal runaway, improper maintenance, and manufacturing defects, the analysis of which can enhance Namibia's training, maintenance practices, and operational protocols. The chosen cases document severe impacts on human health, safety, property, and energy production, helping Namibia to better prepare for potential emergencies and develop robust response strategies [5, 14, 32].

Many incidents occurred in markets with mature energy storage sectors, offering lessons for Namibia, an emerging market for BESS, to avoid repeating the same mistakes [5]. Additionally, some cases are from developing countries or regions with similar economic contexts to Namibia, ensuring that financial and logistical recommendations are realistic and applicable [1, 36]. These cases were chosen because they provide relevant insights into the specific technological, environmental, and operational conditions anticipated in Namibia, allowing proactive risk addressing and ensuring the safe and efficient deployment of battery storage systems [1, 36].

3.1.1. APS McMicken, Arizona Fire Incident

A 2 MW Battery Energy Storage System at the APS McMicken plant in Surprise, Arizona, assisted in balancing the national grid during times of peak demand [37]. The BESS had a HVAC system to regulate the indoor temperature and used NMC pouch cells in modules of 28 cells each. In order to reduce the working temperature, the HVAC units were designed to turn on when necessary. A NOVEC 1230 fire suppression system was also installed, which releases gases to control fires at the top of the racks [37].

The APS McMicken facility in Surprise, Arizona, experienced a fire on April 19, 2019 [37]. After the fire started in battery rack 15, it culminated in an explosion that injured four firefighters. Figure 5 shows the aftermath of the explosion, where thermal runaway spread vertically within rack 15 [37].

Figure 5. Damage to the BESS's interior following the explosion (left), and following the removal of debris to allow entry for start of the forensics investigation (right) [37].

Following an analysis of the incident's data, it was concluded that a series of events contributed to the explosion, and that the fire in rack 15 started in a single-cell module as a result of aberrant lithium metal deposition and dendritic development, which caused a short circuit [37]. This initiated a thermal runaway that spread to adjacent modules, as illustrated in stages 1 through 4 as shown in Figure 6 [37]. The timeline of incidents shown in Figure 6 (a) illustrates the sequence (1 to the 13th) of events leading up to an explosion, whereby there was a delay between 11 and 12, which can be because the firefighters had to assess the situation before they open the door [37]. The explosion was preceded by a significant voltage drop and rising temperatures in rack 15, which triggered fire protection systems and led to a ground fault [37]. Despite the activation of the fire suppression system, APS and Fluence took steps to confirm and investigate the situation. However, after the fire department arrived and the front door was opened, an explosion occurred [37].

The lack of thermal barriers at the APS McMicken site accelerated the spread of the thermal runaway. Upon activation of the fire suppression system, gases from cells began to build up inside the system, as show in Figure 6 (b) [37]. Contrary to expectations, the NOVEC was unable to cool down and stop the thermal runaway. As shown in Figure 6 (b), the combustible gases that had vented were displaced by the NOVEC 1230 gas and accumulated in the BESS storage chamber. When firefighter open the door, air rushed in, allowing the NOVEC 1230 to escape the BESS. This mixture of air and flammable gas then encountered Rack 15, which remained hot due to the ongoing thermal runaway, triggering an explosion. The timeline of incident in Figure 6 (c) focuses on the action taken by emergency responders and the outcome of the explosion [37]. The causal chain of events is as follows:

1. **Emergency responders open the side door** – This action allows the cell gases from the battery cells to escape and mix with air in the vicinity of rack 15.
2. **An explosion occurs** – The flammable gases from the cells make contact with an ignition source in rack 15, leading to an explosion.

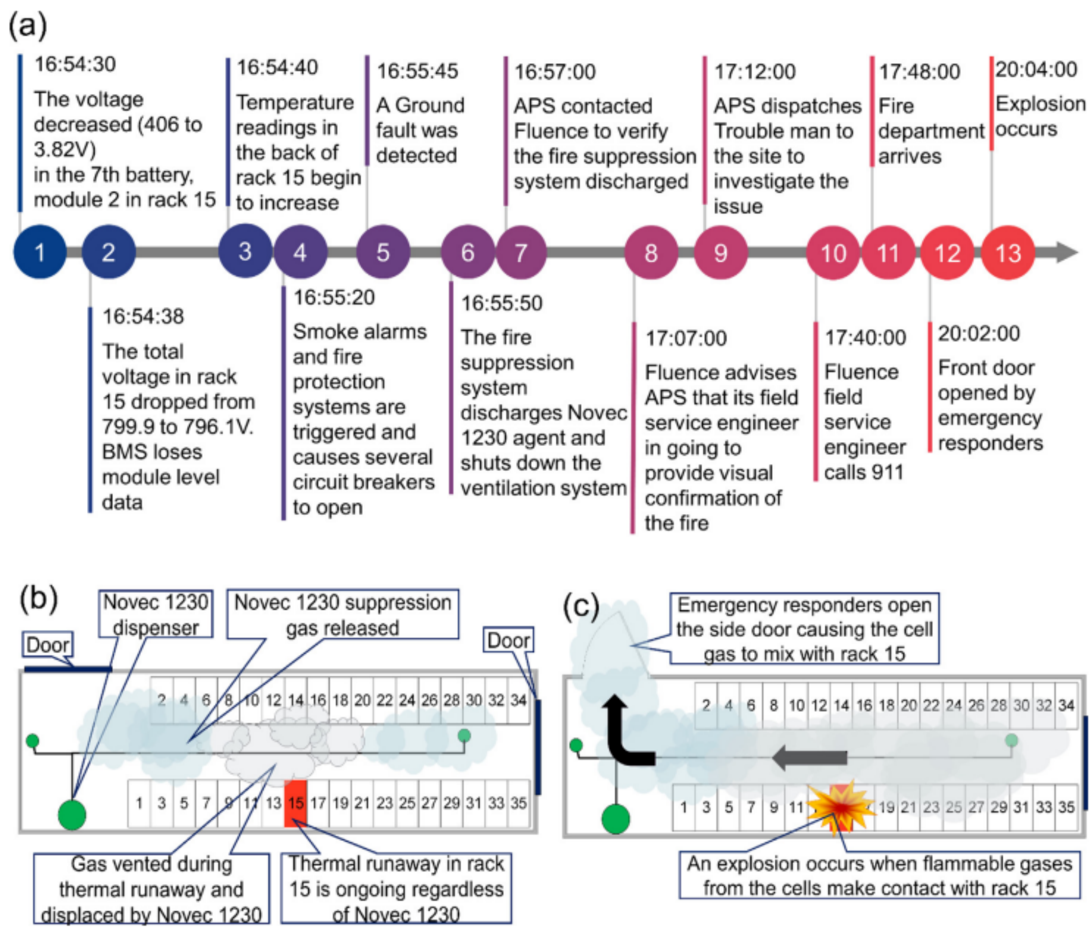


Figure 6. (a) Timeline of the incident. (b) Top-down diagram of the APS BESS during stages 1 to 10 on the timeline. (c) Top-down diagram of the APS BESS during stages 11 to 13 on the timeline [37].

The following was learned from the incident:

1. The BESS unit's NOVEC 1230 suppression system and activated fire alarm failed to stop the fire or explosion. The accumulation of gas, which resulted in ignition and deflagration, was caused by a design error in the suppression system.
2. The thermal runaway spread more readily and the vented gases were able to approach the lower flammability limit because there were no thermal barriers between the cells and modules.

3. The released gases accumulated and became more concentrated as a result of the fire suppression system and the absence of ventilation.
4. Prior to first responders entering the BESS, the emergency plan should incorporate enhanced system monitoring, gas detection, and ventilation protocols. By doing this, responders would be less likely to open the door in potentially explosive situations.
5. Thermal runaways and their transmission between cells were not adequately addressed by the engineering standards in place. UL9540A, the new standard, provides tests to describe flammability and gas emissions. To reduce danger, including the prevention of thermal runaway propagation, these requirements require additional recommendations and future development.
6. To identify possible battery failure issues and gas evolution during thermal runaways, the BESS industry should work with suitable third party to carry out experiments and investigations. The safety and dependability of the systems can be improved by putting danger assessments and sound engineering practices into effect [37].

3.1.2. BESS fire incident in Bouldercombe, Australia

Tesla Megapack battery modules were installed at the Bouldercombe Big Battery in Queensland, Australia, which underwent its commissioning process in September 2023 [38]. The project consisted of 40 Tesla Megapack 2.0 battery modules in Bouldercombe, owned by Genex Power. The Bouldercombe Battery project is a 50 MW and 100 MWh initiative, which was a month old at the time [38]. Instead of installing the lithium-nickel-manganese-cobalt-oxide batteries that were originally intended, Genex put Tesla Megapack lithium-iron phosphate battery cells at the location, which are more fire-resistant [38].

A fire that was limited to a single Megapack 2.0 module started in the Bouldercombe Big Battery project's lithium battery storage on Tuesday, September 26, 2023, at 19:45 [38]. The incident was described as a minor fire that did not require water to extinguish [38]. The fire only affected a single unit, leaving the other many units unharmed[38]. However, the fire caused dangerous smoke to be discharged into the surrounding region, so locals were advised to stay inside and keep respiratory medications close at hand [38]. By Wednesday morning at 08:20 AM, the Queensland Emergency and Fire Services had successfully contained the fire [38]. Figure 7 show the blaze as it erupted.

Figure 7. The Australia, Queensland, Bouldercombe fire incident [38].

At the time, the cause of the fire was unknown, therefore Genex Power, along with Tesla Motors Australia Pty Ltd and Consolidated Power Projects Pty Ltd, started an inquiry to find out what caused the catastrophe [38]. Residents who witnessed the fire described it as having multicoloured flames with a few bangs and pops [38]. Figure 8 shows the aftermath of the fire incident.

Figure 8. Shows the aftermath of the BESS fire incident in Bouldercombe, Australia [38].

3.1.3. BESS Incident in California, USA (2023)

The Valley Center Energy Storage System, a 140MW/560MWh battery storage facility located near San Diego, California, experienced a fire incident on September 18, 2023, at approximately 5:15 pm [39]. The fire broke out in a battery storage unit, equipped with lithium-ion batteries, leading to a dispatch of Fire and Sheriff's departments, road closures, and evacuation orders for the surrounding quarter-mile area [39].

By 9:15 pm, all public safety measures were lifted, with no hazardous conditions detected in the air or water by the San Diego County Hazardous Materials team. This incident follows a previous issue earlier in the year when 100 decommissioned LG lithium-ion battery packs were stolen from the site [39]. Sprinkler system issues that have impacted other large-scale BESS projects, such as the Moss Energy Storage facility, may have contributed to the fire.

Figure 9. Southern California's Valley Centre Energy Storage Project [39].

3.1.4. Moss Landing BESS Facility Incident

Vistra Corporation owns the Moss Landing Power Plant, which has a 1600MWh total capacity and is among the biggest BESS in the world. Located in Moss Landing, California, the facility comprises a 400MW consisting of numerous battery arrays, protected by a water-based suppression system [40]. On September 4, 2021, the facility experienced a significant meltdown, which damaged approximately 7% of the battery modules [40].

Smoke was detected in the facility, triggering the activation of the water-based heat suppression system [40]. However, due to coupling failures in the suppression system, water exposure led to short-circuiting and electrical arcing in the batteries [40]. This arcing caused the initial fire, and the ensuing smoke further activated the suppression system, worsening the situation by short-circuiting additional batteries and causing more to melt. Additionally, cracks in the floor allowed water to seep down to lower-level battery racks, spreading the damage [40].

The fire was contained without the need for outside assistance. No injuries were reported, and the surrounding community was unharmed [40]. The investigation revealed that a programming error allowed the suppression system to activate at smoke concentrations lower than the design limit [40]. The small amount of smoke was likely due to a bearing or other friction source, rather than the batteries themselves. Furthermore, the coupling failures occurred in flexible hoses that had not been pressure tested to withstand the suppression system, resulting in the extensive failure. Future corrective actions include complete pressure testing of the system, proper programming for suppression systems, sealing gaps on high floors, and other precautionary measures [40].

The incident caused significant disruptions, including the closure of a highway in both directions and surrounding areas due to concerns over potential toxins in the smoke from the burning lithium-ion batteries [40]. The failure of the detection and heat suppression systems highlighted the crucial role these play in ensuring the safe operation of BESS facilities [40].

To Mitigate such risks in the future testing to verify the suppression system's reliability in case of a BESS failure and identifying safeguards and mitigation strategies should be conducted. Laboratory testing, such as battery abuse testing and gas chromatography, should be performed under controlled conditions to measure battery safety and ensure compliance with various codes and standards [40].

3.1.5. BESS Fire, Moss California, USA

The Moss Landing battery complex in California, the largest grid battery installation in the United States, experienced another fire incident on September 20, 2023, barely two years after a previous large-scale accident. This complex includes PG&E's 182.5MW/730MWh Elkhorn plant and Vistra's 400MW, 1600MWh facility, situated at a crucial transmission-grid junction south of the Bay Area [41]. The fire ignited in the early hours of the morning at the Tesla-supplied Elkhorn plant and was contained by the evening. This incident is the latest in a series of fires at this location, with Vistra's facility having suffered two fires in the past year [41]. Figure 10 below shows the ariel view of the facility.

Figure 10. Vistra's Moss Landing energy storage facility (centre) before the incident [41].

The local authorities responded swiftly, issuing warnings to nearby residents to keep windows closed and turn off ventilation systems while testing for hazardous emissions was conducted. The incident also led to the temporary closure of the stretch of a nearby highway causing economic disruptions in the area [41].

The cause of the fire at the Elkhorn plant was still under investigation, but initial theories suggest a possible issue related to moisture, given the history of similar incidents at Tesla battery installations [41]. The fire did not spread, thanks to the facility's design improvements and effective safety protocols. These procedures include designing techniques to stop fires from spreading from one unit to another and deflagration panels to safely channel hazardous gases. The fire was allowed to burn itself out under controlled conditions, following Tesla's recommended response strategy [41].

The Moss Landing fire highlights the continuous difficulties in guaranteeing the security and dependability of extensive battery storage systems, even with the modest damage [41]. The energy-storage industry has made significant strides in safety improvements since previous high-profile incidents, such as the 2019 Arizona fire that hospitalized four emergency responders [41]. However, the recurring fires at Moss Landing highlights the need for continuous advancements in safety measures and rigorous testing of all system components, including cooling and fire suppression systems [41].

The incident resulted in localized economic impacts, including disruptions for nearby businesses and residents. The surrounding community had to endure a day of lockdown and potential exposure to hazardous air, although no harmful emissions were detected [41].

3.1.6. Risks of Thermal Runaway in San Diego BESS fires

A large fire broke out at the Gateway Energy Storage Facility in Otay Mesa, San Diego, on May 15, 2024. The 250MW plant, run by Rev Renewables, is essential to the power system in California's electrical supply [42].

The facility's third building was the initial site of the incident, which was caused by a thermal runaway chain reaction [42]. Because of the number of reactions, the fire kept reoccurring even after firefighters have tried to ventilate the building and soak the batteries. Hazardous materials teams were called in due to the toxic smoke and fumes released by the burning LIBs. Rev Renewables, the facility operator, acknowledged the inherent challenges in extinguishing fires involving lithium-ion technology. The fire severely damaged the structure, including burning through part of the roof [42].

3.1.7. Australia, Victoria, Geelong

In July 2021, a significant incident occurred in Australia's Victoria BESS site in Moorabool, near Geelong [43]. Victoria's site, managed by Neoen in collaboration with Tesla, is poised to become the largest battery installation in the southern hemisphere, aiming to bolster Victoria's renewable energy capacity [43]. There are questions over the safety and dependability of such massive energy storage systems after two Tesla Megapacks caught fire during early testing on July 30 [43].

It was concluded that the most probable cause of the fire was a coolant leak within the cooling system Megapack by the Energy Safe Victoria investigation [43]. It is thought that the leak caused an electronic component to short circuit, which in turn caused the battery to overheat and catch fire. This initial fire triggered a thermal runaway event, resulting in flames spreading to a second battery [43]. Notably, the battery was offline at the time, meaning that monitoring and protection systems were inactive, allowing the fault to go undetected and escalate [43].

The fire had significant immediate impacts, with two Tesla Megapacks being engulfed in flames. The incident also led to the issuance of toxic smoke warning for the surrounding area [43]. Firefighters took four days to bring the blaze under control and secure the site. The incident underscored the potential hazards associated with large-scale battery storage, particularly concerning fire risks and toxic emissions [43].

Following the investigation, authorities have granted permission for testing at the Victorian Big Battery site to resume, subject to enhances safety measures [43]. Key changes include rigorous inspections of Megapack cooling systems for leaks and the implementation of a new “battery module isolation loss” alarm in the firmware. Neoen and Tesla are collaborating to ensure such incidents do not recur, with an emphasis on sharing lessons learned across the industry [43]. Additional independent investigations by the Energy Safety Response Group and Fisher Engineering are ongoing, with a comprehensive report expected by November [43]. Despite the setback, the project remains on track to significantly enhance Victoria’s renewable energy capacity, targeting an additional 250 megawatts of peak capacity by its projected completion in November 2021 [43].

3.1.8. Beijing Jimei Dahongmen fire accident

The Beijing Jimei station was a 25 MWh of Direct Current (DC) solar-storage-charging integrated system, that was commercialized in March 2019. This was the biggest commercial energy storage station for customers in central Beijing city, the largest scale public charging station, the first MWh-level solar photovoltaic energy storage-charging station [12]. 94 parking spots with 150 kW single extremely powerful DC fast charging piles were utilized in this project. 25 MWh capacity was divided in two sections whereby, 12.5 MWh was used for charging Electric Vehicles, and the other 12.5 MWh for indoor electricity supply [12]. The project utilized lithium-ion phosphate cells of 3.2V and 10.5 Ah, and they were provided by Guoxuan High-Tech Co., Ltd [12].

Two firefighters were killed, one was injured, one station employee went missing, and property was damaged in a fire incident that happened at the Beijing Jimei Dahongmen station in April 2021 [12]. According to the accident analysis, around 14:15 pm, fire fighters were extinguishing another fire on the southern part of the station (causes of this fire not known). While busy extinguishing the fire, a sudden explosion occurred on the northern part of the station without a warning [12]. The open flames were extinguished around 23:40 that same day, although the cooling of the batteries continued for several hours to prevent re-ignition and ensure safety [12]. Figure 11 shows the accident scene and the damage that occurred.

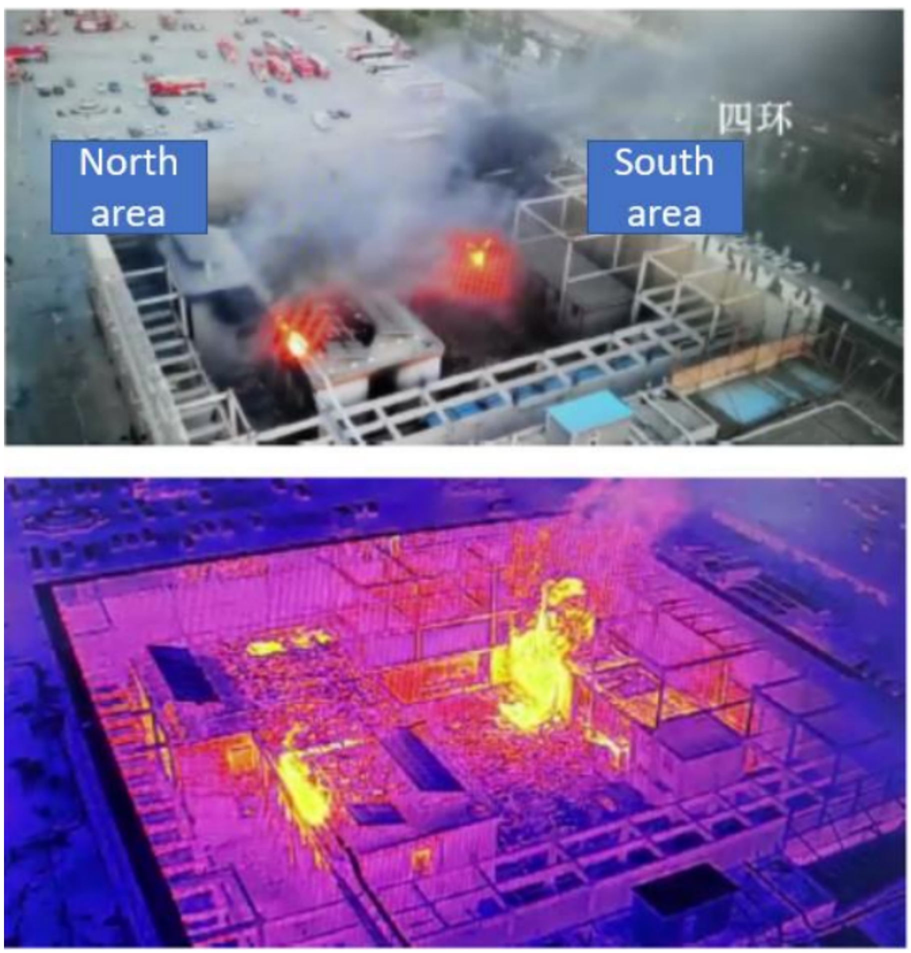


Figure 11. An aerial photography and thermal image of the accident scene [12].

It was hard to determine what initiated the fire accident due to limited information. Two scenarios were looked at: (1) Did the low-quality batteries cause the fire disaster, or (2) the input overwhelming the batteries, surpassing their carrying capacity [12]. The potential explanations that were put out were as follows: (1) batteries state; (2) energy storage's electrical topology; (3) battery management system (BMS); (4) arrangement of wires and cables; (5) the station's fire protection design; (6) fire water and the station's fire monitoring, warning, and extinguishing system; (7) meteorological environment factors; (8) people on-site system for management and operation [12].

Figure 12. The power station after the fire accident [12].

3.1.9. France, Martinique, Saint-Esprit

A SICA Mandras poultry farm in Saint-Esprit, Martinique, France, was equipped with lithium-ion batteries [44]. The poultry farm had a solar-integrated operational power supply. A fire broke out on the night of Friday, September 29, 2023, ravaging the technical room of a chicken breeding operation on the farm. The fire led to the explosion of the photovoltaic batteries, causing damage of more than one million euros [44].

According to the Territorial Fire and Rescue Service (STIS), the explosion was felt by at least 300 homes around the site [44]. The fire started on the evening of September 29 and lasted until the morning of September 30, 2023. The explosion caused damage to nearby homes, blowing out windows and leading to the evacuation of the residents [44]. The situation on-site was managed and brought under control after three hours, requiring around 20 firefighters supported by EDF (Électricité de France) agents [44]. Toxic fumes from the burning batteries could not be inhaled because the site's perimeter was protected to achieve this, water was first used to create a curtain to protect local residents from toxic fumes [44]. The fire was eventually brought under control with powder and foam containing extinguishing products [44]. Figure 13 shows the damage caused by this disaster.

Figure 13. Saint-Esprit, Martinique, France, fire and explosion accident [44].

3.1.10. France, Saucats, Barban

The Claudia Battery Energy Storage System project was developed by Amarenco Group in Saucats, Gironde [45]. With a power capacity of 105 MW, it is one of Europe's largest storage projects [45]. Developed in partnership with Nidec Industrial Solutions, the project aims to enhance supply security and power system reliability. The site contained 50 containers of batteries, spaced apart [45].

On Tuesday, August 22, 2023, a fire erupted at the end of the morning at the new electricity storage plant in Barban, Saucats, within a container housing lithium-ion batteries [45]. The incident, which occurred amid a recent heat wave, required a day and night of intervention by firefighters [45]. The blaze was visible from several hundred meters away [45]. The fire protection system effectively contained the fire, prevented it from spreading. Gas was used by the firefighters to smother the flames inside the containers and created a protective curtain, avoiding the use of water due to the nature of lithium battery fires [45]. Figure 14 shows the fire and smoke on the Claudia site.

Figure 14. The fire accident at Claudia site [45].

3.1.11. Neermoor (Lille district), Germany

On the April 24, 2024, a lithium battery energy storage container caught fire shortly before 9 p.m. in the business district of Neermoor (Lille district), Germany, leaving two firefighters injured [46]. When the firefighters arrived on the scene, they could see light smoke [46]. After consultation with on-site personnel, the energy storage container was opened, leading to an explosion with a flash of flame, injuring the firefighters [46]. A crane was used to move the energy storage container to prevent the fire from spreading to other containers [46].

With the support of fire brigades and police from nearby cities, the fire was finally put out in about 10 hours [46]. Due to the large amount of thick smoke produced by the fire, one of the highways was completely closed off for about 6 hours [46]. Figure 15 shows the scene at the site.

Figure 15. Lithium battery energy storage container caught fire in the business district of Neermoor [46].

3.1.12. Hwaseong city, South Korea

A business called Aricell focusses on producing lithium batteries [47]. On its second floor, the Aricell plant held an estimated 35 000 battery cells. These were examined and packaged, and additional batteries were kept in other locations [47]. Leading manufacturer of lithium batteries, which are utilised in a variety of products, including computers and electric cars, is South Korea [47]. The three-story Aricell plant has a gross floor space of around 2300 square meters and is made of reinforced concrete. Its principal activity is the production and distribution of lithium primary batteries [47].

Aricell’s lithium battery production facility experienced a fire on June 24, 2024, at 10:31 a.m., caused by exploding lithium batteries [47]. It was reported that the incident left 22 employees dead and injured 8 others. The fire eruption at the battery manufacturing factory in Hwaseong is shown in Figure 16.

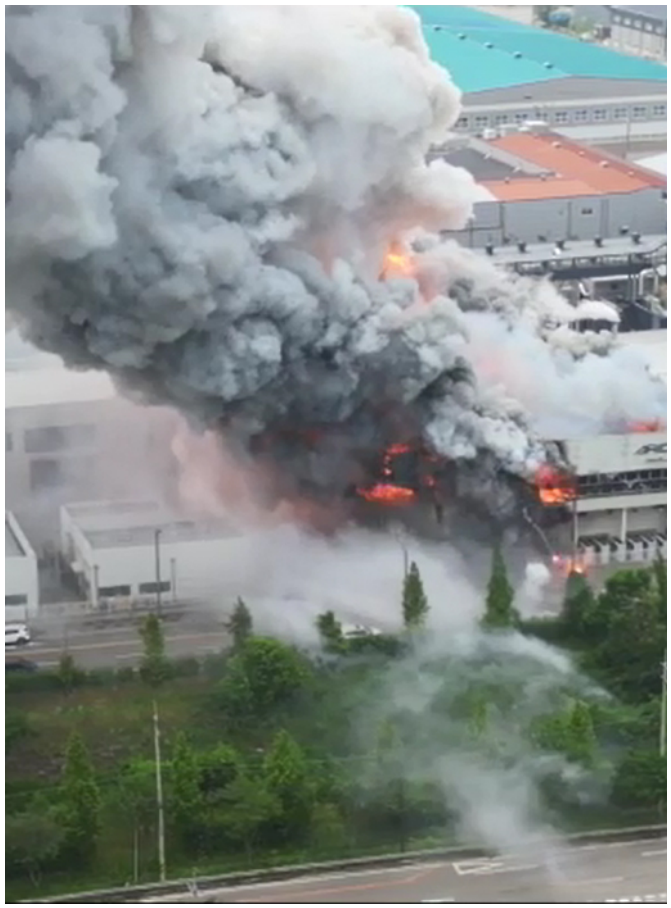


Figure 16. The BESS fire eruption in Hwaseong, Gyeonni Province [47].

The authorities reported that the firemen originally had trouble because the blaze on lithium batteries could not be extinguished with water [47]. Because lithium batteries continuously produce heat within, they can reignite a fire even after it seems to have been put out, making lithium battery fire challenging to put out [47]. Figure 17 shows the building after the fire was brought under control.

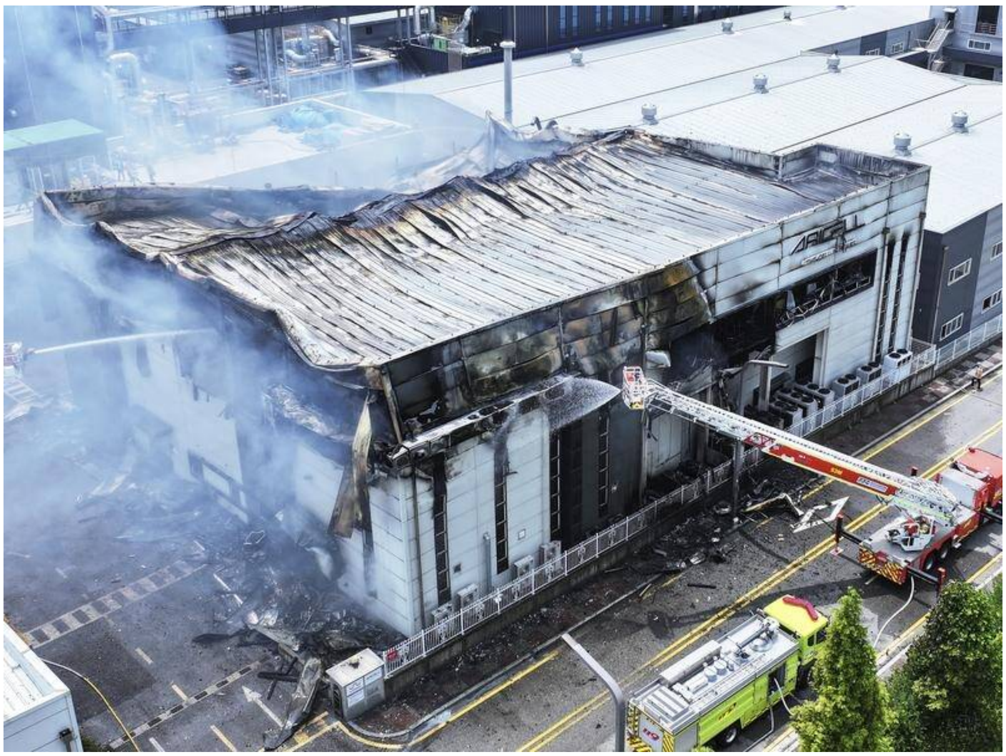


Figure 17. Hwaseong, South Korea, battery fire aftermath [47].

3.1.13. BESS Incident/Accident Database

An overview of world BESS incident database content that is presented in Chapter 5, section 5.1 because it serves as a structured reference for analyzing global BESS incidents. It provides key details such as incident locations, system size, capacity, age, causes, and damage in a table format. By organizing this information separately, the section ensures clarity and allows for easy comparison of incidents, helping to identify trends and recurring issues in BESS safety and the database was used to carry out statistical analysis [36].

3.2. Regulatory framework and guidelines of BESS

A summary of the LIB-safety standards developed in different jurisdictions in the past ten years are listed in Table 1 below [5, 9].

Table 1. BESS international standards

Standard No.	Latest Version	Intended for LIB	Applicable to LIB	Applicable to SIB
Chinese standards GB/T 31485	Dated May 15, 2015	+	+	-
Society of Automotive Engineers (SAE) Standards J2464	Dated August 1, 2021	-	+	+
International Electrotechnical Commission (IEC) standard IEC62133	Version 1.0, date: 2017 - 02	+	+	+
United Nations (UN) standards UN38.3	4th Revised Edition	+	+	-
Japanese Industrial Standard (JIS) C8714	Dated 2007	+	+	-
Underwriters Laboratories (UL) standard UL2580	Version 3.0 Dated March 11, 2020	-	+	+
International Standard Organization (ISO) standard ISO 16750-2	Dated 2023 - 07	-	+	+
IEC TS62933	Edition 1.0, date: 2023 – 01 - 06	-	+	+
NFPA 855	Edition 2023	-	+	+
IEC 62619	Edition 2.0, date: 2022 - 05	+	+	-
UL 1940A	Edition 4.0 Dated November12, 2019	+	+	+
UL 1973	Edition 3 Dated February 25, 2022	-	+	+

The Stationary Energy Storage System Installation Standard, NFPA 855, was approved by the USA's NFPA Standards Council in April 2016 [48]. The U.S. Department of Energy and the Fire Protection Research Foundation conducted seminars that revealed regulatory loopholes, which led to the creation of the NFPA 855 [48]. The NFPA is also a code body that provides technical guidance.

These standards are applicable to the ESS exceeding the values shown in Table 2. Key provisions include guidelines on installation locations, fire safety measures such as fire suppression systems and fire-resistant barriers, and ventilation requirements to manage heat and gases [48]. The standard mandates a hazard mitigation analysis and emergency response protocol, specifies construction material standards, and requires clear labelling of ESS components. Electrical safety is addressed through specifications for installations, grounding, bonding, and monitoring systems to ensure safe operation [48]. Procedures for initial testing, regular maintenance, and inspection are outlined to maintain ongoing safety and performance. Additional requirements are provided for different battery types, ensuring tailored safety measures [48]. NFPA 855 also ensures compatibility with existing building and fire codes and includes guidelines for the safe decommissioning and disposal of ESS components to minimize environmental impact and safety risks. Adhering to these standards mitigates risks associated with ESS and supports their safe integration into various applications [48].

Table 2. Quantities at the Threshold that the NFPA 855 is applicable to.

Energy Storage System Technology	Aggregate Capacity	
	kWh	MJ
Battery Energy Storage Systems		
Lithium-ion, all types	20	72
Batteries in one-and two-family dwelling and townhouse units	1	3.6
Lead-acid, all types	70	252
Other batteries technologies	10	36
Nickel including Ni-Cad, Ni-MH, and Ni-Zn	70	252
Flow batteries	20	72
Sodium nickel chloride	20	72
Capacitor Energy Storage Systems		
Electrochemical double layer capacitors	3	10.8
Other Energy Storage Systems		
All other Energy Storage Systems	70	252

Standard UL 9540A, "Test Method for Evaluating Thermal Runaway Fire Propagation in Battery Energy Storage Systems," is a key standard assessing fire safety performance in battery energy storage systems (BESS). It evaluates the potential for thermal runaway and fire propagation across various battery chemistries and system configurations. The standard includes test at the cell, module, unit, and installation levels to understand how thermal runaway initiates and propagates, using methods such as heating, overcharging, or physical abuse. Critical parameters like temperature, pressure, gas emissions, and fire propagation are monitored, with detailed data collection to assess impacts. Safety measures such as fire containment, suppression, and gas emissions analysis are evaluated to determine the effectiveness of integrated systems. Comprehensive documentation of test procedures and results is provided, along with safety recommendations for design improvements and operational guidelines. UL 9540A ensures compatibility with other relevant standards, like NFPA 855, offering a comprehensive strategy to BESS safety.

This standard is crucial in providing actionable data and mitigating fire risks in BESS installations.

UL 1973 applies to batteries designed for stationary and auxiliary power applications in motive systems [49]. The UL 1973 standard ensures that batteries used in these applications meet rigorous safety and performance criteria, reducing the risk of malfunctions and accidents [49]. The UL 1973 standards cover battery systems used as energy storage for stationery applications such as PV, wind turbine storage or for UPS. These standards also include safety tests to evaluate batteries under various conditions, such as thermal cycling, overcharge protection, short circuit protection, and mechanical integrity. Batteries must also meet specific performance criteria for capacity, efficiency, and longevity. Additionally, manufacturers are required to provide clear labeling and documentation with instructions for safe installation, use, and maintenance [49].

The International Electrotechnical Commission (IEC) is a global body responsible for creating standards related to electrical and electronic technologies. It works in collaboration with national electrotechnical committees, known as IEC National Committees, to achieve international standardization. The requirements for guaranteeing the safe operation of secondary lithium cells and batteries, especially in industrial settings, are outlined in IEC 62619, one of its main standards. Emergency power, telecom, utility switching, electrical energy storage systems, uninterruptible power supply (UPS), and other stationary applications. The standard is applicable to batteries and cells that use non-acidic or alkaline electrolytes [50].

Both batteries and cells are covered by the standards, which state that if a battery is split up into smaller parts for testing, the smaller parts must faithfully depict the battery as a whole. However, the standard does not address topics such as re-used batteries, first or second-life applications, or response time [50].

The International Electrotechnical Commission has a standard called IEC 62133 that outlines the safety requirements for portable sealed secondary cells and batteries produced from them for use in lithium system portable applications. Alkaline or other non-acid electrolyte-containing cells and batteries are covered by the standards [51].

IEC 62133 ensures that the design, testing, and performance of rechargeable batteries meet stringent safety criteria to prevent risks like overheating, short-circuiting, leakage, and thermal runaway. It outlines the tests that must be carried out on cells and batteries, which include electrical, mechanical, thermal, and environmental assessments. Part 1, covers nickel-based rechargeable batteries and Part 2, covers lithium-ion batteries [51].

IEC TS62933 is a technical specification developed also by the International Electrotechnical Commission (IEC) that focuses on electrical energy storage (ESS) systems. For the safety functionality, and testing of energy storage systems – especially those that store electrical energy for use in a range of applications, such as backup power, grid stabilisation, and renewable energy systems – it offers standards and guidelines. It works with ESS systems that are connected to the electrical grid [52].

The IEC TS 62933 standard applies to several form of electrical energy storage, such as BESS, Flywheel energy storage systems, Supercapacitors and Hybrid systems. And it is essential for ESS used in a different industries, such as residential solar power storage to large-scale utility and industrial applications [52]. It includes specific testing procedures to ensure that energy storage systems meet performance and safety requirements, by evaluating energy Capacity, Round-trip efficiency, Lifespan and Safety features [52].

3.3. Firefighting methods applicable to LIB

Lithium-ion (LIB) battery fires present unique challenges that differentiate them from conventional or traditional fires. These challenges necessitate specialized firefighting methods. Understanding these differences and the appropriate responses is critical for effective fire suppression and safety.

Lithium-ion battery fires are different from conventional fires due to chemical composition, thermal runaway and reignition risk [14]. Lithium-ion batteries contain flammable electrolytes that can ignite when the battery is damaged or malfunctions. Thermal runaway is a self-sustaining reaction that can occur in batteries, releasing a large quantity of heat and perhaps causing the battery to explode. Even after the flames are extinguished, lithium-ion batteries can reignite due to damage and heat.

Conventional fires can be put out using four main techniques: cooling, isolation, smothering and chemical suppression. However, LIB fires do not follow these standard approaches because part of the fire involves direct chemical reactions between the battery components [14]. Lithium-ion battery fires can be combatted by isolation, cooling, specialized extinguishers, monitor for reignition and professional assistance [48]. Specialized techniques are necessary to combat lithium-ion battery fires, because lithium-ion batteries store a high amount of energy in a small volume, which makes the fires more intense [5, 14]. The reactions within the battery can produce toxic and flammable gases, requiring careful handling, and the significant heat generated by thermal runaway can melt or vaporize materials, complicating extinguishment [9, 14].

Several fire extinguishing agents have been utilized, such as, water, water mist, firefighting foams, and powders. These agents also have side effects on the LIBs [14]. The good electrical conductivity of water makes it unsuitable for extinguishing LIB fires because water may cause short circuits [14]. However, water has a high heat capacity and a high heat of vaporization, making it the ideal cooling agent [14, 24]. Because of its excellent cooling efficiency and inhibitory ability, the water mist is one of the best extinguishing agents. Applying water mist may momentarily increase the rate at which hydrogen fluoride (HF) is produced, but combining it with a surfactant can enhance the water mist's ability to put out fires, and the surfactant aids in absorbing flammable gases [14, 24]. Although they can put out the LIB pack's open flames, agents like carbon dioxide, ABC powder, and 3% aqueous film-form foam cannot stop the fire from starting again [14]. It was found by Qingsong et al. [14] that the fire extinguished by these agents have re-ignition time of 8 to 45 seconds after extinguishing the open flame fire. While Carbon dioxide is not an effective agent for LIB fires, it was observed that extinguishing a battery fire with a CO_2 system is challenging. The flow of the extinguishing agent is reduced when steam condenses into ice and adheres to the pipeline during the emissions of liquid CO_2, [14, 24]. For lithium-ion battery fires, CO_2 fire extinguisher chemicals are therefore not advised [14, 24]. However, while Halons (Halogenated hydrocarbons) may offer partial suppression of a LIB fire, the cessation of Halon application means that the temperature within the cell keeps rising, and the agent is unable to penetrate the cell casing, and they as well cannot prevent the reignition of the LIB fire [14, 24].

3.4. Summary of Chapter 3

In conclusion, Chapter 3 has provided a review of various incidents involving BESS across different regions, highlighting the critical importance of understanding the unique challenges posed by these systems. The reports of case studies from regions with similar climatic and environmental conditions to Namibia, such as Australia and parts of the United States, has offered valuable insights into potential risks and mitigation strategies that are highly relevant to Namibia's context. These incidents underscore the need for rigorous safety standards, proper system design, and comprehensive emergency response protocols to prevent catastrophic failures, particularly in hot and arid environments where the performance and safety of lithium-ion batteries can be compromised.

Key incidents include the Moss Landing Power Plant incident in the US, the APS McMicken explosion, and the Tesla Megapack fire in Australia, among others. These incidents reveal common issues such as thermal runaway, design flaws in fire suppression systems, and inadequate emergency response protocols. The chapter emphasizes the importance of improved safety standards, such as NFPA 855, UL 9540A, IEC 62619 etc., while also acknowledging the need for more robust ventilation and gas detection systems to prevent the accumulation of flammable gases.

The chapter identifies several gaps, including limited case-specific information and inadequate risk analysis. The chapter concludes that while valuable lessons can be drawn from mature energy markets, more localized insights are necessary to ensure the safe and effective deployment of BESS in Namibia.

Chapter 4: Methodology

4.1. Research Design

This research adopted a mixed-method design, combining both quantitative and qualitative approaches to assess fire and explosion hazards in BESS. The study quantitatively analyzed historical incident data of BESS failures and qualitatively evaluated case studies of similar incidents and conducted a Policy and Regulatory Reviews. These qualitative methods provided insights into both real – world experiences and the existing regulatory frameworks surrounding BESS safety.

4.2. Data Collection

To ensure the reliability and relevance of the data, the sources for data collection was selected based on the following criteria: Publications and sources were in English to ensure comprehension and consistency. Sources should be from the past 10 years to reflect the latest advancements and current trends in BESS technology and safety standards. Sources must contain specific keywords such as “Lithium ion”, “LIB”, “Li-ion battery failures”, “BESS accidents,” “BESS Fire hazards,” “BESS Explosion risks,” “Energy storage safety,” “Large-scale BESS,” and “renewable energy integration”. Sources were obtained from accessible and reputable database such as Fraunhofer ISE, IEEE Xplore, ScienceDirect, Google Scholar, and industry-specific database such as NREL and IEC. The collected data was categorized based on Age of the BESS, Type of Application, Size of the BESS, State during the Incident, and Local Conditions for further analysis.

4.3. Data Analysis

Descriptive statistics were used to summarize and understand trends in BESS failures, categorizing data by factors such as system age, application, size of the BESS, operational state during the incident, and local environmental conditions. Inferential statistical methods were then applied to identify significant correlations and draw conclusions from the data. The primary techniques used included Correlation analysis and Statistical Tests.

Pearson correlation was applied to assess the relationships between variables, particularly between fire/explosion incidents and factors such as ambient temperature, age, and size of the BESS. This method was chosen for its ability to measure the strength and direction of linear relationships between continuous variables, providing insights into potential risk factors that could inform mitigation strategies.

Goodness-of-Fit (GOF) Tests were conducted to evaluate how well the observed incident data fit expected distributions. These tests were essential for validating the assumptions underlying the analysis and ensuring accurate risk modeling.

The RStudio programming language was utilized for data analysis and risk assessment due to its robust statistical capabilities. Additionally, Fault Tree Analysis (FTA) was performed to evaluate the risk and reliability of the BESS system, offering a systematic approach to identifying failure pathways and system vulnerabilities.

Chapter 5: Results and Discussion

5.1. Incident Data Overview

An overview of numerous fire and explosion occurrences involving Battery Energy Storage Systems (BESS) in diverse settings and locales is given by the incident data in Table 3. Location, capacity, battery type, application, date of the event, temperature, system age, degree of damage, condition at the time of the incident, root cause, and failed components are among the details included in the data [36]. Average ambient temperature at these locations on the day these incidents occurred were also added separately [53].

Table 3. Historic Fire and Explosion Accidents/Incidents [36].

Location	Application	Power (MW)	Capacity (MWh)	Event Date	Temperature (℃)	System Age (year)	Root Cause	Degree of damage	Application	Condition at the time of the incident	Failed Components	Source URL
Australia, Bohle Plains	VPP	4.0	8.0	2021-04-07	20.6	1.3				Commissioning		https://epri.box.com/s/31jolklmn9pxakjvlx3jgccbt02t6o78
Australia, Brisbane				2020-03-17	26.1	6.7		Explosion				https://epri.box.com/s/7sv3r6qx1g70zvz0k6o2yo614l0mvcj0
Australia, Queensland, Bouldercombe		50.0	100.0	2023-09-26	27.8	0.1		Single container on fire, possible damage to surrounding containers	Integration, Construction, or Assembly	Operational	Balance of plant	https://epri.box.com/s/6iiixec4c24f76rpulzbsxotd4u7zmau

Australia, Victoria, Moorabool	Grid Stability	300.0	450.0	2021-07-30	15	0.0	A leak in the Tesla Megapack's internal coolant system was determined to be the most likely cause.	Fire	Integration, Construction, or Assembly	Construction, Commissioning	Balance of plant	https://epri.box.com/s/zefzcuifdg33gwkepnvhcb2u4kov0rjy
Belgium, Drogenbos	Frequency Regulation	6.0		2017-11-11	6.82							https://epri.box.com/s/oyy8xw3hzgy5btfxqb31233din583w0p
China, Beijing	Solar Integration		25.0	2021-04-16		2.0	Though it is not coclusive, the paper lists a number of potential causes. Cell flaws, dust/sand buildup, overcharging, and other factors were among the potential reasons.	Explosion. Death of 2 firefighters, injury of 1 fighter, 1 missing employee of the power station and property damage.		Construction, Commissioning		https://epri.box.com/s/s8mj93w4md9dng0wygznqrolcpjm7z2r
China, Hainan	Solar Integration	25.0	50.0	2022-10-20	10	0.0		One of the ten battery containers destroyed		Commissioning		https://epri.box.com/s/x0ssb49bjyryp6iin2pwlxrtt8dlgddi
China, Shanxi				2017-03-07	20							https://epri.box.com/s/imcjofqfulicog9sx6s7t6w3ccqi5xn8
China, Shanxi				2017-12-21	-1.7							https://epri.box.com/s/senpq3dpc0eta14d5bf8vhpluy9eh28r

China, Xiangzhou District, Zuhai City				2023-08-19								https://epri.box.com/s/hsn360uwto0vl70f5xa8w3s7jftty6wv
France, Ariege, Perles-et-Castelet	Hybrid Supercacitor plus Storage System	0.5	0.5	2020-12-01	11.1	0.0	Insulation and Electrical failure	Fire		Commissioning, testing		https://epri.box.com/s/y2bd6xooip6lmz0mlks13a8roluq8xx0
France, Martinique, Saint-Esprit	Solar Integration			2023-09-29	32.8			Explosion		Operational		https://epri.box.com/s/u7ajvcm8olu2ozwxysmktj7r2cgi8by4
France, New Caledonia, Boulouparis	Solar Integration			2021-07-13								https://epri.box.com/s/ns5555g1tdjckk6je8fqzocsglo6b81c
France, Saint-Trivier-sur-Moignans				2023-03-28	12.8							https://epri.box.com/s/bf44bu8ckxdhvy6skkr5snu5gqq3jro7
France, Saucats, Barban		105.0	98.0	2023-08-22	36.1	0.0		Single container damaged		Pre-commissioning		https://epri.box.com/s/mde86q61vrb3dlt7799p4jsvz4wzjg99
France, Vitry-sur-Seine				2019-09-16	27.2					Maintenance		https://epri.box.com/s/pe78cd6cz2rtpxqnq77asduhxes3r5hx
Germany, Neuhardenberg	Solar Integration and Frequency Regulation	5.0	5.0	2021-07-18	26.1	5.0						https://epri.box.com/s/8dfqc4jrjheesqlkbevphiia1snne22t
Gogyeong-myeon, Gyeongsangbuk-do, South Korea	Solar Integration		4.0	2021-03-11	17.8							https://www-newspim-com.translate.goo

												g/news/view/20210311001212?_x_tr_sl=auto&_x_tr_tl=en&_x_tr_hl=en-US
Hwaseong city, South Korea				24/06/2024			Exploding lithium batteries.	22 employees dead, injuring 8 employees.		Manufacturing		
Japan, Kagoshima, Isa	Solar Integration			2024-03-27	17.2							https://epri.box.com/s/xj4wegae6xpnoc3xm3lpsyxoxllh8q5v
Neermoor (Lille district), Germany				24/04/2024				Injury of two firefighters. 500K euros of damage		Storage		
South Korea, Chungcheongbuk-do, Yeongdong	Solar Integration		5.989	2018-09-01	30	0.7				Charged, inactive		https://epri.box.com/s/r319tohqeytg1ylwiu4ay6y9yee1jphu
South Korea, Chungcheongnam, Taean	Solar Integration		6.0	2018-09-07	26.1	0.0				Installation		https://epri.box.com/s/z60hm5iurktmp28a8aa19pye56is7dqr
South Korea, Gangwon, Samcheok	Solar Integration		2.662	2018-12-22	12.2	1.0				Charged, inactive		https://epri.box.com/s/anlmrsfubbd8h11lcf5lqugzg6cp3vrr
South Korea, Gimhae	Solar Integration		2.2	2019-10-27	17.8	1.5			Operation	Charged, inactive	Controls	https://www.sciencedirect.com/science/article/abs/pii/S2352152X2301589X
South Korea, Gunwi	Solar Integration		1.5	2019-09-29	30	1.8		Fire	Operation	Discharging	Controls	https://www.sciencedirect.com/science/article/abs/pii/S2352152X2301589X

South Korea, Gunwi-gun, Gyeongsangbuk-do	Solar integration	0.45	1.5	2022-01-17	5.0	3.0		Fully burnt. Explosion	Manufacturing	Operation. Fully charged	Controls	https://epri.box.com/s/05zf0bihru9sdsw2x8wt1g76n87tsm13
South Korea, Gyeonggi, Yongin	Frequency Regulation		17.7	2018-10-18	17.8	2.6			Operation	Maintenance	Controls	https://epri.box.com/s/uiszql67kemhdc4cou14ck9syfq18oiw
South Korea, Gyeongsangbuk-do, Mungyeong	Solar Integration		4.16	2018-11-21	6.1	0.9				Charged, inactive		https://epri.box.com/s/i27asaogje51090edm5d5euob2y3uizf
South Korea, Hadong	Solar Integration		1.3	2019-10-21	21.7	1.3		Fire	Integration, Construction, or Assembly	Charged, inactive	Balance of Plant	https://www.sciencedirect.com/science/article/abs/pii/S2352152X2301589X
South Korea, Haenam	Solar Integration			2020-05-27	21.1	2.2	Overcharge	Fire	Manufacturing		Cell/Module	https://epri.box.com/s/0fs9nzeoa7c4ohogrb9qjtsj1yv13eqk
South Korea, Hongseong	Solar Integration			2021-04-06	20	3.0			Operation		Controls	http://www.businesskorea.co.kr/news/articleView.html?idxno=64241
South Korea, Incheon	Energy Shifting	103.0		2022-09-06	27.2					Operational		https://epri.box.com/s/j9r6qo81e9zhnx01efcqncywmd3dlfaw
South Korea, Jangseong-gun	Solar Integration			2022-05-02	18.9							https://epri.box.com/s/2fp8fm04q3qdh972k94r10unw20rpi7a
South Korea, Jeju	Solar Integration		0.18	2018-09-14	27.2	4.0			Integration, Construction, or Assembly	Charging	Balance of plant	https://epri.box.com/s/i6g42c5qefetay9563z67ge0qvdkfghj

South Korea, Jeollanam-do, Damyang-gun, Mujeong-myeon, Deokgok-ri	Solar Integration	2.5	9.1	2022-12-08	27.2	5.5		System destroyed		Operational		https://epri.box.com/s/3jzjdsmtv1q186pt0gbrop8zx506vv6d
South Korea, Jeollanam-do, Yeongam-gun, Geumjeong-myeon	Solar Integration		251.0	2022-12-27	6.1	1.8		At least one of 24 BESS buildings destroyed		Operational		https://epri.box.com/s/aroriw7lw45hgemvr1ka6ha56slj7arf
South Korea, Nam-gu, Ulsan	Peak Load Reduction	10.0	50.0	2022-01-12	2.8	2.0		Fully burnt		Operational		https://epri.box.com/s/d0q5n4o49hbo4crjpsekltu735fwdcx2
South Korea, North Chungcheong, Jecheon	Demand Charge Mgmt		9.316	2018-12-17	10.6	1.0				Charged, inactive		https://epri.box.com/s/fhj58frb2mfj9ilbf03w69jpi88mxq66
South Korea, North Gyeongsang, Chilgok	Solar Integration		3.66	2019-05-04	28.9	2.3				Charged, inactive		https://epri.box.com/s/i0wtmevs5cqa5zpnt0rntxda01auvtr0
South Korea, North Gyeongsang, Gyeongsan	Frequency Regulation		8.6	2018-05-02	16	1.8			BMS Design failure(insulation distance)	Maintenance		https://epri.box.com/s/0ohn1fnl9gtmk14l57uitoa9kpwy2sgu
South Korea, North Gyeongsang, Yeongju	Solar Integration		3.66	2018-11-12		0.8				Charged, inactive		https://epri.box.com/s/43lsvu2vm9y3dqjh2qnu3a53r9mdiq9w
South Korea, North Jeolla, Gochang	Wind Integration		1.46	2017-08-02	33.3	0.0				Installation		http://www.motie.go.kr/motie/ne/presse/press2/bbs/bbsView.do?bbs_cd_n=81&bbs_seq_n=161771
South Korea, North Jeolla, Gunsan	Solar Integration		18.965	2018-06-15	27.2	0.5			Poor construction	Charged, inactive	Deterioration of insulation due to	https://epri.box.com/s/cn3knmg79a4egtqe1d71dcplcd7w5bqz

											environmental factors	
South Korea, North Jeolla, Jangsu	Solar Integration		2.496	2019-01-15	9.4	0.8				Charged, inactive		http://www.motie.go.kr/motie/ne/presse/press2/bbs/bbsView.do?bbs_cd_n=81&bbs_seq_n=161771
South Korea, North Jeolla, Jangsu	Solar Integration		1.027	2019-05-26	27.8	1.0				Charged, discharging		https://epri.box.com/s/263vxd5ntm28ftn38frvmp55xsxtqjrn
South Korea, Pyeongchang	Wind Integration		21.0	2019-09-24	23.3	2.7			Operation	Charged, inactive	Controls	https://www.sciencedirect.com/science/article/abs/pii/S2352152X2301589X
South Korea, Sejong	Demand Charge Mgmt		18.0	2018-07-28	36.1	0.0				Installation		https://epri.box.com/s/88x2jj4ifudyfgt71w1m94h490zik8kx
South Korea, South Chungcheong, Cheonan	Solar Integration		1.22	2018-11-12	16.1	0.9			Operation	Charged, inactive	Controls	https://epri.box.com/s/cp38w3knshyv955p1xftmm8j73c7fgvb
South Korea, South Gyeongsang, Geochang	Wind Integration		9.7	2018-07-21	34.4	1.6				Charged, inactive		https://epri.box.com/s/fia4tnq8kdhkf4dylg8dxpft47teldvk
South Korea, South Gyeongsang, Geochang	Solar Integration		1.331	2018-11-22	10	0.6				Charged, inactive		https://epri.box.com/s/7rc6lizifau3ebbq1ziistfob1dxtzco
South Korea, South Gyeongsangnam, Yangsan	Demand Charge Mgmt		3.289	2019-01-14	11.1	0.8				Charged, inactive		https://epri.box.com/s/jty3zsu5x4dqn76lbv5ihjjs0rl67kv5

South Korea, South Jeolla, Haenam	Solar Integration		2.99	2018-07-12	32.2	0.6				Charged, inactive		https://epri.box.com/s/9y5d7r6wtrlc81hhburznicng1ukdf4a
South Korea, South Jeolla, Wando	Solar Integration		5.22	2019-01-14	7.2	1.2			Operation	Charging	Controls	https://epri.box.com/s/5o1v320dpcitnqqzu5kl0hj99b3lnzgl
South Korea, South Jeolla, Yeongam	Wind Integration		14.0	2018-06-02	28.9	2.5			BMS System Error	Maintenance		https://epri.box.com/s/tbb7gdkagkvntj71rx94alio18d44t8i
South Korea, Ulsan	Demand Charge Mgmt		46.757	2019-01-21	8.3	0.6				Charged, inactive		http://www.motie.go.kr/motie/ne/presse/press2/bbs/bbsView.do?bbs_cd_n=81&bbs_seq_n=161771
South Korea, Yesan	Solar Integration		1.5	2019-08-30	26.1	1.7		Fire	Operation	Charged, inactive	Controls	https://www.sciencedirect.com/science/article/abs/pii/S2352152X2301589X
South Korea, YoungCheon City	Solar Integration		8.4	2021-03-11	31.1			$770k est.				
Sweden, Gothenburg, Vastra Frolunda			0.875	2023-04-26	7.8	0.0	Investigation concludes that the most likely cause was a leak into the battery cell during pressure testing of the cooling system, which caused a short circuit	Explosion	Integration, Construction, or Assembly	Pre-commissioning	Balance of plant	https://epri.box.com/s/56nj1tgilz9th2tn8lc4t5223v63epyh

							and thermal runaway.					
Taiwan, Lanyu		1.1		2023-12-28	25.6					Operational		https://epri.box.com/s/57ner8t8d0ibjz0lfyqywjk3x09ze2qp
Taiwan, Taichung City, Longjing District	Solar Integration	1.0	1.0	2022-03-30	27.8	2.0		Fire		Operational		https://epri.box.com/s/rj5d8qsuzzk065fhonkhgwxllqkmr7kv
Taiwan, Taichung City, Longjing District				2023-07-04	32.8			At least one container was damaged. Burn extent was reported to be 30 sq. m.				https://epri.box.com/s/qtv3dwmlcwtbh3wqvs9kyycf2ns494ax
UK, Liverpool	Frequency Regulation	20.0	10.0	2020-09-15	26.1	1.5	Thermal runaway, which caused the combustible gases the cells produced to ignite, is thought to be the cause.	Explosion	Manufacturing		Cell/Module	https://epri.box.com/s/ro9v9uyekoen9638b9e5etppd97rq113
US, AZ, Chandler		10.0	40.0	2022-04-18	33.9	3.0				Operational		https://epri.box.com/s/6g99qrtf68vg658xxakt00zspf78cg3d
US, AZ, Surprise	Volt Reg., PQ, Solar int.	2.0	2.0	2019-04-19	36.1	2.1	Cell defect	Explosion	Manufacturing		Cell/Module	https://epri.box.com/s/eapg9tmt5bize3yqjb0wmz1rj5z07b9i
US, CA, Moss Landing	Solar Integration	300.0	1200.0	2021-09-04	20	0.8		Scorched racks, melted wires	Integration, Construction, or Assembly		Balance of plant	https://epri.box.com/s/wq43x5o5g

												6lh4oqaxud08i6324ti2qvp
US, CA, Moss Landing	Solar Integration	100.0	400.0	2022-02-13	21.1	1.0		Burnt racks	Integration, Construction, or Assembly	Operational	Balance of plant	https://epri.box.com/s/t13m9uitve0393j2wqmirmyvwikgjzye
US, CA, Moss Landing	Energy Shifting, Ancillary Services	182.5	730.0	2022-09-20	22.8	0.5			Integration, Construction, or Assembly Design	Operational	Balance of plant Controls	https://epri.box.com/s/ajpl489n7uisy4dtvwa4c4cqnbeduua7
US, CA, Moss Landing		182.5	730	20/09/2023			Possible Moisture					
US, CA, Rio Dell	Solar Integration / Backup			2022-08-03	18.9	4.0		Explosion. Nearby building damage		Operational		https://epri.box.com/s/wftn1n71z070g32q593kfq75c4u31w12
US, CA, Santa Ana	Industrial			2024-07-17	25.6							https://www.ocregister.com/2024/07/17/fire-at-energy-storage-facility-prompts-evacuations-in-industrial-area-of-santa-ana/
US, CA, Valley Center		140.0	560.0	2022-04-05	18.9	0.2		Damage to single rack	Design	Operational	Controls	https://epri.box.com/s/f39znipkdb3bbvcanu9p7j5w6tnpy8ry
US, CA, Valley Center		140.0	560.0	2023-09-18	22.8	1.6		Damage to single container		Operational		https://epri.box.com/s/e4qgw3d06rhvyu6q3qcozxp2ock2lvas
US, IL, LaSalle	Solar and Wind Integration, Frequency	36.0	36.0	2021-07-19	29.4	1.6			Integration, Construction, or Assembly		Balance of Plant	https://epri.box.com/s/sb4xtyqqa1guk2bfbuoo29m9ga1z9rld

	Regulation											
US, MI, Standish	Demand Charge Mgmt			2021-04-19	9.4			Fire				https://www.wsgw.com/standish-battery-installation-fire-causes-shelter-in-place-no-adverse-conditions-found/
US, NY, Chaumont	Solar Integration	5.0	15.0	2023-07-27	26.11	0.4			Design	Operational	Controls	https://epri.box.com/s/2ab8y88a0mu1p295xabx0lxx7vmn5lrc
US, NY, East Hampton	Resiliency, Utility Peak Reduction	5.0	40.0	2023-05-31	18.9	4.8				Operational		https://epri.box.com/s/g5u5a66gkp7jtaljoefyja4e6xwj993p
US, NY, Warwick	Energy Shifting, Backup	8.0	36.0	2023-06-26	22.2	0.1		Multiple racks destroyed	Design	Operational	Balance of plant	https://epri.box.com/s/alxfty4t2nwmffw08o4vjju68p1xj7et
US, NY, Warwick	Energy Shifting, Backup	4.0	17.9	2023-06-27	25.0	0.1		It is unclear if this site experienced a fire, but the system "was experiencing problems" and fire alarms were triggered. The batteries were later removed from the site to be disposed of.	Design Integration, Construction, or Assembly	Operational	Balance of plant Controls	https://epri.box.com/s/0w7jtekm9sw0w84g51ap97a2ohaevka4

US, OR, Tualatin	Manufacturing/Testing			2019-04-11	12.8	0.0		Fire		Testing		https://epri.box.com/s/y4wwm0713u4n2h5coidatjakmi0zfb38
US, PA, Millvale	Solar Integration			2023-01-30	2.8			System destroyed with severe damage to basement		Operational		https://epri.box.com/s/lf29l81sve6q2m4ce3zmundll47oohed
US, WI, Franklin				2016-08-10	26.7	0.0		Fire		Assembly, Installation		https://epri.box.com/s/a634woxxwjqf2bx29k6fhsxdyfc2t1m6
USA, CA, San Diego	Energy shifting	250.0	250.0	2024-05-15	16.7	3.7	Caused by a chain reaction that is thermally runaway					https://epri.box.com/s/xr9v1ji8bxbs9hwjdrgvuiwqe98zvie0
USA, ID, Melba	Distribution Resource	2.0	8.0	2023-10-02	17.8	0.0		Several stacks appeared to be burnt	Design	Pre-commissioning	Balance of Plant	https://epri.box.com/s/xg87c55wzkxxnp5c4g215tdntwytp1s9
USA, Wyoming, Yellowstone National Park	Solar Integration			2022-09-06	27.2			Exterior of building was undamaged.				https://epri.box.com/s/m46rum88qse1bamxhsoqiprxteaanyze

5.2. The historical fire/explosion incident Pearson correlation Analysis

5.2.1. Fire/Explosion Incident and System Age

In this section, the relationship between fire/explosion incidents and system age (years) of the BESS was analysed. The analysis aims to determine if there is a statistically significant correlation between these two variables, using the Pearson correlation coefficient. The goal is to identify whether older systems experience more incidents compared to newer systems. The Pearson correlation is plotted in Figure 18.

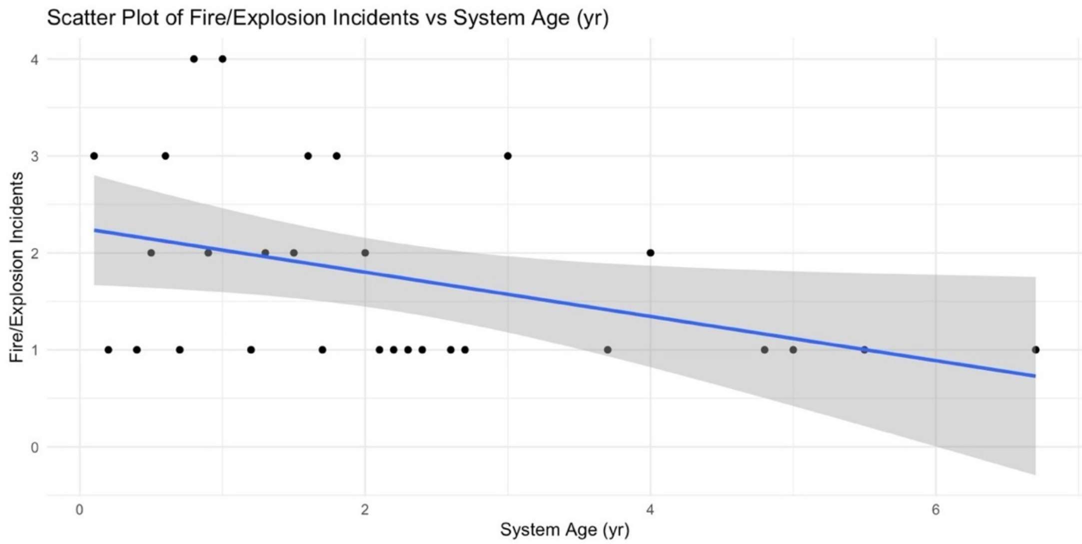


Figure 18. Pearson correlation of Fire and Explosion Incidents and System Age.

Table 4. The Pearson correlation results of Fire/Explosion Incident and System Age

Test statistic (t – value)	Degree of freedom	P - value	95% Confidence Interval	Correlation coefficient (r)
-2.2014	27	0.0336	$-0.6619638, -0.0275331$	-0.3901022

The Pearson correlation coefficient between the number of fire/explosion incidents and age of the BESS on twenty-seven degrees of freedom ($df = 27$) is $r =$

-0.3901022 indicating a moderate negative correlation. The 95% confidence interval for this correlation ranges from -0.6619638 to -0.0275331. This correlation is statistically significant at the 5% significance level as shown in figure 18, with a $p-value = 0.033643$, which is less than 0.05.

Therefore, the data does not provide strong evidence that more of these incidents occur in aged systems. Many incidents occur also quite early in the life of BESS with a number occurring as early as installation time or soon after installation. This shows that there are other factors that contribute to Fire/Explosion incidents. Given that most large-scale BESS installations are relatively recent, the available data on system aging effects remains limited. Therefore, conclusions regarding the influence of system age on fire and explosion incidents should be interpreted with caution. Long-term data collection over at least one to two decades will be necessary to establish clear trends.

5.2.2. Fire/Explosion Incident and Capacity (MWh)

The Pearson correlation analysis was carried out in this section, to determine whether is a relationship between the capacity (MWh) of the BESS and the occurrence of fire/explosion incidents. Aiming to investigate whether larger capacity systems are safer or more prone to incidents compared to smaller capacity systems. By exploring this correlation, we can better understand whether system capacity plays a significant role in the risk profile of BESS installations. The Pearson correlation is plotted in Figure 19.

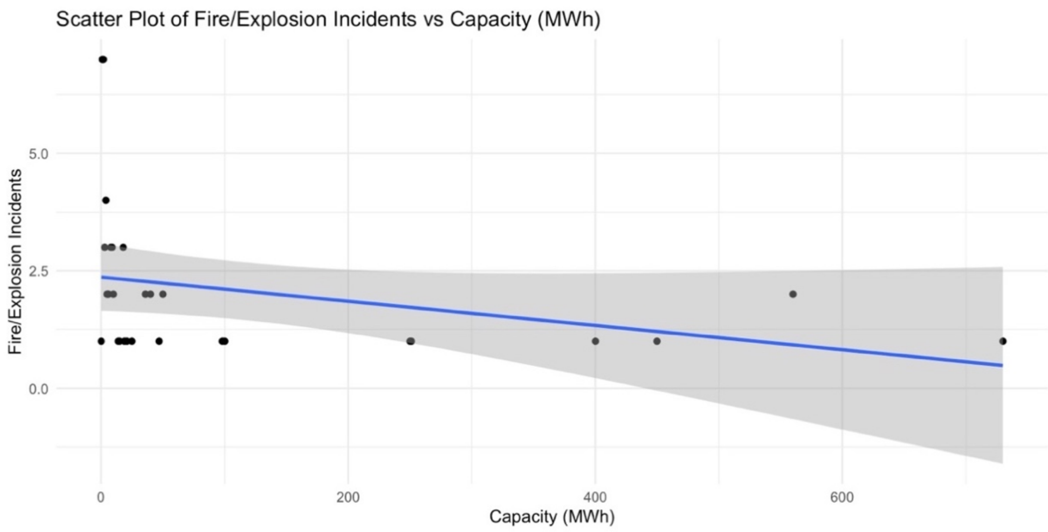


Figure 19. Scatter plot of Fire/Explosion incidents and Capacity (MWh).

Table 5. The Pearson correlation results of Fire/Explosion Incident and Capacity

Test statistic (t – value)	Degree of freedom	P - value	95% Confidence Interval	Correlation coefficient (r)
−1.6289	26	0.1154	−0.60832089, 0.07757786	−0.3043065

The Pearson correlation coefficient between the number of fire/explosion incidents and Capacity (MWh) of the BESS on twenty-six degrees of freedom ($df = 26$) is $r = -0.3043065$ indicating a weak moderate negative correlation. The 95% confidence interval for this correlation ranges from $-0.60832089, \ 0.07757786$. This correlation is not statistically significant at the 5% significance level as shown in figure 19, with a $p - value = 0.1154$. Therefore, the data does not provide strong evidence of a relationship between system capacity and the number of fire/explosion incidents.

Although there is a slight tendency for incidents to decrease as capacity increases, and this is due to the fact that smaller installations are done by small companies (local electricians) that are not on the same level as major companies that are in larger installations, reason being that there are more measures in place to prevent accidents. Many incidents occur with low system capacity as shown in figure 19. The analysis presented is based solely on reported and recorded incidents, and as such, it is subjected to inherent bias due to the lack of data on total BESS installations. Consequently, while the findings indicate a higher number of incidents in smaller BESS systems, this observation should be interpreted with caution, as the total population of installed systems is unknown.

5.2.3 C – rate and the Fire/Explosion Incidents

The Pearson correlation analysis in this section, investigates the relationship between the C – rate (the charge or discharge rate) of the BESS and the likelihood of fire/explosion incidents. The analysis seeks to determine whether systems operating at higher C – rate are more prone to safety incidents or if higher C – rates might be associated with better safety performance.

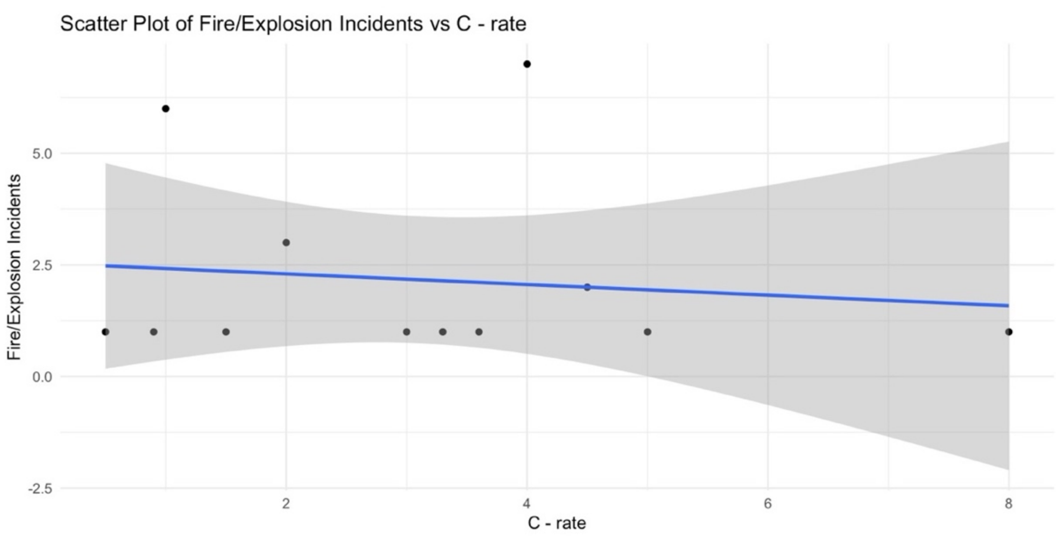


Figure 20. C – rate and the Fire/Explosion Incidents scattering graph

The graph or scattering presented in figure 20 present a relationship between C – rate of BESS and the number of fire/explosion incidents, whereby, C – rate on the x-axis represents the charge or discharge rate relative to the battery's maximum capacity. The blue line represents a linear regression fit to the data points, indicating a weak negative correlation between the C – rate and fire/explosion incidents. As the C – rate increases, the number of incidents tends to decrease slightly (this could be due to data limitations).

Table 6. The Pearson correlation results of Fire/Explosion Incident and C - rate

Test statistic (t – value)	Degree of freedom	P - value	95% Confidence Interval	Correlation coefficient (r)
−0.3828	10	0.7099	−0.6492950, 0.4873384	−0.120174

The graph and results in Table 6 suggests a weak relationship between the C – rate and fire/explosion incidents, where a higher C – rate is slightly associated with fewer incidents. However, the confidence interval and scatter of points suggest the relationship is not strong or highly predictable.

The Pearson correlation between C – rate and fire/explosion incidents were carried out using the data presented in table 3 above, whereby the C – rate was calculated using Capacity (MWh) and Power (MW). Due to limited data of Power (MW) missing in Table 3 of the incident database plants (We could only use Capacity of the incident that had Power data provided). The analysis provided the results as presented in figure 20.

5.2.4. Fire/Explosion incidents and Average Location temperature

In this section, the relationship between fire/explosion incidents of the battery energy storage system (BESS) and average location temperature (℃) was analysed. The analysis aims to determine if there is a statistically significant correlation between fire/explosion incidents and average location temperature, using the Pearson correlation coefficient. The goal is to identify whether locations with high average temperature experience more incidents compared to location with lower average temperatures. The Pearson correlation is plotted in Figure 21.

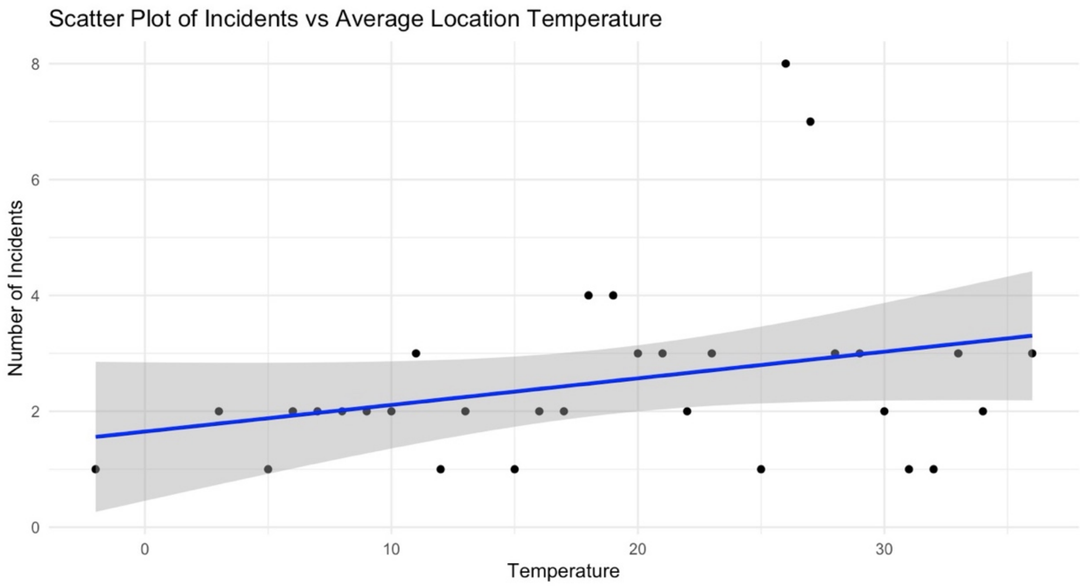


Figure 21. Scatter plot of Fire/Explosion incidents and Average Location temperature (℃)

Table 7. The Pearson correlation results of Fire/Explosion Incident and Average Location temperature (℃)

Test statistic (t − value)	Degree of freedom	P - value	95% Confidence Interval	Correlation coefficient (r)
1.6824	29	0.1032	−0.06277878, 0.59017549	0.2981947

The Pearson correlation coefficient between the number of fire/explosion incidents and average location temperature of the degrees of freedom ($df = 29$) is $r = 0.2981947$ indicating a weak positive correlation, but it is not statistically significant with a p – value of 0.1032. The data suggests a potential trend that higher temperatures might be associated with more incidents, but give a p – value and confidence interval, it cannot be confidently conclude that temperature has a meaningful or consistent impact on the number of incidents based on this analysis.

5.2.5. State during Accident/Incident

In this section, the Pearson correlation analysis tested the relationship between the operational states of BESS and the occurrence of fire/explosion incidents. It examined which operational states are most prone to incidents, providing insights into when BESS systems are at the highest risk for accidents.

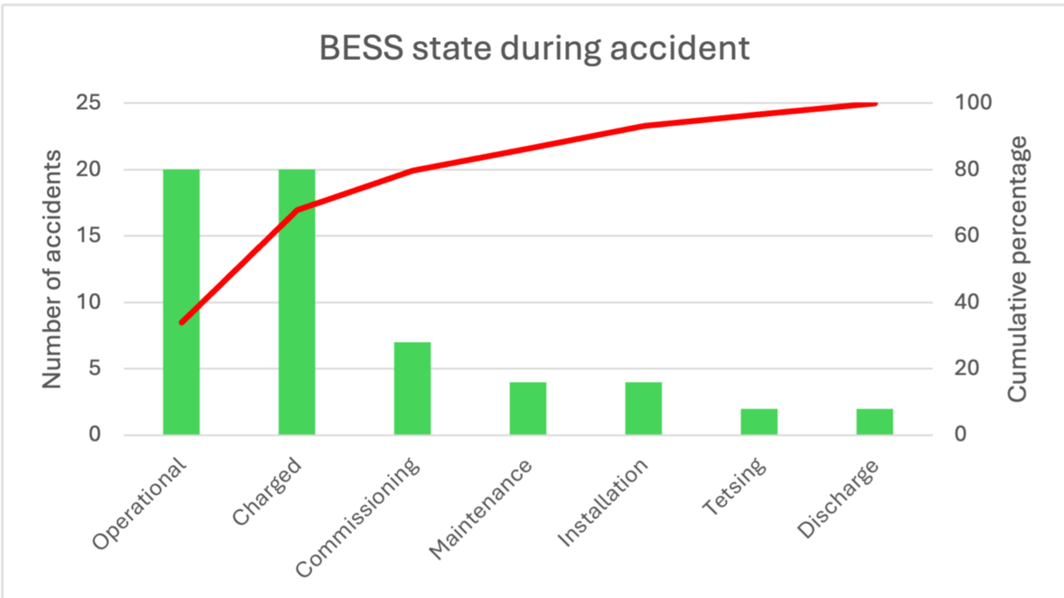


Figure 22. Analysis of Battery Energy Storage System States during Accidents.

The distribution of incidents by different operational states are presented above, whereby, it indicates that the highest risks of fire/explosion incidents occur when systems are in their operational or charged states, likely because these are the most demanding and dynamic phases for equipment. This implies a need for enhanced safety measures and monitoring during these states to mitigate risks. States involving transitions or controlled processes, such as commissioning and testing, are less risky but still require attention to prevent incidents.

While the operational and charged state are individually the most accident-prone in the BESS contributing 50% of all accidents, the combined contribution of the other states – commissioning, maintenance, installation, testing, and discharge – is equally significant. When these states are added together, they collectively account for several incidents comparable to the operational and charged states.

The cumulative line (red) reaches 100% at the Discharge state as presented in figure 22 indicating that by addressing safety in the top three states (Operational, Charged, and Commissioning), the majority of accidents (about 80%) can be prevented.

This highlights the importance of maintaining vigilance across all stages of BESS operation, as neglecting safety protocols during any of these phases can lead to a substantial number of accidents.

Incidents occur in both standard and non-standard operating modes, but non-standard modes are more dangerous due to their rarity and the increased risk associated with unpreparedness. Additionally, a charged system presents greater risk compared to a discharged one, due to the higher potential energy or stress involved.

Charge and Discharge are states that are also part of operational state or maintenance state, which can then increase the risk of incidents.

5.3. Goodness-of-fit test (GOF) and Test of Independence between variables

The Chi-squared Goodness of Fit test is a statistical method used to determine whether the distribution of a categorical or discrete variable matches a specific hypothesized distribution. This test is particularly useful for evaluating whether observed proportions of outcomes align with expected proportions. Analysts often use this test to evaluate if categories occur in equal proportions or to compare observed data with a predefined distribution, such as the Poisson distribution.

The goodness of fit test works by calculating the squared differences between observed and expected frequencies, which helps quantify the deviations. If the resulting p – value is below a threshold, typically 0.05, it suggests that the observed frequencies significantly differ from the expected ones, implying a poor fit between the data and the hypothesized distribution. The historical data presented in Table 3 was used to carry out this statistical analysis.

5.3.1. Fire/Explosion Incident and System Age (yr)

The goodness-of-fit test (GOF) was applied to evaluate how well the observed distribution of BESS fire/explosion incidents across different system age categories aligns with the expected distribution.

Table 8 present the contingency table of GOF test for fire/explosion and system age, whereby the expected frequencies is 9.6, which was obtained by using the Uniform distribution. Meaning:

Expected incidents of each group = Total observed incidents / Number of age groups.

Table 8. Contingency table of GOF test for fire/explosion and system age

System Age Bins (yr)	Observed	Expected
(0 - 1)	17	9.6
(1 - 2)	16	9.6
(2 - 3)	8	9.6
(3 - 4)	4	9.6
(4 - 5)	3	9.6

The Chi-square GOF results for Fire/Explosion incidents and System Age (yr) is presented in Table 8.

Table 9. Chi-square GOF results for Fire/Explosion incidents and System Age (yr)

X^2	Degree of freedom	P - value
18.042	4	0.001211

The result in Table 9 suggests that the observed distribution of BESS fire/explosion incidents does not fit the expected distribution, with a p – value well below the conventional significance level of 0.05. This shows that there is a statistically significant difference between the observed and expected frequencies of incidents across system age categories, with strong evidence against the null hypothesis.

5.3.2. Fire/Explosion Incidents and Capacity (MWh)

The Chi-square Goodness-of-fit (GOF) test was applied to assess whether the observed distribution of BESS fire/explosion incidents across different capacity categories follows a hypothesized or expected distribution.

Table 10 represent the contingency table of fire/explosion incidents and capacity (MWh), whereby capacity was divided in three groups which are represented by the rows, number of fire/explosions are represented in columns. 1 incident, 2 incident, 3 incident, 4 incident and 5 incident represent number of incidents of a system at a particular capacity (for example for low capacity, there is 1 system that had 1 incident.

Table 10. The Contingency table of Fire/Explosion incidents and Capacity (MWh)

Capacity Group(MWh)	**1 Incident**	**2 Incidents**	**3 Incidents**	**4 Incidents**	**7 Incidents**
Low Capacity (0-10)	1	3	3	1	2
Medium capacity (11-100)	8	3	1	0	0
High capacity (101 +)	5	1	0	0	0

The Chi-square GOF results for fire/explosion incidents and capacity (MWh) is presented in Table 11 below.

Table 11. Chi-square GOF results for Fire/Explosion incidents and Capacity (MWh)

X^2	Degree of freedom	P - value
13.75	8	0.08852

According to the null hypothesis, the observed and expected number of occurrences across the various capacity categories do not differ significantly. Since the p – value is 0.08852, which is greater than a typical threshold of 0.05, the null hypothesis rejection failed. This mean that there is no enough evidence in the data to support the idea that the distribution of fire and explosion occurrences between capacity groups differs statistically significantly from what was predicted. This shows that the distribution of fire/explosion incidents is consistent with what is expected, given the system capacities, and there is no evidence that certain system capacities are more or less likely to experience incidents than expected.

5.3.4. Fire/Explosion Incidents and State during Accident/Incident

The GOF was carried out to evaluate the relationship between BESS fire/explosion incidents and the operational state during the accident. The results of the GOF test are presented in Table 12.

Table 12. Chi-square GOF results for Fire/Explosion incidents and State during Accident

X^2	Degree of freedom	P - value
25.09	4	0.00004824

Given that the $P - value = 0.00004824$ is much smaller than the common significance level of 0.05, gets the null hypothesis rejected, which implies that there is a significant difference between the observed fire/explosion incidents and the expected distribution.

Table 13. The Contingency table of Fire/Explosion incidents and State during Accident

State during accident	Observed	Expected
Operational	20	11
Charged	20	11
Commissioning	7	11
Maintenance	4	11
Installation	4	11

5.3.5. Fire/Explosion Incidents and Average Location Temperature (℃)

The goodness-of-fit test (GOF) was applied to evaluate if the temperature ranges significantly influence the frequency of fire/explosion incidents in BESS. Temperature is a crucial factor, as extreme levels can stress batteries, potentially leading to thermal runaway and safety incidents. By testing for a statistical association, we aim to determine if specific temperature ranges correlate with higher incident frequencies.

The contingency table is presented in Table 14, which shows frequencies of fire/explosion incidents (represented by various counts) across temperature ranges (intervals).

Table 14. Contingency table for fire/explosion incidents and Average location temperature

Temperature Groups (℃)	1 Incident	2 Incidents	3 Incidents	4 Incidents	7 Incidents	8 Incidents
-2 - 5	1	1	0	0	0	0
5 - 10	1	4	0	0	0	0
10 - 11	0	1	0	0	0	0
11 - 15	1	1	1	0	0	0
15 - 20	1	2	0	2	0	0
20 - 25	0	1	3	0	0	0
25 - 30	1	0	2	0	1	1
30 - 36	2	2	1	0	0	0

The results of the GOF test of fire/explosion incidents and Average location temperature are presented in Table 15 below.

Table 15. GOF test results fire/explosion incidents and Average location temperature

X^2	Degree of freedom	P - value
36.137	35	0.4153

Based on the Chi-square test results as presented in Table 15, shows a non-significant p – value of 0.4153, suggesting that there is no statistically significant association between the two variables. This outcome also suggests that, within this data, temperature intervals alone (or temperature alone) do not explain the frequency of incidents.

5.4. The Chi-square Test of Independence

Chi-squared test of independence assess whether there is a relationship between two categorical variables. Essentially, the test examines if the values of one variable are influenced by those of the other. When the variables are independent, knowing the value of one does not reveal any information about the other.

The chi-squared test of independence consists of the following hypothesis:

- The Null Hypothesis: the variables are independent (relationship does not exist)
- Alternative Hypothesis: there is a relationship between the two variables.

5.4.1. Fire/Explosion Incidents and System age

The Chi-squared test of independence between fire/explosion incidents has been performed, the contingency table is presented in Table 16 below, represent the distribution of observed counts of fire/explosion incidents categorized by System age. The system age is categorized into 5 groups, while number of accidents are classified as Low, Medium and High.

Table 16. Contingency table of Test of Independence for fire/explosion and system age

Age categories (yr)	Number of Accident Low	Number of Accident Medium	Number of Accident High
0 - 1	3	4	1
1 - 2	3	4	1
2 - 3	6	1	0
3 - 4	1	1	0
4 - 5	1	1	0

The results of the Test of independence for fire/explosion and system age are presented in Table 17 below.

Table 17. Test of independence results for fire/explosion and system age

X^2	Degree of freedom	P - value
5.99	8	0.648

Given the high p – value of 0.648, this suggest that there is no statistically significant association between the two variables. This means that the system age does not seem to influence the occurrence of fire/explosion incidents in a way that is detectable using this analysis.

5.4.2. Fire/Explosion Incidents and Capacity (MWh)

The Test of Independence between the fire/explosion incidents and Capacity result is presented in Table 18.

Table 18. Test of Independence results of the fire/explosion incidents and Capacity

X^2	Degree of freedom	P - value
112	108	0.3767

Given that the p – value (0.3767) is greater than the standard significance threshold of 0.05, the null hypothesis does not get rejected. It indicates that there is no statistically significant relationship between fire/explosion incidents and capacity, suggesting that these variables are independent.

5.4.3. Fire/Explosion Incidents and State during Accident

A chi-square test of independence was carried out to examine the relationship between the occurrence of fire/explosion incidents and the state in which the accident occurred. The result of the test is presented in Table 19.

Table 19. Test of Independence results of the fire/explosion incidents and State during Accident

X^2	Degree of freedom	P - value
25	4	0.00004824

The null hypothesis in the Chi-square test of independence states that fire/explosion incidents and State during accident are independent. Given the very small p – value of 0.00004824, the null hypothesis is rejected, concluding that there is a statistically significant association between the two variables. The magnitude of the Chi-square statistic of 25 also suggests a notable difference between the observed and expected frequencies, indicating a strong association between fire/explosion incidents and State during accident.

5.4.4. Fire/Explosion Incidents and Temperature (℃)

The Chi-squared test of independence between fire/explosion incidents and Average location temperature has been performed, the contingency table is presented in Table 20. The observation frequencies of fire/explosion incidents (represented by various counts) across temperature ranges (intervals) were carried out, potentially assessing whether there's a significant association between temperature intervals and the likelihood or frequency of incidents.

This means that, under the null hypothesis, the occurrence of fire/explosion incidents is assumed to be independent of temperature ranges. Temperature does not influence or predict the frequency of incidents, and any observed difference in frequencies across temperature ranges are due to random chance rather than a significant relationship.

Table 20. Contingency table of Test of Independence between fire/explosion incidents and Average location temperature

Temperature Groups (℃)	1 Incident	2 Incidents	3 Incidents	4 Incidents	7 Incidents	8 Incidents
-2 - 5	1	1	0	0	0	0
5 - 10	1	4	0	0	0	0
10 - 11	0	1	0	0	0	0
11 - 15	1	1	1	0	0	0
15 - 20	1	2	0	2	0	0
20 - 25	0	1	3	0	0	0
25 - 30	1	0	2	0	1	1
30 - 36	2	2	1	0	0	0

The results of the Test of independence for fire/explosion and Average location temperature are presented in Table 21 below.

Table 21. Test of independence of the fire/explosion incidents and Average location temperature

X^2	Degree of freedom	P - value
36.137	35	0.4153

Since the p – value (0.4153) is greater than 0.05, we fail to reject the null hypothesis. Suggesting that there is no statistically significant association between temperature ranges and the occurrence of fire/explosion incidents. Based on the test of independence, temperature does not appear to have a significant impact on the frequency of incidents, indicating that the distribution of incidents is independent of the temperature intervals.

5.5. Green Hydrogen Projects battery sizing

A large-scale BESS will be necessary since one of Namibia's planned green hydrogen projects will use roughly 5 GW to 7 GW of solar and wind renewable energy facilities. To determine how many batteries are required, the energy capacity (in GWh) need to be considered.

Assuming the system needs to store energy for a specific duration, say for 4 hours, then the energy storage requirement would be: Assuming the project will use Lithium Iron Phosphate (LFP) Neue cells.

$$E = 5\,GW \;\times 4 \;= 20\,GWh, \qquad for\ the\ lower\ end.$$

$$E = 7\,GW \;\times 4\,HR = 28\,GWh, \qquad for\ the\ higher\ end.$$

Between 20 GWh and 28 GWh of energy storage are needed.

Find out each LFP cell's energy capacity to determine the overall storage potential. The energy storage capacity of a single LFP depends on its specifications, which vary by manufacturer. A typical LFP cell has a capacity around 100 – 200Wh (Watt-hours). Assuming each LFP Neue cell has a capacity of 200 Wh.

The estimated number of cells required for 20 GWh would be:

$$number\ of\ cells = \frac{20\ 000\ 000\ 000\ Wh}{200\ Wh} = 100\ 000\ 000\ cells,$$

The estimated number of cells required for 28 GWh would be:

$$number\ of\ cells = \frac{28\,000\,000\,000\,Wh}{200\,Wh} = 140\,000\,000\ cells,$$

Taking into account additional elements like battery management systems and depth of discharge. The BMS and other losses could reduce the efficiency by around 5 – 10 %. So, additional cells may be required to compensate for these losses.

Which will lead to the number of cells required to be: For 20 GWh will be 110 000 000 cells including the 10 % margin for DoD and system efficiency, for 28 GWh will be approximately 154 000 000 cells required for energy storage of 4 hours.

An estimate between 110 million to 154 million battery cells will be required for such a project. The exact number may vary based on the specific battery technology and desired duration of energy storage. With such many battery cells in use, the probability for failures will increase proportionally [31].

5.6. Fault Tree Analysis

One common method for analyzing system failures is known as Fault Tree Analysis. The Fault Tree Analysis (FTA) method uses a top-down approach to evaluate the factors that contribute to a failure event [5, 54]. It is well understood that the failure of a Battery Energy Storage System (BESS) can have a devastating effect on both human life and the environment. These systems are expected to maintain a high level of dependability, which refers to their ability to avoid frequent and severe failures. Dependability encompasses several key characteristics, including safety, reliability, and ease of maintenance [55]. In fault trees, the relationships between faults and their causes are shown visually through diagrams as presented in figure 24, whereby the whole purpose of the analysis is to calculate the probabilities at various stages or gates that lead to the top event [5].

The key components of a fault tree consist of the TOP event, which represents the description of critical event within the system, and basic events, which are the most fundamental identified causes. Additionally, logic gates, such as OR and AND gates, define the logical relationship that link the TOP event to the basic events [54-56]. Fault tree analysis is often conducted according to the following steps: 1. Hazard classification, 2. Identification of necessary hazard cause factors, 3. Localisation of Hazard causes, 4. System Failure Tree construction [54]. Figure 23 present the symbols used in FTA diagrams and their meanings.

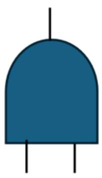
Symbol	Meaning and Description
	AND gate: It requires the occurrence of all input events for a resulting output event
	OR gate: It requires the occurrence of any single input event for a resulting output event
	Basic event: The last finding event which cannot further be defined
	Intermediate gate: It is the resulting event of different interacting events
	Undeveloped event: When the required information is unavailable the event cannot be further developed

Figure 23. Symbols used in FTA diagrams. Source: [54].

As indicated in Figure 23, the Fault tree in this study of fire/explosion accidents or incidents only **OR** gates, reason being that either one of the basic events can lead to an intermediate event, which then can lead to a **TOP** event. For example thermal runaway can be caused by either overcharging, or short circuit, or either external heat source (if there was an **AND** gate, then for thermal runaway to occur, all three basic events below it have to occur simultaneously), in this case either basic event can lead to thermal runaway, which then can also lead to battery failure an event on top of thermal runaway.

Once the Fault Tree diagram has been constructed, both qualitative and quantitative analyses are required to assess the system's reliability and identify potential failure risks. A key component of the qualitative analysis is the evaluation of minimal cut sets, which highlights the smallest groupings of basic events that could cause the system's top – level failure if they all occur simultaneously [56].

This analysis serves several purposes. Firstly, it allows for the identification and verification of single points of failure, which are individual events or combinations of events that can independently cause the system to fail. Recognizing these points is essential for understanding where the system is most vulnerable. Secondly, the analysis uncovers other primary contributors to failure, even if they do not individually cause the system to fail. Understanding these contributors can guide decisions on where to apply additional protective measures [56].

In addition to identifying the critical cut sets, the qualitative analysis often extends to a common cause and dependency review. This step involves ensuring that events connected by logical **AND – gates** in the fault tree are independent. In cases where dependencies are found, such as correlated failures between components, these need to be explicitly modeled. For example, a review of minimal cut sets up to order 3 (sets involving up to three events) helps in identifying such dependencies, which can otherwise undermine the accuracy of the analysis.

A Fault Tree Analysis (FTA) was conducted, as illustrated in Figure 24 with the top event identified as a Battery Energy Storage System (BESS) failure. The top event is triggered by five primary hazard factors: Battery failure, Power Conversion System (PCS) failure, Control system failure, Environmental/External failure, and Human error. Each of these hazard factors has multiple underlying causes, each associated with their respective probabilities, failure rates, repair times, and likelihood of occurrence.

Over a given time period, the failure rate shows how frequently a specific system or component fail. The probability of an event is measure of the possibility that failure will occur. Repair time is the approximate amount of time, usually in hours or days, needed to correct or recover from a failure.

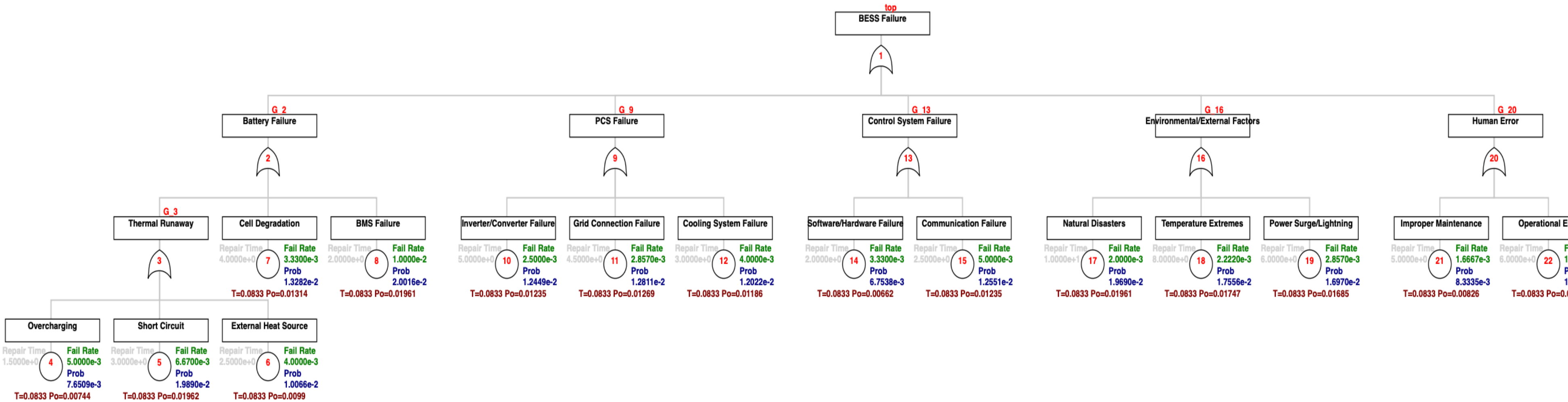


Figure 24. Visualization of failure events and Fault Tree Analysis of a BESS failure.

A thorough analysis of the various failure scenarios that could results in the system's complete failure is provided by the Battery Energy Storage System Fault Tree Analysis diagram in figure 24. Key metrics like the MTTF and MTTR are computed to evaluate the risks associated with each event, and each failure mode is examined in terms of its probability and effect on the system. At the top level, the diagram represents the failure of the BESS as the cumulative results of various subsystem failures, including Battery Failures, PCS (Power Conversion System) Failures, Control System Failures, Environmental Factors, and Human Error. Each of these subsystems has multiple failure modes contributing to the overall risk.

The Mean Time to Failure (MTTF) at every event for the FTA diagram in figure 24, was calculated using formula (3) below.

$$MTTF = \frac{1}{\lambda} = \frac{1}{Failure\ rate}, \qquad (3)$$

Whereby the Mean Time to Repair (MTTR),

$$MTTR = Repair\ time, \qquad (4)$$

The repair time of every event is indicated in the FTA diagram in figure 24 in hours.

The Fault Tree Analysis (FTA) presented in figure 24 differs from other FTAs in literature by focusing on failure events and root causes that lead to the failure of the BESS as a whole. Unlike some existing FTAs, such as reference [6], which primarily analyzes failure of single safety component within a BESS, our FTA takes a more comprehensive approach. The literature often focuses on isolated components, limiting the scope to specific aspect of BESS safety rather than overall system reliability.

Table 22. MTTF and MTTR for Failure modes of the FTA Diagram

Failure Mode	Failure Rate (failures/hour)	Repair Time (hours)	MTTF (hours)
Overcharging	0.005	1.5	200
Short Circuit	0.00667	3	149.9
External Heat Source	0.004	2.5	250
Cell Degradation	0.00333	4	300.3
BMS Failure	0.01	2	100
Inverter/Converter Failure	0.0025	5	400
Grid Connection Failure	0.002857	4.5	350.02
Cooling System Failure	0.004	3	250
Software/Hardware Failure	0.00333	2	300.3
Communication Failure	0.005	2.5	200
Natural Disasters	0.002	10	500
Temperature Extremes	0.002222	8	450.05
Power Surge/Lightning	0.002857	6	350.02
Improper Maintenance	0.0016667	5	599.99
Operational Error	0.0018182	6	549.99

The Mean Time to Failure of BMS is 100 hours. This means on average; the component fails once in 100 hours (or 87.6 failures per year). That led to the BMS to be highlighted as a crucial component with a high failure rate of 0.01 failures per hour, a probability of 0.020016, making it a major contributor to the overall system failure. Despite it relatively quick repair time (MTTR) of 2 hours, the frequency of failure makes this a high-risk event. BMS failure can be a software-based failure (minor glitch) or hardware-based failure (sensor malfunction, circuit failure). Repair time for BMS failure can vary depending on the nature of the issue. For software resets, the repair time might be very short compared to hardware malfunctions. Short Circuit with a failure rate listed, at 0.00667 failures per hour, which gives a Mean time to Failure (MTTF) to 149.9 hours and probability of 0.01989. The repair time slightly higher listed at 3 hours, leading to a probability of occurrence (P_0) of 0.01962. While natural disasters have a lower failure rate, listed at 0.002 failures per hour, their long repair time (10 hours) and high probability of occurrence (0.01961) make them a significant risk. Similar to natural disasters, temperature extremes pose a serious threat, especially with long recovery times (MTTR) of 8 hours, with the MTTF of 450.05 hours, and especially in regions with volatile weather patterns. Power Surge/Lightning can damage critical components, leading to significant downtime, with a failure rate of 0.002857 failures per hour, MTTF of 350 hours, and MTTR of 6 hours. Cell degradation has MTTF of 300.30 hours, and MTTR of 4 hours. As batteries age, the cell degrade, which can lead to failures over time. While it poses a moderate risk, the relatively long MTTF reduces its criticality. While overcharging is a risk, its lower repair time of 1.5 hours and probability of 0.0076509 make it less critical than other failure modes. With its failure rate of 0.005 failures per hour, makes overcharging a moderate factor but remains important due to its potential to cause severe damage. Human error during maintenance activities poses a risk, though with a relatively low failure rate of 0.0016667 failures per hour. While operational errors are slightly more frequent than improper maintenance errors their repair time (6 hours) is still manageable. Failure in the Inverter/Converter are considered moderate risks that could lead to PCS failure and, subsequently, BESS failure. Grid connection failures are depicted as potential pathways to BESS failure, underscoring the importance of reliable grid connectivity. The diagram also emphasizes the significance of the cooling system in maintaining safe operating temperature within the BESS, identifying it as a critical risk factor. Software/Hardware and Communication Filatures within the control system are shown as potential risks that could compromise system functionality.

5.7. Summary of Chapter 5 and Research

An in-depth analysis of fire and explosion incidents related to BESS, are presented in this chapter. Whereby the study utilized historical incident data and statistical analyses to explore the relationship between BESS fire/explosion and various factors, including system age, capacity, and operational state during incidents. A detailed fire and explosion incidents dataset that was examined across various BESS installations in the world is presented in table 3. The dataset covered a range of factors such as location, capacity, system age, application, root cause, and the extent of damage. This information formed the basis for correlation and goodness-of-fit (GOF) tests that were conducted. The incidents happened in systems used for solar power, wind energy, and grid stability, as well as other applications.

The Pearson correlation analysis indicated a moderate negative correlation between system age and the frequency of fire/explosion incidents, suggesting that older systems are not necessarily more prone to incidents than newer systems, with many incidents occurring shortly after installation, indicating other contributing factors beyond age. Additionally, a weak negative correlation was found between BESS capacity (MWh) and the number of fire/explosion incidents, but this was not statistically significant, implying that system capacity does not strongly influence the occurrence of these incidents. The results also show that the incidents most frequently occur when systems are operational or charged, which are more demanding and dynamic states. Systems in testing, commissioning, or maintenance phases have lower incident frequency. These findings underline the importance of enhancing safety protocols during operation and charging phases.

The system age does not significantly affect fire/explosion events, according to the results of the independence and goodness-of-fit tests. The GOF test rejected the null hypothesis, suggesting that the distribution of incidents does not follow an expected pattern based only on age. Similarly, the chi-square and GOF tests found no significant relationship between system capacity and incident occurrence, with p-value above the significance threshold, suggesting that the capacity is not a critical factor. Furthermore, tests for operational states during the incident showed that there is a significant deviation of fire/explosion incidents and the expected model.

A Fault Tree Analysis (FTA) identified key root causes of BESS failures leading to fire/explosion incidents, including thermal runaway due to overcharging, short circuits, and external heat sources, as well as Battery Management System (BMS) failures, which had a high failure rate and significantly contributed to incidents. Other factors such as grid connection failures, extreme environmental conditions, power surges, and improper maintenance were also found to pose risks to system reliability. The FTA underscored the complexity of BESS, where failure in components like battery, power conversion system (PCS), and cooling systems can trigger larger systematic failures, highlighting the importance of robust safety mechanisms, regular maintenance, and vigilant monitoring during critical operational phases.

FTA in figure 24 provides a holistic view of the BESS failure by identifying and categorizing failures across multiple subsystems, including battery failure, power conversion system failure, control system failure, environmental/external factors, and human errors. This broader perspective allows for more complete understanding for BESS failure mechanisms, improving risk assessment and mitigation strategies.

Chapter 6: Conclusion and Recommendations

6.1. Introduction

The conclusions from the findings are presented in this chapter along with safety advice for Namibia's green hydrogen projects and energy stakeholders. The purpose of this research was to identify the cause of fire and explosion hazards associated with lithium-ion batteries that are currently being utilized in the energy industry to store excess energy from wind and solar, collect data from historical accidents/incidents to create mitigation measures to prevent the same incidents from happening, establish extinguishing technics for lithium-ion battery fires and cooling systems.

6.2. Research Summary and Discussion of major findings

This study assessed fire and explosion incidents in Battery Energy Storage Systems (BESS), aiming to identify and understand the factors contributing to these failures, and establish safely guidelines for safely implementation for these systems. The study analyzed incident historical data from various BESS installations globally, focusing on aspects such as system age, system capacity, and operational states during incidents. Key findings indicate a moderate negative correlation between system age and incident frequency, suggesting that both newer and older systems are prone to incidents, with many occurring early in the system's life cycle due to factors like design or installation issues. Additionally, no significant relationship was found between system capacity and the number of incidents, indicating that larger systems are not necessarily more vulnerable to accidents.

The analysis presented that most incidents happen during operational or charged states, highlighting the need for stricter safety measures in these high-stress phases. Statistical tests did not show any clear pattern between system age or capacity and incident frequency, reinforcing the importance of other factors, such as operational conditions.

A Fault Tree Analysis (FTA) identified key risks like failures in the battery management system (BMS) with the failure rate listed, at 0.01 failures per hour, a probability of 0.020016. Despite it relatively quick repair time (MTTR) of 2 hours, the frequency of failure makes this a high-risk event. Short Circuit with a failure rate listed, at 0.00667 failures per hour, which gives a Mean time to Failure (MTTF) to 149.9 hours and probability of 0.01989. The repair time slightly higher listed at 3 hours, leading to a probability of occurrence (P_0) of 0.01962. While natural disasters have a lower failure rate, listed at 0.002 failures per hour, their long repair time (10 hours) and high probability of occurrence (0.01961) make them a significant risk. Similar to natural disasters, temperature extremes pose a serious threat, especially with long recovery times (MTTR) of 8 hours, with the MTTF of 450.05 hours. Power Surge/Lightning can damage critical components, leading to significant downtime, with a failure rate of 0.002857 failures per hour, MTTF of 350 hours, and MTTR of 6 hours. Cell degradation has MTTF of 300.30 hours, and MTTR of 4 hours. As batteries age, the cell degrade, which can lead to failures over time. While it poses a moderate risk, the relatively long MTTF reduces its criticality. Overcharging with lower repair time of 1.5 hours and probability of 0.0076509, with a failure rate of 0.005 failures per hour, making it a moderate factor but remains important due to its potential to cause severe damage.

Human error during maintenance activities poses a risk, though with a relatively low failure rate of 0.0016667 failures per hour. While operational errors are slightly more frequent than improper maintenance errors, their repair time (6 hours) is still manageable. Failure in the Inverter/Converter are considered moderate risks that could lead to PCS failure and, subsequently, BESS failure. Grid connection failures are depicted as potential pathways to BESS failure, underscoring the importance of reliable grid connectivity. The diagram also emphasizes the significance of the cooling system in maintaining safe operating temperature within the BESS, identifying it as a critical risk factor. Software/Hardware and Communication Filatures within the control system are shown as potential risks that could compromise system functionality.

It was noticed that most available failure rate data on BESS are not derived from FTA diagrams or analysis. Instead, they are based on general statistical assessments of failure incidents, often focusing on overall systems reliability trends rather than detailed component-level failure rates. or instance, studies indicate that over half of BESS failures occur within the first two years of operation, with root causes primarily linked to operational and integration issues rather than inherent battery cell or module defects. However, comprehensive datasets providing granular failure rate statistics for specific BESS components, such as those in our FTA diagram, remain scarce in publicly available literature.

6.3. Recommendations

Best recommendation of international standards that can be adopted in Namibia are UL 9540A, which focuses on determining the fire safety risks associated with thermal runaway in BESS, particularly large-scale lithium-ion battery systems. This standard is also applicable to manufacturers, installers, and regulators. UL 1973 that covers stationary batteries and battery systems used for energy storage in various applications. The standard ensures the safety, reliability, and performance of these ESS by evaluating their electrical, mechanical, and environmental durability. However, adopting this standard would involve some regulatory adjustments and careful consideration of local conditions and costs. IEC 62619 is a valuable standard for Namibia to adopt. Adopting this standard would align Namibia with global best practices for battery safety, helping to prevent safety risks, promote investor confidence, and ensure compliance with international trade requirements. Namibia needs to invest in training for engineers, technicians, and safety inspectors to ensure proper understanding and enforcement for IEC 62619. Additionally, the country needs to develop or partner with certification bodies that can evaluate whether imported battery systems comply with the standards. Although Namibia does not have infrastructure to accommodate electric vehicles, it is recommended to adopt UL 2580 standards because the world is moving to sustainable transportation, pushing for electric vehicle, the UL 2580 is essential safety standard for lithium-ion batteries used in electric vehicles.

Based on the lessons learned from historical incidents, several key measures must be taken to improve the safety and resilience of Battery Energy Storage Systems. Because there are no thermal barriers between cells and modules, thermal runaway occurs much more quickly, increasing the risk of fire. To mitigate this, the installation of robust thermal barriers is essential. These barriers should be coupled with an adequate ventilation system, which will not only prevent the buildup of hazardous gases but also facilitate their safe release, especially through deflagration panels. This approach will help channel dangerous gases away from storage units, minimizing the chances of explosion and fire escalation.

Fire management in BESS installations requires a multi-faceted approach. Given the complex nature of lithium-ion battery fires, which are prone to reignition, a combination of extinguishing methods and cooling systems is recommended. For example, utilizing traditional extinguishing agents such as ABC powder (even though it has limited effect) or CO_2, in conjunction with water-based cooling systems, will help to not only suppress the flames but also reduce the risk of reignition. It is therefore recommended that battery storage units be equipped with water ponds or tanks to ensure sufficient cooling capacity during emergency incidents. This will significantly reduce the likelihood of fire resurgence.

The geographical location of BESS installations should also influence design choices. In environments such as Namibia, where conditions are characterized by high winds, sand, humidity, and salinity, specific protective measures are necessary. It is recommended that all BESS units be housed in sealed, corrosion-resistant enclosures to prevent dust, sand, and saline particles from entering the systems. These environmental contaminants, if left unchecked, can lead to equipment failure and operational inefficiencies. Furthermore, regular maintenance schedules should be enforced to ensure that sand and salt do not accumulate within the power electronics and other critical components.

Ensuring the ongoing functionality and safety of BESS also depends on the implementation of real-time monitoring systems and predictive maintenance tools. The integration of sensors that track temperature, gas emissions, and other critical metrics will allow for the early detection of potential issues. By leveraging thermal sensors and gas detectors, operators can act swiftly to contain minor problems before they evolve into serious incidents. Additionally, predictive maintenance algorithms should be employed to forecast failures and schedule maintenance accordingly, which will help prevent sudden breakdowns or safety hazards.

Another critical area is the need to address human error in BESS operation and emergency response. It is recommended that all personnel involved in the operation, maintenance, and emergency response of BESS installations undergo mandatory training. This should include specialized training on fire and explosion safety, hazards identification, and incident response protocols. Moreover, the establishment of regular safety audits and emergency drills will ensure compliance with international and local safety standards while preparing personnel for potential emergencies. These drills should be complemented by third-party inspections and simulation-based testing to validate the overall safety readiness of the system.

To further enhance safety, BESS installations should be designed with compartmentalization in mind. Isolating battery modules in separate compartments can significantly reduce the risk of small incidents escalating into larger failures. In conjunction with compartmentalized designs, the installation of early detection systems is paramount. By utilizing thermal sensors and gas detection systems, operators can detect and respond to fire or gas leaks at an early stage, thereby containing incidents before they spread and cause widespread damage.

Lastly, effective temperature control is vital to maintaining the safe and efficient operation of BESS. The installation of air conditioning systems within the storage units will ensure that batteries operate within an optimal temperature range, thus preventing overheating and performance degradation. However, it is crucial to carefully monitor these cooling systems to avoid excessively low temperatures, which could also negatively affect battery performance. A balanced cooling strategy is required to manage both fire risks and ensure long-term reliability.

In conclusion, implementing these recommendations will enhance the safety, reliability, and resilience of Battery Energy Storage Systems, significantly minimizing the risks of thermal runaway, fires, and environmental impacts. A proactive, multi-layered approach is necessary to ensure that BESS systems are not only operationally efficient but also capable of withstanding both internal and external challenges.

6.4. Limitations and areas of further research

The study primarily relied on global data or case studies from various geographical contexts, many of which had limited data. Most of the reported case studies lack important information that would have significantly benefited the research. Critical details such as the causes of accidents, ambient temperature, and other relevant factors were often missing. Additionally, the lack of localized data on large-scale battery energy storage systems has also impeded the ability to gather sufficient information on local conditions that affect the behavior of these systems.

The study primarily focused on lithium-ion batteries, potentially overlooking other technologies, such as solid-state batteries and flow batteries, which may have different hazard profiles. This limits the generalizability of the findings across all energy storage technologies. The study did not consider the entire lifespan of batteries, including their disposal or recycling at the end of their use. These stages could bring extra risks of fire and explosion that were not covered during the regular operation of battery energy storage systems.

Further research is necessary to identify more effective extinguishing agents specifically designed for lithium-ion battery fires. The goal is to find an agent that can not only extinguish the fire but also prevent reignition, without causing adverse side effects or additional damage to the battery modules. The current extinguishing methods, while somewhat effective, still present challenges in terms of reignition and potential harm to battery systems (short circuit), highlighting the need for innovation in this area.

In addition, the development of advanced cooling systems that can maintain the optimal thermal conditions for battery units without lowering temperatures to detrimental levels is crucial. Excessive cooling could impair battery performance or lead to operational issues, whereas insufficient cooling might fail to prevent thermal runaway. Future studies should explore novel cooling technologies, such as phase-change materials, liquid cooling systems, or enhanced ventilation designs, to ensure effective heat dissipation without compromising battery health or safety.

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APPENDICES

APPENDIX A – ETHICAL CLEARANCE CERTIFICATE

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ETHICAL CLEARANCE CERTIFICATE

Ethical Clearance Reference Number: SOS-0228 **Date: 23AUGUST 2024**

This Ethical Clearance Certificate is issued by the University of Namibia Ethics Committee (REC) in accordance with the University of Namibia's Research Ethics Policy and Guidelines. Ethical approval is given in respect of undertakings contained in the Research Project outlined below. This Certificate is issued on the recommendations of the ethical evaluation done by the ethics committee.

Title of Project: ASSESSMENT OF FIRE AND EXPLOSION HAZARDS IN THE LARGE-SCALE BATTERY ENERGY STORAGE SYSTEMS OF THE GREEN HYDROGEN PROJECT IN THE TSAU//KHAEB NATIONAL PARK

Student: LAUDIKA LIFOSHIWANA JOHN

Student Number: 201081563

Supervisor(s): DR. PETJA DOBREVA
MR. STEPHAN LUX

Centre for Research Services

Take note of the following:

1. Any significant changes in the conditions or undertakings outlined in the approved Proposal must be communicated to the ethics committee. An application to make amendments may be necessary.
2. Any breaches of ethical undertakings or practices that have an impact on ethical conduct of the research must be reported to the ethics committee.
3. The Principal Researcher must report issues of ethical compliance to the ethics committee (through the Chairperson) at the end of the Project or as may be requested by the ethics committee.
4. The ethics committee retains the right to:

i) Withdraw or amend this Ethical Clearance if any unethical practices (as outlined in the Research Ethics Policy) have been detected or suspected,
ii) Request for an ethical compliance report at any point during the course of the research.

The ethics committee wishes you the best in your research.

Prof. Ezekeil Gwinyai Kwembeya (Chairperson Ethics Committee)

Prof. Davis Mumbengegwi (Head, Multidisciplinary Research)

APPENDIX B – RESEARCH PERMISSION LETTER

CENTRE FOR RESEARCH SERVICES
Office of the Pro-Vice Chancellor: Research, Innovation & Development
University of Namibia, Private Bag 13301, Windhoek, Namibia
340 Mandume Ndemufayo Avenue, Pioneers Park, Office F223 - Fblock, Second Floor
☎ +264 61 206 4673; E-mail:lembulu@unam.na; URL.: http://www.unam.edu.na

UNAM
UNIVERSITY OF NAMIBIA

RESEARCH PERMISSION LETTER

Date: 29/10/2024

Student Name: LAUDIKA LIFOSHIWANA JOHN

Student Number: 201081563

Programme: Master of Science in Renewable Energy

Approved Research Title: ASSESSMENT OF FIRE AND EXPLOSION HAZARDS IN THE LARGE-SCALE BATTERY ENERGY STORAGE SYSTEMS OF THE GREEN HYDROGEN PROJECT IN THE TSAU//KHAEB NATIONAL PARK

TO WHOM IT MAY CONCERN:

I hereby confirm that the above-mentioned student is registered at the University of Namibia for the programme indicated. The proposed study met all the requirements as stipulated in the University guidelines and has been approved by the relevant committees.

The proposal adheres to ethical principles as per attached Ethical Clearance Certificate. Permission is hereby granted to carry out the research as described in the approved proposal.

Best Regards

Dr. AEE Shikongo
Head: Postgraduate Research Support Services
Tel: +264 61 206 3129
E-mail: aeshikongo@unam.na

CENTRE FOR RESEARCH SERVICES
Office of the Director
2024 -10- 29
University of Namibia
UNAM

APPENDIX C – RAW GLOBAL INCIDENT DATA