Understanding the Potential Environmental Impacts of Operating Battery Energy Storage Systems (BESS) in Scotland

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Acronyms

AC	Alternating Current
BESS	Battery Energy Storage System(s)
BMS	Battery Management System
BS4142	British Standard 4142 (noise abatement)
dB(A)	A-weighted decibels (noise level)
DC	Direct Current
EcS	Event-Centric Systemic analysis
EES	Electrical Energy Storage
ESS	Energy Storage System(s)
ETA	Event Tree Analysis
FMEA	Failure Modes and Effects Analysis
FTA	Fault Tree Analysis
GW	Gigawatt(s)
GWh	Gigawatt hour(s)
HF	Hydrofluoric acid
HSE	Health and Safety Executive
HVAC	Heating, Ventilation and Air Conditioning
IEC	International Electrotechnical Commission
Li-ion	Lithium-ion (battery)
LiOH	Lithium hydroxide
$Na\text{-}NiCl_2$	Sodium-nickel chloride (battery)
Na-S	Sodium-sulphur (battery)
NESO	National Energy System Operator
Ni-Cd	Nickle-cadmium (battery)
Ni-MH	Nickle-metal hydride (battery)
PF_5	Phosphorus pentafluoride
RAG	Red-Amber-Green (risk rating)
STPA	Systems Theoretic Process Analysis
Zn-air	Zinc-air (battery)

1. Executive Summary

Battery Energy Storage Systems (BESS) are now pivotal assets in Scotland's strategy to achieve net zero carbon emissions and ensure energy security amidst a shift to renewables-led power generation. Although Scotland's current installed BESS capacity is modest, momentum is growing rapidly, with a large volume of projects under planning or construction or in the pipeline. This transformation is occurring in a context where BESS facilities are almost exclusively sited near renewable generation hubs or areas of high grid demand, reinforcing their significance in enabling the flexible and reliable integration of intermittent wind and solar power.

At present, lithium-ion battery technology dominates both operational and planned BESS installations. However, ongoing research and pilot projects are investigating more sustainable and potentially safer alternatives such as sodium-ion, flow, and graphene-zinc batteries, with promising early results. Scotland's unique combination of abundant renewables, grid constraints, and ambitious decarbonisation goals make these innovations highly relevant, particularly in distributed or remote locations.

The operational phase of BESS, which is the exclusive focus of this review, presents a distinctive cluster of environmental and safety risks. Chief among these are fire and explosion hazards, which, although rare and especially rare in Scotland, remain the greatest concern due to the potential release of toxic gases (such as hydrofluoric acid), air pollution, and environmental contamination from fire-fighting run-off. Acute and chronic chemical release, even in the absence of fire, is another key consideration, particularly given the hazardous contents of lithium-ion and other advanced batteries. Water contamination from firefighting or stormwater run-off, noise emissions from thermal management units, and the visual and land use impacts associated with larger BESS installations also merit careful attention, although recent evidence demonstrates that noise and visual effects are usually kept comfortably within regulatory limits through effective design and mitigation.

Scotland currently benefits from a relatively robust, if complex and sometimes non-statutory, regulatory and planning guidance landscape that applies to BESS developments. This structure, while effective, does contain gaps (especially regarding system interactions, guidance harmonization, and adaptation to evolving technology) which highlights areas for further policy development and research. Comparisons with international practice, notably in Asia and the USA, reveal that a lack of unified standards can result in higher risks and costly incidents, as seen in several high-profile battery fires abroad. Recent scholarship advocates for more nuanced, systems-based approaches to risk assessment, such as combining event tree and systems theoretic analyses, rather than relying solely on traditional, component-based methodologies.

2. Introduction

Battery Energy Storage Systems (BESS) are increasingly recognised as essential infrastructure for supporting Scotland's transition to a low-carbon, renewable energy future. As variable wind and solar generation expand, BESS facilitate grid stability by balancing electricity supply and demand, enhancing system flexibility, and helping meet ambitious net zero and energy security goals. While BESS capacity in Scotland is currently modest, exponential growth is underway, with a substantial pipeline of projects planned or under construction. This report focuses on understanding the potential environmental impacts associated with operating BESS in Scotland, examining dominant technologies, emerging alternatives, and the nature of operational hazards. The analysis aims to inform policy, planning, and best practice for safely integrating large-scale energy storage within Scotland's power system landscape.

3. Background and Scope

Battery Energy Storage Systems (BESS) have emerged as a key component in the increasing shift to renewable power generation as part of Scotland's, and the wider UK's, net zero and energy security commitments. BESS currently provide a relatively small contribution to Scotland's energy mix, with an installed capacity of approximately 0.5 GW as of December 2024. However, the BESS market is projected to grow significantly, both within GB and globally, due to increasing demand for grid flexibility and the integration of renewable energy – balancing over- and under-production from renewable sources to match grid electricity demand. For practical reasons BESS are usually sited near areas of renewable grid generation or intensive grid electricity use. In Scotland the number of planned BESS or BESS under construction is increasing rapidly. BESS capacity range estimates, published in the UK Government's Clean Power 2030 Action Plan, indicate that 5.8 GW of grid scale BESS capacity could be required in Scotland by 2030. As of March 2025, there were approximately 24 GW of BESS projects in planning or under construction in Scotland. Of this, around 1.9 GW is already under construction and 11.4 GW has been approved and is awaiting construction, therefore exceeding the estimated required capacity (Scottish Energy Statistics Hub). Recently the National Energy System Operator (NESO) has proposed Connections Reform that is likely to have implications for the existing project queue (NESO 2025).

While existing local planning legislation applies to BESS, there are currently no specific regulatory regimes that apply to BESS to take into account any particular risks that BESS may pose to people and the environment during a site's lifecycle; in E&W, UK Government is considering whether BESS should be included in their Environmental Permitting Regulations with an initial consultation in August – October 2025 (Consultation on modernising environmental permitting for industry - Defra - Citizen Space). There are currently no such plans in Scotland.

Finally, at the time of writing, SG's Planning, Architecture and Regeneration Division is in the process of commissioning independent consultants to prepare BESS Planning Advice with input from planning authorities. It is intended that the guidance will promote good practice in determining BESS applications as well as set out information on other relevant regulatory regimes applicable to BESS in Scotland.

3.1 Objective

Scottish Government is seeking a better appreciation of what potential environmental impacts BESS may pose during a site's operation. This will contribute to the evidence informing the future Scottish Government policy position on BESS. Other stages of a site's lifecycle – from sourcing battery components, its construction and grid connection, to its decommissioning and decontamination – are out of scope for this project.

Risk of fire from battery malfunction during operation or problems that stem from poor planning/construction remain a major concern for such sites, as are the risks the plumes from such fires pose for people. Most current BESS sites use lithium-ion batteries, and these will be the focus of this review. However, as the BESS market develops, other battery types may become more widely available, including salt-based technologies. Commentary is included on these emerging technologies as appropriate.

4. Brief Overview of BESS

The rapid exploitation of renewable energy sources, such as wind and solar power, has led to an increased need for effective energy storage solutions to address intermittency and grid stability challenges (Basit et al., 2020). Battery energy storage systems (BESS) have emerged as the prominent technology for storing excess energy generated from renewables and releasing it when needed (Abaku & Odimarha, 2024; Fawole et al., 2023). Thus, BESS systems are becoming increasingly crucial in enabling the widespread adoption of renewable energy and reducing dependence on fossil fuels (Suman, 2021).

Figure 4.1 depicts the various components that go into building a BESS that can be either stand-alone or can also use energy arising from renewable energy sources for charging. A stand-alone BESS is connected directly to the electricity grid or a specific local load, charging from the grid and discharging when required to provide grid services such as frequency regulation, load shifting, backup power, or peak shaving, without relying on co-located renewable generation.

The electrochemical cell is the fundamental component of BESS and these cells are grouped into modules to provide the required capacity and voltage. It is the physical arrangement of modules in racks that we refer to as a 'battery'. A battery management system (BMS) enables the monitoring and control of the charge and discharge of the battery. Thermal management of the battery is achieved via a heating, ventilation, and air conditioning (HVAC) system that controls the environmental temperature and humidity. Integrating BESS with renewable energy sources to enable battery charging can be done directly through an AC/DC inverter (batteries operate with DC while renewable energy sources can produce both AC and/or DC current). The AC/DC inverter also enables BESS to be integrated with the wider electricity grid by demanding energy when needed or supplying excess energy (Jeevarajan et al., 2022). So-called Grid-forming Battery Energy Storage Systems (BESS) are advanced energy storage solutions capable of autonomously establishing and regulating grid voltage and frequency, thereby providing essential system stability services independent of synchronous generation. By supporting "islanding" operations and enabling higher shares of inverter-based renewables, grid-forming BESS are critical for maintaining resilience and reliability in increasingly decarbonised power systems (What is Grid Forming? | National Energy System Operator).

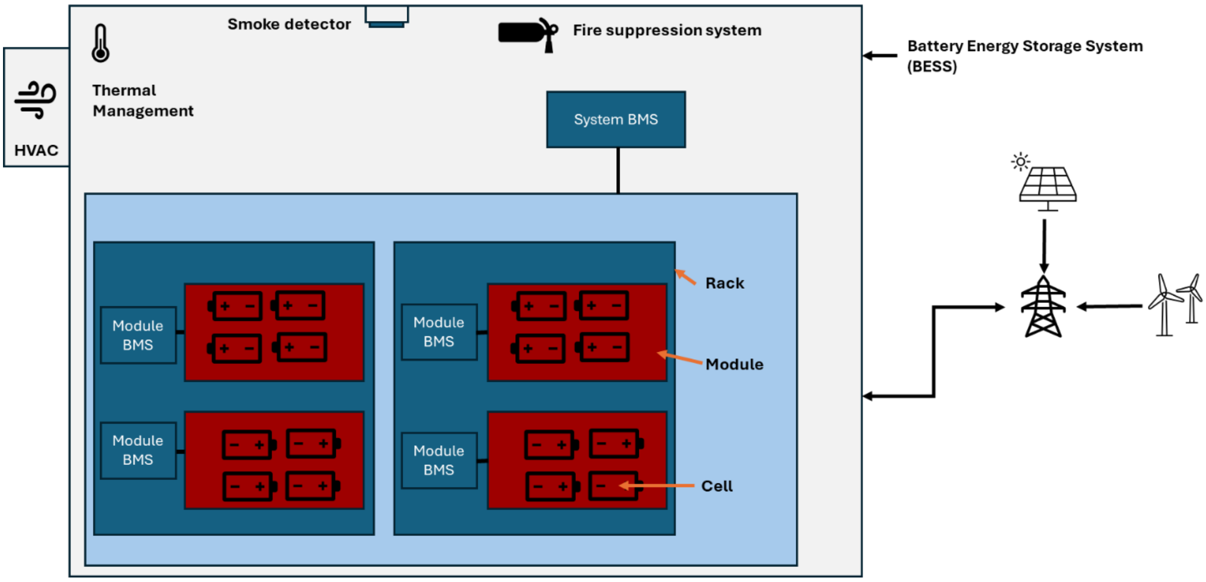

Figure 4.1. Schematic of a typical battery energy storage system (BESS) charged via grid connection to renewable energy production. HVAC refers to the heating, ventilation and cooling system for the BESS.

Battery technologies currently utilised in grid-scale BESS are lithium-ion (Li-ion), lead-acid, nickel-metal hydride (Ni-MH), nickel-cadmium (Ni-Cd), sodium-sulphur (Na-S), sodium-nickel chloride (Na-$NiCl_2$), and flow batteries (DOE 2021; Fan et al., 2020; Argyrou et al., 2018). The properties of these different battery types are summarised in Table 4.1.

Table 4.1. Key properties of common battery technologies used in grid-scale BESS (Kebede et al., 2022; Fan et al., 2020; Argyrou et al., 2018).

Property	**Li-ion**	**Flow**	**Na-S**	**Na-$NiCl_2$**	**Lead-acid**	**Ni-Cd**	**Ni-MH**	**Zn-air**
Specific energy (Wh Kg^{-1})	100-240	10-85	150-240	100-120	30-50	50-75	40-110	110-650
Specific power (W Kg^{-1})	500-2000	45-166	150-240	150-200	180-200	150-300	200-1200	100
Nominal cell voltage (V)	3.6-3.8	1.2-1.9	2	2.6	2	1.2	1.2	1.4
Energy efficiency (%)	>98	>75	75-90	90	75-85	70-85	60-80	50-65
Cycle life	1000-10000	6000-14000	>2500	>2500	500-1000	2000-2500	300-2000	100-300

According to global data amassed by the US Department of Energy over the past 20 years, the most popular battery technologies for BESS are flow batteries, sodium-based batteries, and Li-ion batteries which account for over 80% of global battery energy storage (DOE 2021). Li-ion batteries dominate new grid installations thanks to falling costs, broad availability, and diverse chemistries (Jeevarajan et al., 2022), with potential for second life use from electric vehicles although safety, compatibility, and economic challenges remain (Preger et al., 2022; Hesse et al., 2017). Indeed, Li-ion batteries make up the vast majority of BESS installations in Scotland. Emerging types like lithium-sulphur, sodium-ion, and magnesium-ion show promise but suffer from poor cycle life. Flow batteries, especially vanadium and zinc–bromine, are mature for grid use, offering lower cost, long life, and safer deep discharge tolerance, though large-scale behaviour under fault conditions still needs study (Jeevarajan et al., 2022). Graphene zinc batteries are an emerging rechargeable battery technology that combines a zinc anode with a graphene-based cathode or supercapacitor element. This configuration leverages graphene's exceptional conductivity, surface area, and robustness alongside zinc's abundance, safety, and low environmental impact. These batteries offer strong potential for grid-scale energy storage in Scotland due to their non-flammable, water-based electrolytes (which reduce fire risk), lower reliance on scarce critical minerals, and robust performance in harsh or variable climates—making them well-suited for remote, renewable-rich Scottish locations. Furthermore, graphene zinc batteries promise high cycle life, rapid charge-discharge capability, and competitive efficiency, positioning them as a safer and potentially more sustainable alternative to lithium-ion for future Scottish BESS deployments (Aizudin et al., 2024).

The Na-S battery is also promising for large-scale applications due to the desirable properties listed in Table 4.1. However, it requires 300-350 °C operating temperatures, posing fire risks from molten Na-S reactions (Fan et al., 2020). The $NaNiCl_2$ battery is a similar high temperature system but designed to mitigate some of the risks associated with Na-S systems (Argyrou et al., 2018). Other types such as lead-acid, Ni-MH, Ni-Cd, and Zn-air, make up only a small percentage of grid-level applications.

Lithium-ion batteries can be hazardous under abnormal conditions leading to safety incidents that can cause extensive damage to BESS. The Electric Power Research Institute has been documenting all BESS failure incidents worldwide since 2011 (EPRI 2025). BESS failure incidents are extremely rare in Scotland. Only a single incident in February 2025 is listed for Scotland. This occurred in Rothienorman, Aberdeenshire, and while very few details are in the public domain, we do know that it was a lithium-ion BESS damaged during transportation which was then isolated from the main installation.

When specifically looking at Li-ion incidents, South Korea stands out as particularly prone to battery failure and thermal runaway. A spike in Li-ion BESS failures in South Korea between 2018 to 2019 resulted in formal government investigation and a partial suspension of the country's energy storage facilities (Ji-hye 2019). The investigation cited protection system faults such as BMS failure, harsh environmental conditions (extremes of temperature; temperature fluctuations), installation errors, and lack of overarching controls as contributing to these failures (Ji-hye 2019; Yun-Hwan 2019). Other later reports implicated battery defects due to improper manufacture (Hyun-woo 2020). South Korea has significantly reduced BESS fires by implementing comprehensive investigations, strengthening regulations, improving installation standards, and mandating enhanced battery management and safety systems, resulting in a 98% decrease in incident rates between 2018 and 2024 (South Korea Identifies Top 4 Causes that Led to ESS Fires).

There have been several BESS incidents in Australia, including notable fires at large-scale lithium-ion battery storage sites. The most prominent incidents include the July 2021 Victorian Big Battery fire involving Tesla Megapacks, which occurred during the site's commissioning, and a "minor" fire at the Bouldercombe Battery Project in Queensland in 2023, also affecting a Tesla Megapack. In both cases, the fires were contained to single battery units without propagating, but they triggered emergency responses and local safety concerns (Battery fires in Australia raise safety concerns for big storage projects). Additionally, Australia has reported property damage, recalls, and rising numbers of lithium battery-related fires in solar storage and residential systems.

It is important to put failure incidents into context. The global installed capacity of grid-scale BESS has dramatically increased over the past 5 years (30 GWh in 2020 to >300 GWh by the end of 2024). While failure incidents continue to occur, the overall rate of incidents has sharply decreased, dropping by 98% from 2018 to 2024 in South Korea alone. Reduction in failures comes from learning the lessons from early failures, design improvements, and best practices (EPRI, 2024).

5. BESS in Scotland

Energy storage is rapidly emerging as a cornerstone of Scotland's transition to a low-carbon, renewables-led energy system, with findings highlighting its critical role in managing the intermittency of wind and solar generation, supporting grid stability, and enabling decarbonisation targets. Scotland's unique context, characterised by vast renewable resources, limited connection to major UK electricity loads (Connections_Brief_Final_Reviewed_1_original.pdf), and ambitious climate goals, makes the deployment of BESS especially relevant. Recent years have seen a surge in planning consents and investment in grid-scale BESS projects, with over 24 GW of battery and pumped hydro storage now in the development pipeline (99% of this is BESS), reflecting strong demand from both the renewables and data centre sectors (Scottish Government, 2025).

These projects are not only vital for balancing supply and demand but can also deliver local economic benefits, including job creation (during the construction phase) and supply chain opportunities, as evidenced by major investments like recent and planned BESS facilities near Glasgow (Scottish Government, 2023).

A detailed and current list of BESS sites operating in Scotland can be found on the local energy Scotland website Map · Local Energy Scotland as well as other sites such as Scottish Power Renewables BESS website (Scottish Power 2024), while the UK Government's Renewable Energy Planning Database (Renewable Energy Planning Database: quarterly extract - GOV.UK) provides comprehensive listings for the UK, including Scotland. This site provides information on operational grid-level BESS (such as Whitelee which is co-located with the windfarm at Ardochrig) as well as those under construction and in earlier planning phases. There are also various developments, primarily by private companies such as Zenobe, highlighted in the press.

While Li-ion batteries dominate both current and planned BESS projects in Scotland, several emerging battery technologies are being researched, piloted, or considered for future deployment. Drivers include the desire for longer-duration, safer, and more sustainable grid-scale storage. Sodium-ion batteries could provide an alternative to Li-ion. Sodium is a more abundant and lower cost material compared to lithium. The Nexgenna project, a consortium that includes the University of St. Andrews, is actively developing Na-ion batteries specifically designed for grid-scale storage applications. Their focus is on improving safety of BESS as well as improving supply chain resilience by reducing reliance on lithium (NEXGENNA – The next generation in sodium-ion batteries). Other technologies such as flow batteries are also gaining interest. Flow batteries store energy in external electrolyte tanks rather than within solid electrodes. This allows for lower risk, scalable, and longer-duration storage. Edinburgh-based StorTera is developing flow battery technology for grid-scale, long-duration energy storage. Demonstrators are planned for wind farms to help store excess renewable power and reduce curtailment. Both Na-ion and flow batteries offer lower risk alternatives to Li-ion as well as improved sustainability credentials, thus it would seem likely that these technologies will begin to be adopted in Scotland in the future.

The findings of this section underscore that energy storage enables Scotland to maximise the use of its renewable generation, reduce reliance on fossil fuel backup, and provide resilience against grid constraints. However, various reports also note barriers such as the need for supportive policy frameworks and the commercial viability of long-duration storage, which are crucial considerations for future projects. Overall, Scotland’s experience demonstrates that integrating diverse storage technologies at multiple scales, supported by clear policy, local supply chain engagement, and a focus on both technical and economic benefits, offers a blueprint for other regions pursuing large-scale renewable integration and energy security (Scottish Government 2023; Infield & Hill, 2014).

6. Hazards Associated with Operational BESS

Here the focus is on Li-ion batteries as the dominant battery technology used in BESS in Scotland currently and in planned BESS. Hazards for Li-ion batteries vary with size and volume of the battery, since the tolerance of a single cell under abnormal conditions does not translate to the tolerance of a larger battery system under the same conditions. Statistically, larger grid-scale Li-ion batteries with many cells and modules are more prone to failure than smaller batteries, but the reasons are nuanced. In basic terms, the scale increases the probability of failure. More cells mean more potential points of failure. This is exacerbated by the additional complexity of larger battery systems with respect to their wiring, management, cooling, and control, all of which increase the likelihood that something could go wrong. The consequences of failure are also more significant with larger BESS installations (Edwards & Dobson, 2024; Wand et al., 2019).

Known causes of failure of Lithium-ion batteries are overheating, swelling, electrolyte leakage venting, fires, smoke, and explosions in worst-case scenarios involving thermal runaway. While most failures of Li-ion systems result in combustion that is deflagrant in nature, the gases produced as a result of fire, smoke, or thermal runaway can accumulate within the installation structures to the level where explosion can occur (Jeevarajan et al., 2022). In general, the abnormal conditions that can cause occurrence of catastrophic events with Li-ion batteries can be categorised into electrical, thermal, and mechanical. While the majority of hazards can be described as being internal to the BESS, there are some thermal and mechanical hazards that are external and thus have Scotland-specific elements.

6.1 Electrical Hazards to BESS

The most common electrical hazards are over-charge, over-discharge, and short circuits (whether internal or external).

All Li-ion batteries, regardless of voltage, capacity, or number of cells, are designed with a battery management system (BMS; Figure 4.1). The complexity of the BMS varies widely, depending on the requirements of the battery design and the application in which the battery is being used (Jeevarajan et al., 2022). The BMS monitors and controls voltage, current, and temperature of the battery. It also carries out cell balancing that protects against any individual cell going under or over its voltage limits, which extends the life of the battery as well as protecting against catastrophic events.

Over-charge of Li-ion batteries can occur when they are charged at a high rate or to a voltage that is above their design specification. This can happen when BMS malfunction, incorrect charging protocols, or with battery ageing. Cathode destabilisation (the breakdown or loss of structural stability in the battery's cathode, leading to reduced performance or failure (Juarez-Robles et al., 2020)), lithium dendrite formation (the growth of tiny needle-like lithium metal structures inside a battery during charging (Kim et al., 2015)), electrolyte decomposition, and the heat produced due to the high voltage or high charging rate can lead to catastrophic events. In addition, as batteries age, the electrochemical characteristics such as capacity and internal resistance of the individual cells change. These changes cause deviations in characteristics between the cells in the battery. If no balancing of the cells or cell banks is provided, these deviations tend to grow larger leading to excursions of voltage beyond safe limits. The result is catastrophic failure.

Over-discharge is when the Li-ion cell is discharged below the recommended end-of-discharge voltage and against the manufacturer's design specifications. In a single cell it is not possible to discharge it below 0 V. However, within a bank of cells or a module it is possible to take any one cell into an over-discharge into reversal condition. In other words, the battery is drained beyond empty, so far that one or more cells in the battery actually 'flip' and start running backwards, with their positive and negative ends swapped. This can happen in batteries with several cells linked together, such as in BESS. A weak cell empties first, but the remaining cells (still being used) force current through the weak cell the wrong way causing cell reversal. This situation causes various undesirable electrochemical conditions. Metal components made from copper dissolve, and decomposition of the electrode occurs. Under extreme over-discharge conditions, the dissolved Cu ions deposit on the cathode, anode and other structures and ultimately the system becomes an electrical wire as opposed to an electrochemical system. This creates a short circuit making the cell or battery unstable. It is important to note that less intense over-discharges can also lead to catastrophic outcomes with little warning (Fear et al., 2018). Over-discharging can heat the cell because lithium ions struggle to enter the anode when copper is unevenly deposited (Fear et al., 2018; Guo et al., 2016; Nemanick et al., 2016; Zheng et al., 2016). Eventually, lithium dendrites grow on the copper surface, increasing the risk of thermal runaway, especially in battery modules versus single cells. If cell balancing is missing, repeated over-discharges can set up conditions for catastrophic failure (Jeevarajan et al., 2010). In large BESS, careful voltage monitoring, cell balancing, and under-voltage cutoffs at both module and battery pack levels are vital to prevent these dangerous events.

6.2 Thermal Hazards to BESS

Lithium-ion and other battery types generate heat during charging, discharging, and especially during abnormal events (such as short-circuits, over-charging, etc. as described above). If batteries overheat it can cause capacity loss, shorten lifespan of the BESS, or in worst case scenarios initiate thermal runaway leading to fires and explosions. Thus, thermal management systems (including cooling fans, HVAC, liquid cooling, heat sinks, etc.) should be employed to keep battery modules within safe operating temperatures.

Ambient temperature can also play a role and can affect battery performance as well as the workload of any thermal management system. Environments that experience extremes of temperature (hot or cold) can be hostile to BESS and indeed such conditions were cited as contributing to the catastrophic events in South Korea described previously. Extreme cold will reduce battery efficiency and capacity, while extreme heat will exacerbate internal heat burdens. Scotland's climate, being generally temperate and cool, helps reduce risks from environmental temperature extremes, however risk management stipulates that all BESS are engineered with extremes of temperature in mind. This is especially relevant given large BESS still produce significant internal heat so thermal management systems are still an essential requirement.

6.3 Mechanical Hazards to BESS

Physical impacts, e.g., from construction vehicles, maintenance activities, or even minor seismic events (which can occur in Scotland), can damage battery containers or internal components with associated risks of short circuits, cell rupture, or even fires (Wang et al., 2021). Windy, exposed sites or those close to heavy industry/infrastructure may experience vibration damage loosening connections, damaging cells, or degrading mountings over time. Persistent rain, damp, and especially salty coastal air can corrode enclosures, terminals, and busbars potentially leading to faults, loss of protection or electrical shorts (Gonçalves et al., 2024 (for extreme weather events); How UK weather conditions pose risks on Battery Energy Storage Systems | Marsh). Wildlife (in particular, rodents and birds) and livestock in rural areas can damage insultation or enclosures, exposing BESS systems to further hazards.

Best practices include robust enclosures with high ingress protection ratings to shield batteries from water, salt, dust, and wind-driven debris; resilient enclosure materials and structures to withstand physical impacts and vibration; and clear internal layouts providing easy access and spacing to prevent accidental mechanical damage during maintenance. Additional Scottish context-specific measures involve insulated and weather-resistant cabinets, site layouts with accessible perimeter roads, minimum clearances from vegetation and infrastructure, maintenance routines to check for corrosion or loosening from vibration, and contingency for wildlife or livestock interference. These steps, combined with adherence to safety standards such as NFPA 855 and targeted hazard analysis (HAZID/HAZOP), help minimize mechanical risk throughout the lifecycle of Scottish BESS installations (see Flushing BESS for an example).

6.4 Impact of Ageing on BESS Safety

Large BESS typically function for 10 – 15 years, depending on battery chemistry, usage patterns, depth of discharge, and maintenance. Some high-quality systems, especially those using lithium iron phosphate (LFP) or vanadium flow batteries, may last up to 20 – 25 years under optimal conditions. However, most grid-scale Li-ion BESS are designed for about 10 – 15 years' service before significant capacity loss requires augmentation or replacement (Juarez-Robles et al., 2021a). Cycle life studies have shown that degradation of the electrodes is a common occurrence with ageing and that delamination of the active material can occur, along with other physical degradation reactions. Tests indicate that ageing does not change the nature of the results of abnormal abuse testing, and cells and batteries aged to about 20% capacity do not exhibit catastrophic failures. However, batteries aged to 17% capacity and below may exhibit catastrophic failures (Juarez-Robles et al., 2021a and b). Obviously, ageing of batteries will limit their further deployment in a second use which might be a consideration from a circular economy perspective. Currently no grid-scale BESS in Scotland is older than 5 years of age. Ageing considerations could be addressed through the use of planning conditions.

6.5 Toxic and Combustible Discharges

This is an important consideration with respect to locating a BESS facility. If large BESS experience abnormal conditions, release of flammable gases from BESS can present a risk of explosion in the vicinity of the storage facility. Immediate ignition of flammable vent gases after release may cause minor deflagration, whereas longer accumulation of larger volumes of gases with subsequent ignition can give rise to large explosions (Zalosh et al., 2021). Combustible gases including hydrogen, carbon monoxide, methane, ethylene, and propylene have all be shown to be produced above threshold limits for explosion from Li-ion batteries experiencing abnormal conditions (Jeevarajan et al., 2022). Other chemicals are also emitted during explosion, including hydrofluoric acid (HF), phosphorus pentafluoride (PF_5), and phosphoryl fluoride (POF_3) (Park et al., 2018). While not fully assessed to date, the mixture of gases and other chemicals needs to be assessed for toxicity even at levels well below thresholds for explosion. Such gases may pose health risks to personnel and local populations if exposed.

Lithium-ion batteries do not leak during normal operation, but following deflagration or explosion, due to the hydrophobicity of Li it will react with the humidity in ambient air. When Li reacts with water and OH ions (supplied from HF released form the battery and water) it forms LiOH (Larsson et al., 2017; Xu, 2004). If a battery explodes or catches fire in a confined space, concentrations of HF gas may reach dangerous levels, posing significant inhalation risks to humans and exceeding established safety thresholds for workspaces (Park et al., 2018). By contrast, potential skin exposure to LiOH is generally considered safe under typical accident scenarios. Park et al. (2018) conclude that HF release during battery explosion is a serious health concern. However, BESS tend to be in outdoor environments so risks from HF gas are going to be mitigated against to a large degree, although this is a theoretical assumption rather than a conclusion drawn on direct empirical evidence.

Water run-off is another consideration following a BESS incident. Water remains one of the most efficient fire extinguishing agents for tackling BESS incidents, and large quantities are usually necessary. Since batteries contain various potentially harmful chemicals and thermal runaway-induced incidents are accompanied by complex and (often) multi-stage fume emissions containing both gas and particulate matter, the potential impact of firefighting run-off waters on the environment should be assessed (Bordes et al., 2024). Analysis of run-off waters following firefighting of Li-ion batteries under thermal runaway revealed a complex mixture of metals including Li, Mn, Co, Ni, and Al as well as carbon-based compounds (soot, tar) and undecomposed solvents used in the battery electrolyte (Bordes et al., 2024). Extrapolation of pollutant concentrations to compare with published 'safe' values (i.e., Predicted No-Effect Concentrations, PNEC, published at https://echa.europa.eu/fr/home), suggests that for large scale BESS incidents run-off water could present a risk to environmental biota.

6.6 Noise Emissions

As described previously, maintaining the correct operation temperature is critical for the safe operation of BESS. The thermal management systems responsible for this are the main noise emitters dominating the overall operational noise levels for most battery technologies including Li-ion (Bastasch et al., 2022). The noise from thermal management systems is typically emitted from fans and compressors and is therefore directly associated with both ambient conditions, i.e., cooler or hotter weather associated with heavier fan usage, as well as intensity of battery usage (recharge/discharge). Noise emissions are therefore not constant, but rather intermittent and the level of noise, i.e. dB, is difficult to predict for a given BESS installation (Eriksson, 2024).

Maximum noise levels likely to be emitted by BESS operating in Scotland are typically below 30 – 35 dB(A) at the nearest residential receptors, according to published noise impact assessments. For example, Whitelee windfarm BESS noise assessment predicted a maximum noise of 20 – 28 dB(A) at the nearest dwelling (Scottish Power Renewables, 2023). The Mey BESS noise impact assessment set target limits of 35 dB(A) daytime and 30 dB(A) nighttime in habitable rooms (ITP Energised, 2023). More broadly, UK/Scottish planning reports and industry have confirmed that most BESS projects are designed to emit no more than 4 – 5 dB(A) above typical background levels at residential property boundaries (RMP, 2025). These predicted levels comply with planning and regulatory limits set by Scottish local authorities and standards such as BS4142, which generally require noise from new developments to be no higher than existing background levels or not exceeding 35 dB(A) during the day and 30 dB(A) at night at residential facades. Actual BESS operational noise, mostly from thermal management, inverters and transformers, can reach 70 – 75 dB(A) at 1m from equipment. However, this attenuates rapidly with distance and proper noise mitigation (enclosures, barriers, good site selection, etc.).

In summary, in Scotland BESS noise levels at residential property boundaries are commonly kept below 30–35dB(A), usually matching or not exceeding local background levels, and comply with strict planning regulations. Inverters and cooling systems can briefly emit higher levels close to the device, but mitigation ensures compliance at sensitive receptors.

6.7 Land Use and Visual Impact

Large BESS installations transform land use (though generally less than solar or wind as they are less extensive in terms of area), potentially affecting ecosystems, especially if placed on greenfield or sensitive sites. Overall, BESS have very limited footprint and height which limits levels of visual pollution (Clean Horizon, 2022) although consideration might be given to specific sites that are within landscapes valued for particular characteristics.

7. Existing Hazard/Risk Analyses of BESS

Key studies from Asia, particularly Moa & Go (2023), offer important insights into battery energy storage system (BESS) safety and risk management that are highly relevant for the Scottish context. Moa and Go present a comprehensive, event-centric safety and risk assessment framework explicitly designed for large-scale BESS, focusing on their integration with solar power. This very scenario is becoming increasingly common as Scotland decarbonizes its power sector and integrates renewables at scale. The experience in Malaysia, as documented by Moa & Go, is especially pertinent: while the country is witnessing rapid deployment of solar PV and BESS, it notably lacks formalized, unified frameworks for BESS safety and risk management. This signals a broader international gap in best practice, standardization, and statutory regulation, even as the sector is poised for rapid growth. While Scotland and the wider UK have developed a relatively robust - albeit sometimes complex - policy and regulatory framework that applies to BESS, many requirements take the form of guidance rather than statutory obligation. This nuanced landscape suggests a valuable area for further research, particularly into how best practice and mandatory standards might be harmonised as BESS deployment accelerates.

BESS installations worldwide (across Asia, the US, Australia, and Europe) face significant, well-documented hazards, including thermal runaway, fire, explosion, acute and chronic gas release, and electrical failure. Recent high-profile incidents in Arizona (USA), South Korea, Australia, and China have resulted in injuries, fatalities, and multimillion-dollar losses, often attributable to failures in detection, fire suppression, or emergency response. These incidents underscore the urgency and complexity of effective risk management. The intricacy of contemporary BESS, particularly when hybridized with renewables, creates new systemic risks that go beyond what traditional hazard assessment tools can capture. Mainstream techniques such as Event Tree Analysis (ETA), Fault Tree Analysis (FTA), Failure Modes and Effects Analysis (FMEA), and HAZOP, while widely used in many engineering sectors, are frequently inadequate for the dynamic and highly interconnected risks inherent in grid-scale BESS.

In response, Moa & Go (2023) recommend adopting an "event-centric systemic analysis" (EcS), which combines probabilistic event tree analysis with Systems Theoretic Process Analysis (STPA). This approach goes beyond component-level failures, explicitly accounting for complex system interactions and emergent risks characteristic of modern BESS. These include harmonising formal regulation, advancing risk assessment methodologies, and ensuring continuous guideline development as technologies and configurations evolve. Exploring how these internationally developed frameworks might be integrated or adapted within the UK policy landscape remains a valuable area for continued research and policy innovation.

8. Semi-Quantitative Risk Ranking for BESS Operation in Scotland

A semi-quantitative risk ranking for BESS environmental risks typically scores each hazard against standard criteria. Here, a risk ranking methodology is presented that draws on international and UK-specific standards (IEC 62933-5-2 (IEC 2020)), as well as standard environmental impact assessment approaches, as well as peer-reviewed environmental/hazard analyses. Most authoritative sources agree the hierarchy after (1) fire/explosion is: (2) acute chemical release, (3) runoff/water contamination, (4) noise and visual impacts, (5) land use (adjusted locally as per site and battery chemistry).

Fire and Explosion

Widely regarded as the most severe environmental and safety risk, BESS fires can release toxic gases (e.g., HF, dioxins), cause air pollution, and potentially contaminate soil and water with firefighting runoff and debris.

Event-tree and risk matrix approaches in IEC 62933-5-2 and other sources including peer-reviewed reviews and UK safety reports rank fire/explosion as the highest consequence hazard due to impacts on environment and human health (HSE, 2024; Edwards & Dobson, 2024; Moa & Go, 2023; IEC 2020).

Chemical Release (acute and chronic)

Accidental release of chemicals (HF, heavy metals, solvents, lithium salts) from cell venting or breach can contaminate the air, soil, or water, posing acute or long-term risks to health and the environment.

The majority of environmental impact assessments, IEC 62933-5-2, and incident analyses rate this just below fire/explosion, as release of toxins may be secondary to hazards associated with fire/explosion but they can cause persistent environmental damage (HSE, 2024; IEC, 2020; Park et al., 2019).

Water Runoff/Groundwater and Surface Water Contamination

Firefighting water or stormwater can carry dissolved or suspended hazardous materials (electrolyte chemicals, metals) to surface or groundwater supplies, with associated ecological or human health risks. While best practices and modern BESS site designs usually include engineered drainage, containment, and stormwater management systems to prevent contaminated water from reaching natural water sources, the risk is not entirely eliminated.

Risks associated with water runoff are included in published risk matrices and government technical guidance as a high priority hazard but primarily following from catastrophic BESS failure (i.e. after fire/explosion) (HSE, 2024; Tetra Tech, 2023).

Noise and Visual Impacts

Continuous noise from fans, inverters, chillers, as well as visual/landscape effects can affect residents and wildlife. While less severe in physical terms, these impacts can be widespread and persistent where controls aren’t stringent. In standard EIAs and planning systems, noise/visual impact tend to be ranked as a moderate risk depending on proximity to residential and other sensitive receptors, as well as level of mitigation (Scottish Power Renewables, 2023).

Land Use Change and Habitat Disruption

Large-scale BESS sited on agricultural land, semi-natural land, or close to protected areas can fragment or disrupt habitats, although the impacts are significantly limited compared to solar or wind developments. Assessment of these impacts are mandated within the environmental impact assessment framework and tend to be ranked lower in response to responsible siting (World Bank, 2023).

Routine and Minor Emissions

Many BESS release low levels of gases (hydrogen, CO_2, trace VOCs) as well as degraded chemicals during normal operation. These emissions are very low, especially compared to fossil-based or combustion-based technologies. Studies show that these emissions are short-lived, highly localized, and tend to dissipate quickly with minimal impact often not requiring air quality permits under regulatory regimes. In most circumstances, this is considered to be the lowest environmental risk except in rare, poorly ventilated scenarios. In theory, these releases are regulated under air quality standards (Lin et al., 2024).

A structured semi-quantitative risk ranking for BESS environmental hazards applies a red-amber-green (RAG) framework, assessing each category using established criteria: consequence severity, geographical extent, persistence, and relevant receptor impact (the latter applies to pollutant emissions scenarios only) (Table 8.1). This methodology aligns with standard EIA practice, IEC 2020 risk protocols, and guidance from peer-reviewed studies. For each risk type, a final column summarises practical mitigation options, many of which are already integrated at the planning and design stage for BESS development.

Table 8.1. Risk Matrix

Risk	**Severity**	**Geographical extent**	**Persistence**	**Relevant receptor impact**	**Mitigations**
Fire/Explosion	🟥	🟥	🟨	Air (water and soil via deposition)	Appropriate design and maintenance (e.g., cooling systems, BMS, fire barriers). Systems in place to prevent electrical or mechanical damage (e.g., inspections, cable protection, sensors).
Acute chemical release	🟥	🟥	🟨	Air Water Soil	As above, plus: Measures to prevent build-up of gases (e.g., ventilation) and containment to avoid fluid releases reaching surrounding environment (e.g., bunding, drain interceptors).
Water/runoff contamination	🟨	🟥	🟨	Water Soil	As for Fire/Explosion, plus controls to prevent uncontrolled release of firewater to surrounding environment (e.g., retention ponds, isolation valves).
Land use/habitat	🟨	🟨	🟥	Biota	Suitable siting of facility during development and planning phase (e.g., brownfield preference). Where relevant, apply Biodiversity Strategy measures (e.g., habitat offsetting, buffer zones).
Noise/visual impacts	🟩	🟨	🟥	Biota	As for Land use/habitat, plus correct specification of equipment generating heat or sound (e.g., low-noise fans, acoustic enclosures, screening vegetation).
Routine/minor emissions	🟩	🟨	🟨	Air	Correct specification and maintenance of installed systems (e.g., sealed units, filters, regular servicing).

9. Concluding Remarks

Battery Energy Storage Systems (BESS) are rapidly becoming integral to Scotland's transition to a low-carbon, renewables-led energy system, offering solutions to intermittency and grid stability while contributing local economic benefits. Although lithium-ion remains the dominant technology, emerging alternatives such as sodium-ion, flow, and graphene-zinc batteries hold promise for addressing safety, sustainability, and operational challenges unique to Scotland's environment. As BESS deployment accelerates, robust, yet often non-statutory, regulatory frameworks and continuous risk assessment will be vital for managing relatively rare hazards such as fire, chemical releases, and environmental impacts. The Scottish experience of BESS deployment and its integration with renewable generation should contribute to a valuable blueprint for advancing safe and sustainable energy storage integration more widely.

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